PARTICLE ORDERING USING DEAN FORCE-BASED INERTIAL MICROFLUIDICS

Anandkumar Rane*, Xavier Casadevall i Solvas and Andrew deMello
ETH Zürich, Switzerland

ABSTRACT

Herein, we have studied the effect of channel width, particle size and concentration on particle ordering in Dean force-based devices. We observed that once the particles are focused to their equilibrium position in the channel, they tend to order at an equilibrium inter-particle distance (β). β is independent of width of the device and particle concentration, and is observed to be 18-22 μm for 10 μm and 12 μm particles.

KEYWORDS: Particle Ordering, Particle Focusing, Inertial Microfluidics

INTRODUCTION

Inertial effects in microfluidic channels are known to yield particle focusing at specific positions across the channel cross-section and a relatively uniform spacing (ordering) of particles along the channel length. Although the phenomenon of particle focusing has been characterized extensively [1], few studies have assessed the effect of experimental parameters on particle ordering; a key feature when designing devices for single cell encapsulation [2].

Lee *et. al* [3] studied the effect of inter-particle and fluid interaction on particle ordering and observed that fluid inertia is important for stabilization of inter-particle spacing. In this study, we have attempted to characterized particle ordering in Dean force-based inertial microfluidic devices by examining the influence of various experimental parameters like channel width, particle concentration and particle size on inter-particle spacing after particle focusing and ordering.

EXPERIMENTAL

Devices were based on both geometric and fluid dynamic parameters discussed in [1]. PDMS devices were fabricated using standard soft-lithographic techniques. Polystyrene beads (Sigma Aldrich) were used for all experiments. A representative device design is shown in Figure 1, with the expected equilibrium positions along cross section of channel depending on its structure.

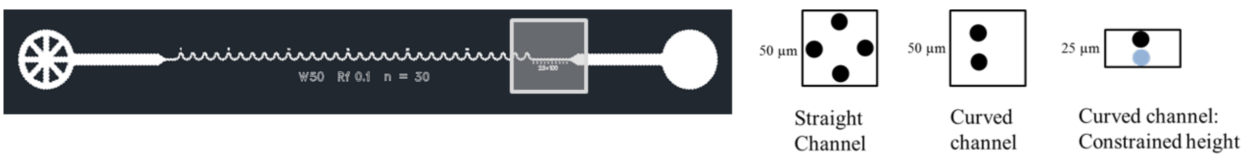

Figure 1: Representative device design with expected equilibrium focusing positions (as viewed in cross-section) for straight and curved channels. Our device has constrained height, and we expect particles to focus close to face (particles in black and blue), but occupy only one in a given cross-section of channel

A high-speed camera (MotionPro Y5, IDT, UK) was used to acquire bright-field movies of particle motion (imaging area of chip shown in Figure 1) and in-house MATLAB codes were used to analyze particle ordering. and Table 1 summarizes chip dimensions and other experimental parameters.

Table 1: Experimental Conditions

Experimental Parameter	Values
Channel Width (μm)	50,75,100
Channel Height (μm)	25
Length (cm)	1,6
Particle diameter (μm)	8,10,12,15
Flowrates (μL/min)	5-100
Particle Concentration (million/ml)	20,40,60

RESULTS AND DISCUSSION

In microchannels with square cross-sections, under high inertial conditions particles tend to focus on four equilibrium positions (Figure 1) close to each wall. This changes to two equilibrium positions (at the center of Dean vortices) under influence of Dean forces [1]. In our design we have constrained the height of Dean force-based channels with respect to particle diameter, and thus we expect particles to focus closer to the top and bottom channel walls [2]. Furthermore, we expect only one particle to occupy one of the two equilibrium positions at a given cross section of the device. Figure 2, which shows a section of a device along the height of the channel, indeed confirms the formation of these two equilibrium positions.

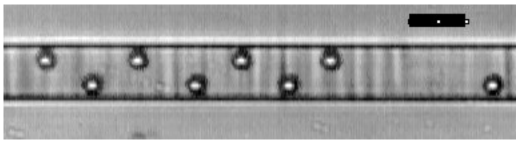

Figure 2: Imaging along height of device, illustrating particles focused to equilibrium position close to face of channel walls and a single equilibrium position occupancy at a given position in channel

Figure 3 shows *particle focusing* and *inter-particle spacing* frequency distributions for a device with a channel width of 50 µm, a particle concentration (C_p) of 20 million particles/ml (20 mn/ml) and flow rates of 5 µl/min and 25 µl/min. It is observed that while at higher flow rates focusing transitions towards an equilibrium position, ordering (inter-particle spacing) evolves in a particular way. For both flow rates, the inter-particle spacing expected from mass-balance (λ) at this concentration and in this device (assuming all particles are focused and ordered) is 40 µm. Regardless, our observations demonstrate that a large fraction of particles become ordered with an inter-particle distance (β) between 18-22 µm at higher flowrates (Figure 5A: packets with closely spaced particles).

