CONTROL OF INTERPARTICLE SPACING USING STRUCTURED MICROFLUIDIC CHANNELS

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ABSTRACT

We report a technique for controlling interparticle spacing and position for inertially-focused particles at high concentrations using structured microfluidic channels. Particle control in flow holds many applications in the development of more efficient microfluidic platforms such as in particle encapsulation for droplet microfluidics, particle separation techniques, and high-throughput flow cytometry. We have evaluated how channel structures, or localized changes to channel width, affect particle behavior and report the following modes of control: expansion and contraction of interparticle spacing, improved accuracy of focusing, and shift of equilibrium positions towards the channel walls.

KEYWORDS

Inertial microfluidics, structured channels, particle control.

INTRODUCTION

High-throughput particle control in microfluidic systems requires operation at high concentrations and at high velocities. Since inertial effects on particles in flow are known to scale with velocity [1], our approach makes use of inertial microfluidics to focus particles and control particle interactions in a high-throughput manner.

Previous work investigating the effects of large channel expansions on particle interactions has been conducted in the context of particle defocusing, particle separation, and vortex formation [2-4]. However, controlled manipulation of particle-particle interactions using refined channel expansions to promote ordering and focusing, as presented in this paper, has been largely unexplored. We have investigated how structures affect particle behavior through the induction of local secondary flows and discuss potential applications for our system.

EXPERIMENT

Particles in flow were focused to equilibrium streams where a balance of the inertial lift force and the shear gradient lift force occurs upstream of the structures [1]. Flow rates tested ranged from 50-100 µL/min, giving Reynolds numbers (Re) between 15-35 for a given geometry. Particles tested were 9.9 µm in diameter, with length fraction (λ) between 0.26-0.59. The number of equilibrium positions observed was dependent on the channel cross-section [1]. Single- stream focusing was achieved by the use of sheath fluid in experiments where one focusing position was desired. Flow was driven with the use of syringe pumps.

Two main categories of structures were tested: extended chambers (Figure 1A), and repeated localized structures (Figure 1B-D). The changes to channel width ranged from 1.6x to 2.25x the original channel width.

High-speed images were analyzed using MATLAB image analysis. Characterization of the structured channels resulted in four main modes of particle control, as summarized in Figure 1.

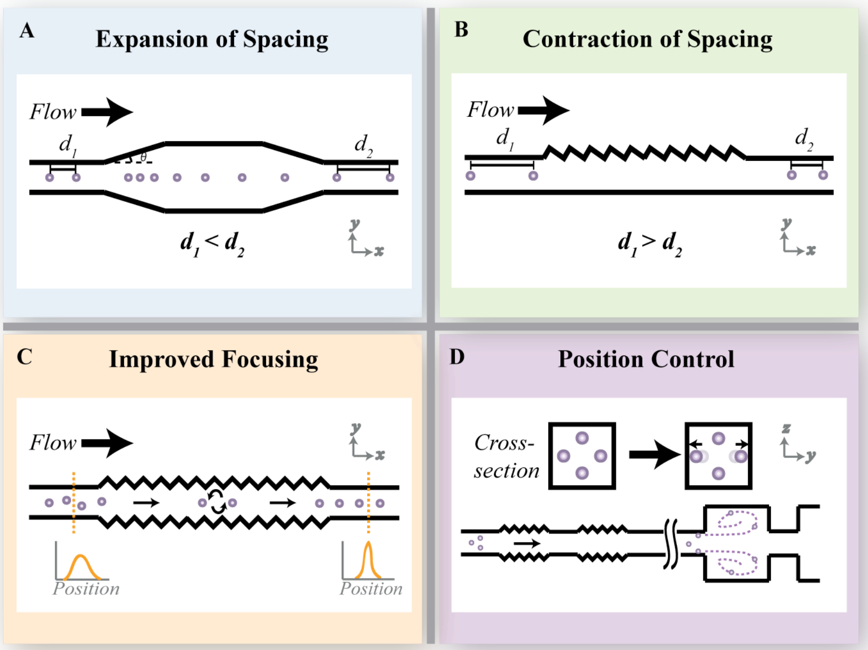

Figure 1: Structured channels create favorable modes of particle control. *(A) Extended chambers result in expansion of interparticle spacing. (B) Asymmetric structures result in contraction of interparticle spacing. (C) Structured channels create secondary flows that allow particles to sample equilibrium positions and improve accuracy of focusing. (D) Alternating structured channels cause a shift of equilibrium positions towards the channel walls, which is useful in particle separation techniques such as vortex trapping. Note: Drawings not to scale.*

RESULTS AND DISCUSSION

Structures that demonstrated an expansion of interparticle distance were extended chambers and symmetric, alternating local structures. To strengthen this effect, both structures were used in series (Figure 2A). Co-flow with water was used to reduce the number of focusing positions, thus isolating same-stream particle interactions. Particle spacing is seen to increase after exiting the structured regions, with up to a 97% increase in interparticle distances greater than 40 μm (Figure 2C). Controllable increase in particle spacing at high concentrations is useful to the development of high-throughput particle interrogation techniques as a method to prevent coincident analysis events.

