DEAN FLOW-COUPLED INERTIAL FOCUSING FOR ULTRA-HIGH-THROUGHPUT PARTICLE FILTRATION

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ABSTRACT

Particle manipulation represents an important and fundamental step prior to counting, sorting and detecting bio-particles. In this study, we report dean-coupled inertial focusing of particles in flows through a single curve microchannel at extremely high channel Reynold numbers (~325). We found the lateral particle focusing position, x_f to be fixed and largely independent of radius of curvature and whether particles are pre-focused (at equilibrium) entering the curvature or randomly distributed. Finally, using a single inlet, u-shaped, microchannel we demonstrate filtration of 10µm particles from 2 µm particles at throughputs several orders of magnitude higher than previously shown.

KEYWORDS: Inertial focusing, filtration, micro separation, Dean flow

INTRODUCTION

Particle focusing is a necessary step for concentrating, detecting, sorting and focusing bio-particles. The enrichment of particles is an essential technique for sample pre-treatment for downstream bio-analyses. Microfluidics has the potential to overcome the shortcomings associated with large-scale equipment through reduction of analyte and reagent volumes as well as favorable scaling properties of several important instrument processes. Microfluidics is particularly amenable to gentle and high throughput cell handling. Very recent, inertial-induced forces developed in microchannels have been proposed by us and others as a promising approach for particle focusing, filtration and separation [1-4]. In inertial microfluidics, dominant inertial forces cause particles to move across streamlines and occupy equilibrium positions along the faces of microchannel walls [1]. The addition of curvature reduces the focusing points by introducing a secondary cross-sectional flow field (Dean flow) characterized by the presence of two counter-rotating vortices located above and below the plane of symmetry of the channel. Using a spiral microchannel, we recently demonstrated for the first time the emergence of two focusing points along the height of the channel and hypothesized the balance between dominant lift forces (F_L) and Dean forces (F_D) as responsible for particle focusing [3-4]. Although recent intense activity in the field, there is limited understanding on how the curvature affects the focusing of particles. In this study, using a u-shaped single curved microchannel, we systematically analysed the interaction of secondary forces with particles and show how randomly distributed particles entering the curvature are focused at a fixed lateral position over a range of radius of curvature and channel aspect ratio. We apply the system for ultra-high throughput filtration applications.

THEORY

Lateral migration of particles across streamlines due to inertial forces (shear induced lift, F_{LS}, and wall induced lift, F_{LW},) was first described by Segré and Silberberg [5]. In flows through curved channel geometries, in addition to lift forces, secondary flows (i.e. Dean flow) due to centrifugal effects on the fluid act on particles and affect the particle equilibrium positions. Secondary Dean flow is characterized by counter rotating vortices, located above and below the plane of symmetry of the channel, such that the flow at the midline is directed outward to the outer wall and fluid at the top and bottom are directed inward. Fig. 1 shows a schematic illustration of how the different lateral forces (F_D, F_P, and F_{CTF},) can interplay with dominant lift forces (F_{LS} and F_{LW}) to trap particles at a single lateral position as they exit from the curved, u-shaped, channel.

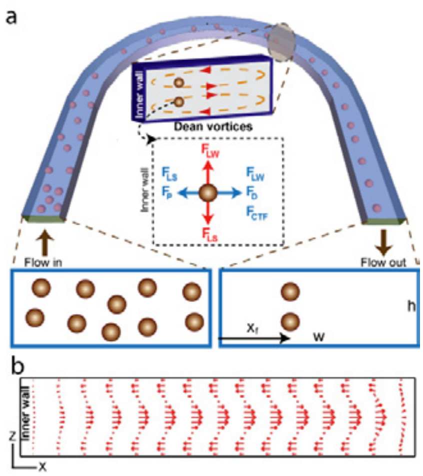

Figure 1: (a) Particle focusing in flow through curved channels. Inset: Dominant forces acting on a particle forcing it to focus in a distinct lateral position exiting the curved channel. (b) Dean flow due to centrifugal effects on the fluid.

Among the lateral forces, Dean force is the dominant and act upon particles entrained in the vortices and are directed in the direction of Dean vortices flow (Fig.1b). Depending on where the particles are in z-height, pressure drag due to curvature is an additional force of significance as it can counteract Dean forces.