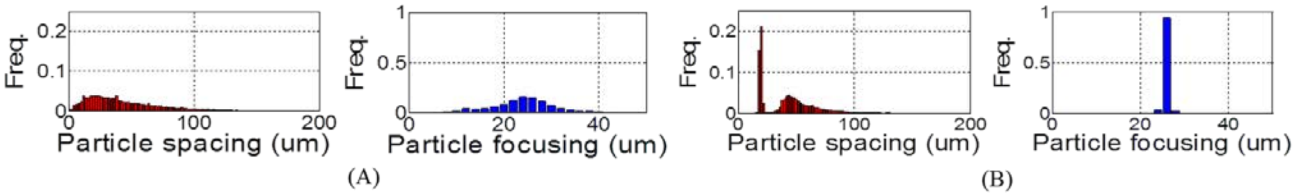

Figure 3: Particle Spacing (red) and Focusing (blue) histogram for a flow rate of (A) 5µl/min and (B) 25 µl/min in a channel with width of 50µm and a concentration of 20 mn/ml

Figure 4 shows particle spacing histogram for 10 µm particles under all the varied experimental conditions. Channel width of 50 µm and C_p of 20 mn/ml was chosen to be the reference case for studying the effects of varying width and concentration. It is observed that for all the different conditions considered, large fraction of particles are again ordered at a conserved inter-particle spacing between 18-22 µm. Furthermore, as shown in Fig 4D, a straight channel with exactly same channel cross section - a different focusing strategy - delivers a similar result, but with inter-particle spacing between 20-25 µm.

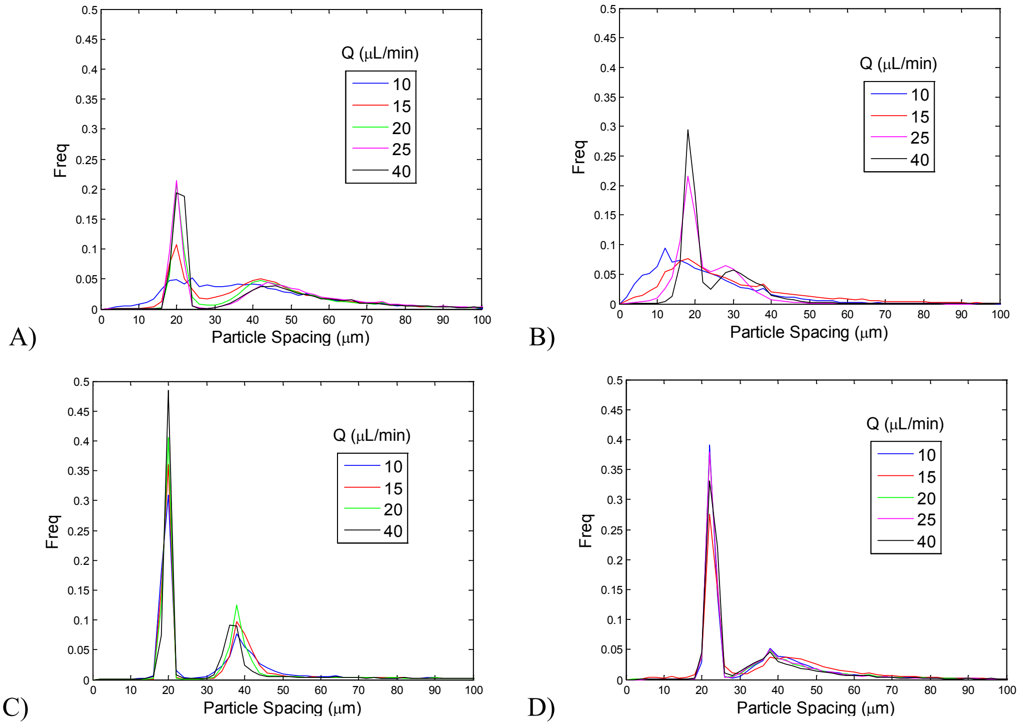

Figure 4: Effect of Channel Width, Particle Concentration and Focusing Strategy on Particle Spacing for A) W 50 µm, C_p 20 mn/ml B) W 50 µm, C_p 40 mn/ml C) W 75 µm, C_p 20 mn/ml D) Straight Channel W 50 µm, C_p 20 mn/ml

Figure 5 shows experimental data for particle ordering at varying concentration of particles under good focusing conditions. For C_p of 20 mn/ml (A) and of 40 mn/ml (B), in which cases $\beta < \lambda$, it can be seen that the particles tend to flow in packets with the same equilibrium inter-particle spacing (β). We suspect that as the flow-rate is increased, more particles are focused onto the equilibrium positions and in the process become ordered in structured packets of $\beta = 18\text{-}22$ µm.