Altering the geometry of the structured regions was seen to dramatically change particle behavior. In the case of asymmetric structures (Figure 3B), interparticle spacing was contracted. However, spacing between particles in different streams (cross-streams) when focused to two positions was unchanged. This suggests that the effects of the induced secondary flows do not translate strongly across different streams. The conservation of cross-stream spacing was observed across various geometries (not shown). The mechanism of the differing spacing effects is still unknown, and is currently being investigated through numerical simulations. Although contraction of spacing may not be desired past a certain threshold, control of particle spacing through both expansion and contraction is required for promoting uniform spacing across particle trains.

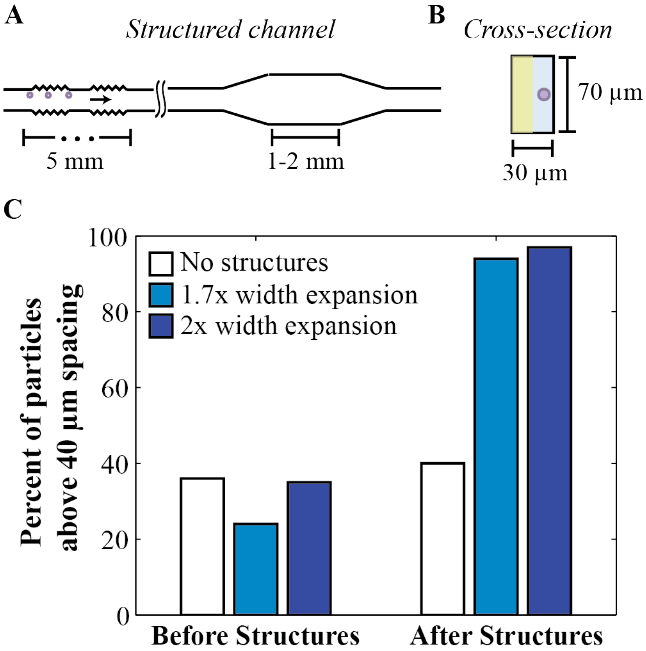

Figure 2: Symmetric structures and extended chambers expand interparticle spacing. *(A) Schematic of structures used in series to expand spacing. (B) Cross-section of microfluidic channel. Sheath fluid was used to create single-stream focusing. (C) The percentage of particles with interparticle spacing greater than 40 μm is greatly increased with the use of structures (up to 97%). Note: Drawings not to scale.*

Structured channels result in other modes of particle control in addition to spacing effects. For one, particles in structured channels were observed to focus to equilibrium positions more effectively when compared to straight channel controls (Figure 4). The induction of secondary flows by the changes to channel width likely results in a degree of particle mixing, enabling the particles to sample the equilibrium positions more quickly and effectively than in the case of straight channels with no mixing. This behavior was seen across various geometries, both symmetric and asymmetric. Improved focusing accuracy is a desirable effect in many microfluidic applications; for example, having more accurate focusing in flow cytometry can enable implementation of a tighter beam spot for optical interrogation, resulting in an increased signal to noise ratio.

A second mode of control achieved with structured channels is a shift of equilibrium positions towards the channel wall. This behavior was seen in both square cross-section channels and in rectangular cross-section channels, and is conserved across a wide range of flow rates (Figure 5). Numerical simulations were completed for a square cross-section to calculate the net change in streamlines for fluid that passes through the structured sections of alternating symmetric structures (Figure 5B). The results of the finite-element analysis show a secondary flow profile

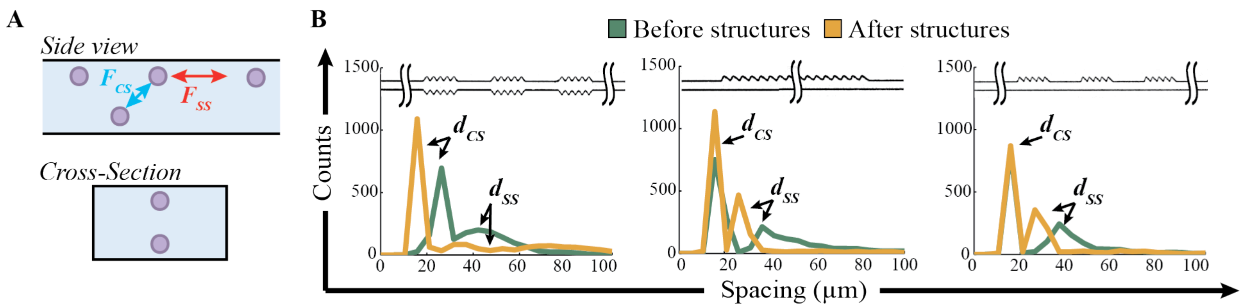

Figure 3: Effect to particle spacing depends on symmetry of structures. *(A) Schematic of particle interactions in the tested microfluidic channel (w: 80 μm, h: 30 μm). Two particle equilibrium positions exist. (B) Histograms for the distribution of particle spacing before and after specific structured channels (see inset). Same-stream spacing (d_{ss}) is expanded in symmetric structures but contracted in asymmetric structures. Spacing effects do not translate strongly across streams.*