EXPERIMENTAL

The experimental system consist of analyzing fluorescent beads flowing through different curved "u-shaped" channels, fabricated in PDMS using standard soft lithography methods. Internally dyed green and red fluorescent polystyrene microspheres (Thermo Scientific.) were diluted to 0.1-0.5% vol with deionized water with 0.1% Tween 80 (Fisher Chemical). The solutions were pumped by a syringe pump (Harvard Apparatus PHD 2000) connected by tubing to the channel inlet. The device was mounted onto the stage of an inverted fluorescent microscope and fluorescent streak images were obtained. For filtration application, a suspension mixture of 10µm (green) and 2µm (red) were pumped together through the device and collected in four fractions. The output were quantified by a coulter counter.

RESULTS AND DISCUSSION

Experimentally, we tested a wide range of flow rates, 2 < De < 80, using several u-shaped, single-turned, devices where we systematically varied the radius of curvature and aspect ratio (AR). We kept the height of the channel constant (50µm), while we varied the width to get different AR (1:1; 1:2; 1:5: 1:10 and 1:20). We obtained single stream focusing for AR 1:1 to 1:10, while AR 1:20 (channel width = 1mm) did not result in any focusing, presumable due to insufficient lift and dean forces developed at the experimental flow rates used (< 7 mL/min). Fig. 2 shows fluorescence image of 10 µm particles, initially well distributed entering the curved channel, focused into a single stream exiting the 180 ° u-shaped channel for AR 1:5 (a) and 1:10 (b). The particles, well distributed across the channel width entering the channel, are focused into a single lateral focusing point exiting the curved section of the channel. In addition, particles move more inward than outward, indicating that the particles are entrained in the Dean vortices and quickly find their lateral focusing positions when exiting the curved section of the channel. We analyzed the De dependence of particle entrainment in the dean vortices in detail. The crossectional intensity of the particles at the entrance and exiting points (see arrows in Fig. 2a-b) of the curved section is shown in Fig. 2c (AR 1:5) and Fig.2d (AR 1:10). At low De, the 10 µm particles were distributed across the width of the channel exiting the u-shaped curved channel due to the weak secondary forces developed at these velocities. When the flow was increased to De = 36 for AR 1:5 (Fig.3c) and De=41 for AR 1:10 (Fig.3d), particles are entrained in the Dean vortices and migrate across streamlines towards a single lateral focusing point due to increased Dean forces. When the fluid velocity is increased, the particles are pushed further away from the inner wall resulting in defocusing, visualized as broadening of the intensity streaks away from the inner wall in comparison to the single stream focusing point.

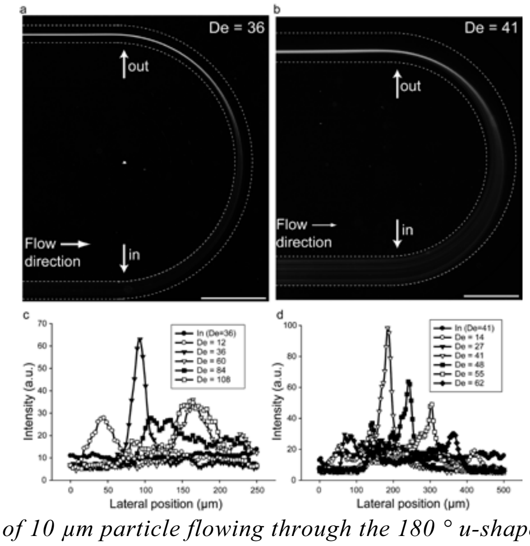

Figure 2:(a-b) Fluorescence image of 10 µm particle flowing through the 180 ° u-shaped channel with channel width of 250µm (a) and 500µm (b). (c-d) Crossectional intensity of the particles at the entrance and exiting points (see arrows in Fig.2a-b) for channel width of 250µm (c) and 500µm (d) over a range of flow rates. Scale bar: 1mm.

Interestingly, we found the lateral particle focusing position to be fixed and independent of radius of curvature (Fig.3). Our results indicate that particles can be predicted to a fixed lateral focusing position. To evaluate the lateral focusing position more detailed we designed and evaluated a new sets of "s-shaped" curved channels (Fig.4). The unique geometry allows for "priming" the particle entering position to the second curvature without "cross-talk" of the secondary forces from previous curvature since the flow field change direction. The particles, pre-focused in the first curvature, are maintained focused exiting the second curvature at a fixed lateral focusing position (Fig.4). The lateral focusing position is in agreement with results in Fig.3b.