The formation of packets is, therefore, a requirement to preserve mass balance: since in these cases $\beta < \lambda$, empty gaps of wider distance between packets are compelled to appear. To support this hypothesis, we performed the same experiment with C_p of 60 mn/ml (λ: 13 µm < β), such that occupancy of particles should be below β. It can be observed from Figure 5C that particles are not focused to their respective equilibrium positions anymore, even at focusing conditions (Q: 60 µL/min) that were very successful before. Furthermore, it can also be observed that inter-particle distance is not conserved either. Therefore, we hypothesize that since particles are too concentrated they cannot become ordered at the equilibrium inter-particle distance (β = 18-22 µm), and this hindrance disrupts both, the ordering and the focusing processes.

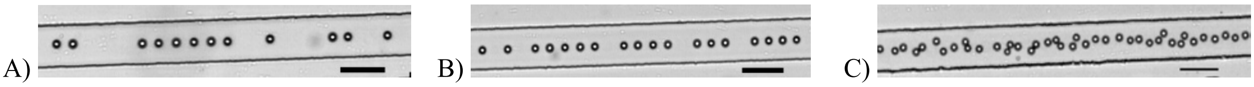

Figure 5: Effect of Particle Concentration on Ordering for A) C_p 20 mn/ml at 25 µL/min B) C_p 40 mn/ml at 25 µL/min C) C_p 60 mn/ml at 60 µL/min. Scale bars are 50 µm

The effect of particle size on inter-particle spacing was also studied and Figure 6 shows particle spacing histograms for various particle sizes on a chip with a channel width of 50 µm and height of 25 µm. It was difficult to obtain good focusing conditions for 8 µm particles for various chip designs and thus these results are not discussed here, although initial results indicate similar β as for 10 µm. It can be observed that β for 10 µm (Figure 4A) and 12 µm particles (Figure 6A) is the same with a peak between 18-22 µm, while for 15 µm particles (Fig 5B) the inter-particle spacing is 28-32 µm. Therefore, particle size seems to be a critical parameter affecting β and further studies are underway to characterize this and other effects (such as particle surface functionalization and suspension medium).

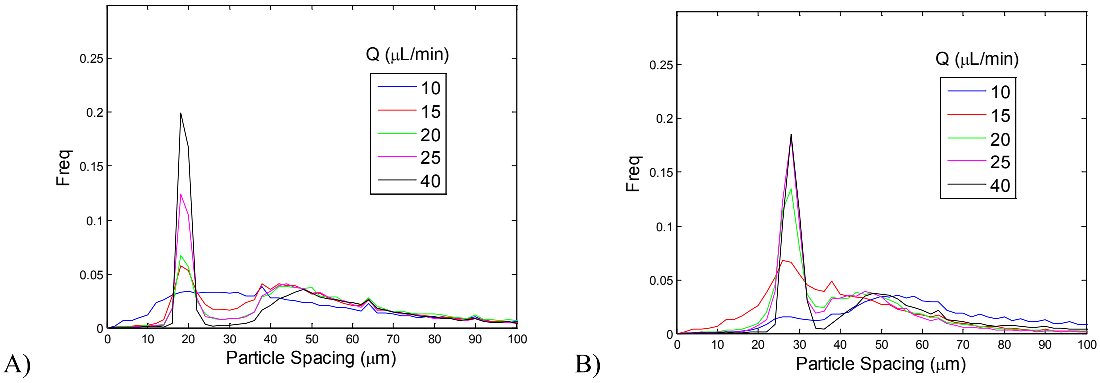

Figure 6: Effect of Particle Size on Particle Spacing for A) 12 µm particles B) 15 µm particles

CONCLUSION

In conclusion, we have investigated particle ordering in Dean force based microfluidic devices and we observe that particles after focusing, flow in structured packets with an equilibrium inter-particle spacing. This equilibrium inter-particle distance is observed under varying experimental conditions (channel width, particle concentration) for similar particle sizes. We observe different inter-particle distances for a different focusing strategy and substantially different particle sizes, and future work is carried out to characterize these effects (and possibly medium and particle type). We suspect that the formation of the conserved inter-particle distance is a result of fluid-particle interactions and we are carrying out further investigations to better understand this phenomenon.

REFERENCES

[1] "Continuous inertial focusing, ordering, and separation of particles in microchannels", D. Di Carlo, D. Irimia, R. G. Tompkins and M. Toner, Proc. Natl. Acad. Sci. U. S. A.,**104**, 18892–7 (2007)

[2] "Controlled encapsulation of single-cell into monodisperse picolitre drops", Jon F. Edd, Dino Di Carlo, Katherine J. Humphry, Sarah Koster, Daniel Irimia, David A. Weitz, Mehmet Toner, Lab on a Chip, **8**, 1262–1264 (2008)

[3] "Dynamic self-assembly and control of microfluidic particle crystals", Lee W, Amini H, Stone HA, Di Carlo D, Proc Natl Acad Sci USA,**107**,22413–22418 (2010)

CONTACT

*Anandkumar Rane, tel: +41 446334314; anandkumar.rane@chem.ethz.ch