EFFECT OF PARTICLE SHAPE ON INERTIAL FOCUSING

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ABSTRACT

Here we evaluate how microparticle shape affects inertial focusing in a microchannel, towards high-throughput shape-based separations. Particles tested in this study consist of 6 µm spheres and rods with different aspect ratios ($R=1:3$ and $1:5$). We assessed the focusing positions of these different particles in channels with different widths and flow rates, and verified that different shaped particles migrated to separate equilibrium positions. Further, through numerical simulations, we determined that the focusing position of the examined particles, regardless of its shape, corresponds to the focusing position of a sphere with similar rotational diameter.

KEYWORDS: Inertial Focusing, Particle Shape, Jeffery Orbits

INTRODUCTION

Focusing of particles and cells using intrinsic inertial effects in microfluidic systems is a promising technique for low cost cytometry, size-based cell separations, and cell washing [1]. Previous works have investigated spherical particles and characterized the ability to separate or focus particles based on only the overall particle diameter [2, 3]. However, particles of interest to separate and focus, such as bacteria, viruses, marine organisms, and bar-coded particles possess a variety of shapes likely to have different hydrodynamic interactions. Here we evaluate how the shape of a particle (while conserving volume) will modify its dynamic equilibrium position in a microchannel under inertial conditions.

THEORY

Recently, Di Carlo and others have shown that inertial focusing can be used to separate microparticles and cells in microchannels [1, 2, 3]. Briefly, two inertial forces are involved: (i) a shear gradient lift force and (ii) a wall effect lift force, inducing particle migration across streamlines when the particle Reynolds number $R_p$ is of order 1 ($R_p = Re(a/H)^2$) with $a$ being the particle diameter, $Re$ the Reynolds number $Re = \rho U_m D_H/\mu$, $\rho$, $U_m$, $\mu$ being the density, maximum velocity, dynamic viscosity of the fluid, $D_H$ the hydraulic diameter of the channel, defined as $D_H = 2WH/(W+H)$. In rectangular or square channels, particles generally migrate to 2-4 distinct equilibrium positions which depend on the fold of symmetry of channel cross-section.

EXPERIMENTAL

6 µm spherical beads (Polyscience) were stretched to rods with different aspect ratios ($R=1:3$ and $1:5$), following the protocol published previously by Champion et al. [4] (Figure 2). Particle suspensions were injected into a straight channel ($H=45\mu m$, $W=25$, $30$ and $35\mu m$) using a syringe pump, at flow rates ($Q$) ranging from 20 to $110\mu L/min$. Particle average equilibrium position ($X_{eq}$) was quantified 4 cm away from the inlet, using high-speed microscopy and a Matlab code which detects particles in each image frame and outputs their size and position. Experiments with beads of the same volume but with different shapes were conducted to study the contribution of shape to $X_{eq}$ for different channel widths and flow rates, $Q$, corresponding to different channel Reynolds numbers ($Re$).

Figure 1: (A, B, C) The microfluidic device used for shape-based separation consists of a simple straight 4cm long channel. Equilibrium positions are measured at the channel outlet, 4cm downstream of the inlet. (D) A table summarizing particle shape and stretching ratios. (E) Pictures of each kind of particle and the corresponding equilibrium position.

In view of separation applications, a Separability Factor ($S_{Type1-Type2}$) can be calculated as the difference in average focusing positions between two kinds of particles, normalized by the average of their standard deviations.
RESULTS AND DISCUSSION

Histograms are plotted for different channel widths and flow rates to illustrate the variation of distribution for various shaped-particles (Figure 2), while the average equilibrium positions, $X_{eq}$, are presented in Figure 3.

(i) As expected [1], initially randomly distributed particles with various shapes migrated towards the channel centerline as $Re$ increased to 13 (20µL/min). Most importantly, different shaped particles migrated to separate equilibrium positions (Figure 2.A).

(ii) In 35µm wide channels (closer to a square shape than other channels tested), as the fluid inertia increases ($Re=72, 110µL/min$), both spherical and rod-shaped particles started to focus and occupy four focusing positions (Figure 2.B, arrow). For future separation applications, focusing on several streamlines may be problematic.

(iii) Decreasing channel width from 35 to 30µm changes the aspect ratio of the channel cross-section, which leads to migration to only 2 distinct equilibrium positions. At 30µL/min ($Re=21$), 1:5 rods were initially separated from spheres and 1:3 rods (Figures 2.D and 3.A): $S_{Spheres/Rods1:3}=0.24$, $S_{Rods1:3/Rods1:5}=2.26$. As $Q$ was increased to 40µL/min ($Re=28$), both families of rods migrate further away from spheres and from each other (Figures 2.E and 3.A), making possible a shape-based separation. At 40µL/min, $S_{Spheres/Rods1:3}=0.85$, $S_{Rods1:3/Rods1:5}=1.46$.

(iv) As $Re$ increased further ($Re=49, 70µL/min$), rods tended to move closer to the walls and where spheres are located, reducing the gap between focusing positions (Figure 2.F and 3.A). At 70µL/min, $S_{Spheres/Rods1:3}=1.05$, $S_{Rods1:3/Rods1:5}=0.51$. These results clearly suggest that an optimum condition exists that maximizes the distance between particle positions and allows for the most efficient particle separation.

(v) Decreasing channel width further to 25 µm makes it difficult to focus all particles. Indeed, even at $Re=37 (50µL/min)$, 1:5 rods are still not focused to a unique streamline (Figure 2.C).

Comsol simulations of equilibrium positions exhibit differences in comparison with experimental results (Figure 3.C) of the focusing position of rods ($W=30µm$, $Q=40µL/min$). This is likely due to their rotation following Jeffery orbits (data not shown), in which the rods are periodically pushed away from the wall (the rotation is not numerically modeled here). However, simulations of spheres with the rods longest dimension ($b$) as the diameter, agree well with experiments (Figure 3.D) and reveal that all tested particles -whatever their shape- follow the focusing trend of spheres with similar rotational diameter. These results are similar to those obtained recently by S. C. Hur et al. with other shapes [5].
CONCLUSION

In conclusion, we emphasized here that (i) inertial microfluidics can be used for the focusing of rod-shape microparticles, and (ii) different shapes will exhibit different equilibrium positions. Shape-dependent differences in particle alignment are important because they may result in a considerable increase in the measurement uncertainty for optical and dielectric cytometry systems that depend on precisely focused streams [6]. Notably, these results could also be applied to high-throughput shape-based sorting of biological particles, such as for extraction of parasites in a blood sample, or to perform quality control during synthesis of encoded microparticles based on their aspect ratio [7].

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REFERENCES


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