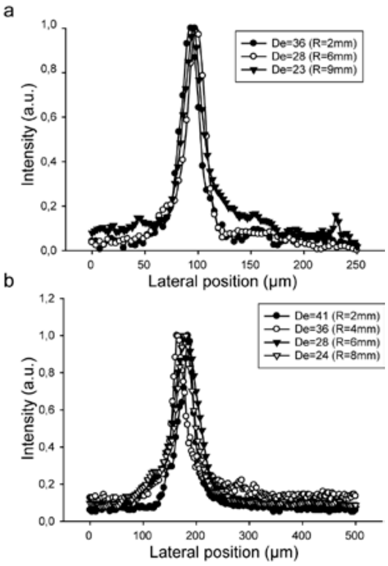

Figure 3: Crossectional intensity of 10µm particles at the exiting points of the curved section for channel width of 250µm (a) and 500µm (b) over a range of radius of curvature. The lateral focusing position was fixed and independent of radius of curvature.

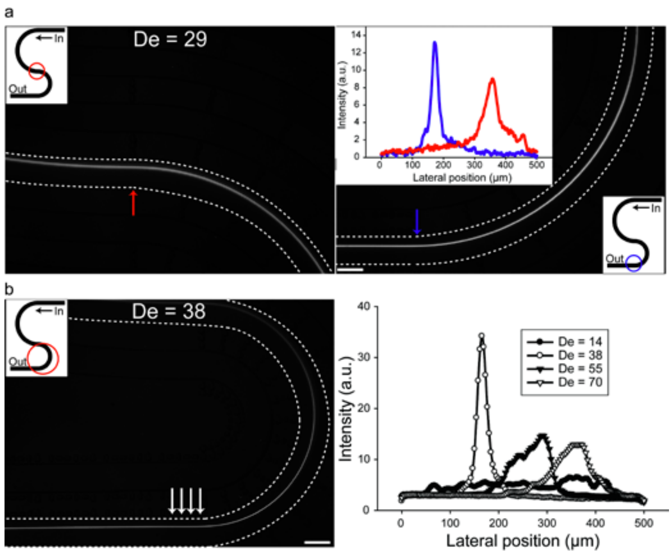

Figure 4: Summary of flow through "s-shaped" double curved channels. (a) Particles, pre-focused in the first curvature of the s-shaped channel (left panel), are maintained focused exiting the second curvature (right panel) with radius of curvature of 4 mm. Inset (right panel), the crossection intensities of particles entering and exiting the second curvature (red and blue arrow) is shown. (b) Intensity of particles flowing through the second curvature with radius of curvature of 2 mm (right panel) and average intensity of the area marked with arrows (left panel). The lateral focusing position was fixed (see Fig.2b for comparison). Scale bar: 500 µm.

Finally, we used the fact that particles focus at a deterministic and fixed lateral focusing position to design a u-shaped device for filtration applications with a single inlet and four outlets. As show in Fig.5, we demonstrate continuous focusing and filtration of 10µm particles from a suspension mixture at throughputs several orders of magnitude higher than previously shown (vol. flow rate of 4.25 mL/min).

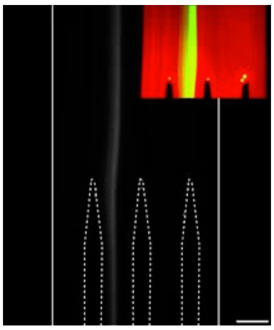

Figure 5: Ultra-high-throughput filtration. 10µm particles are successfully focused and filtered through outlet two, while 2µm particles are unfocused and scattered everywhere (see inset) at flow rate of 4.25 mL/min. Scale bar: 100µm.

CONCLUSION

In summary, we report novel findings in flows through single curved channels. We found the lateral particle focusing position to be fixed and largely independent of radius of curvature and whether particles entering the curvature are pre-focused (at equilibrium) or randomly distributed. We successfully demonstrated continuous particle filtration application, at the highest sample throughput yet reported. The simple, device requiring neither external force fields nor mechanical parts to operate is readily applicable for low cost particle focusing, filtration and separation applications.

ACKNOWLEDGEMENTS

This work is financed by the EU sponsored FP7 project InTopSens (www.intopsens.eu).

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