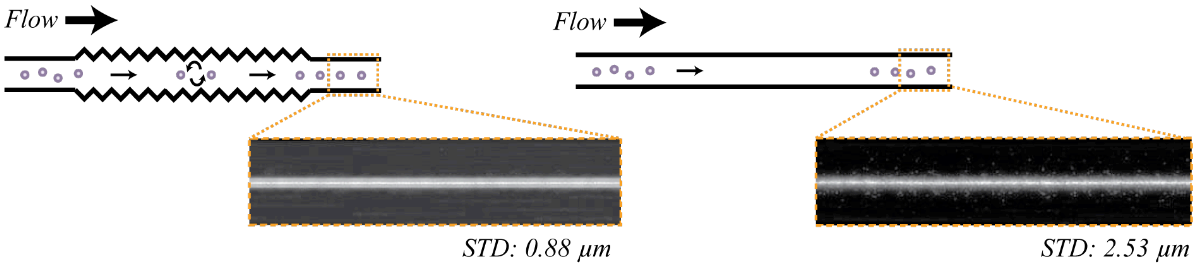

Figure 4: Structured channels improve the accuracy of focusing. *Standard deviation of the particle position for structured channels is less than for straight channels (N=1000). Standard deviation plots per 2000 images visually demonstrate sharper focusing for structured channels compared to straight channels. Images were taken at the same distance downstream in the channels. Channel dimensions are w: 80 μm, h: 30 μm.*

that agrees with the experimentally observed results. This technique can be applied to particle separation techniques such as in vortex trapping (Figure 1D) to improve capture efficiency by bringing particles closer to the vortex for selection [4].

CONCLUSION

Current particle interrogation or separation techniques require dilution of the sample to prevent coincident events statistically ensuring a minimum spacing between particles in flow, resulting in low throughput. Our system allows for operation at high particle concentrations for increased throughput while retaining a minimum interparticle distance to reduce coincident events. Differences in structure arrangement result in two modes of ordering behavior for particles in the same stream (expansion and contraction), while spacing between particles located at different streamlines is typically conserved across various geometries. The potential for creating uniform spacing through the contraction and expansion of interparticle spacing is therefore high. Additionally, our structured channels are observed to shift particle focusing positions towards the channel wall and promote improved accuracy of focusing by inducing local secondary flows, making them useful elements in inertial microfluidic systems that require high-throughput particle manipulation. Further analysis will be conducted towards understanding the range of control of this system.

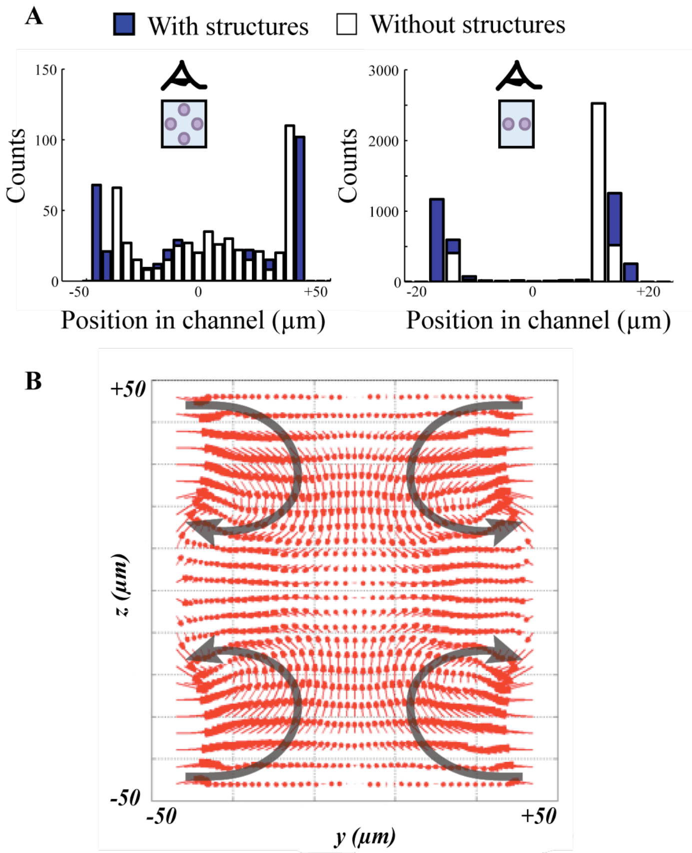

Figure 5: Structured channels shift particle equilibrium positions towards the channel wall. *(A) Histograms for particle position in channel show structured channels have focusing positions closer to the channel wall when compared to straight channel controls. This behavior is conserved across different geometries and flow rates. (B) Fluid flow simulations of the net change to fluid streamlines after passing through symmetric structures agree with experimental data (simulation for square cross-section shown here).*

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