Geometry Induced Microparticle Separation in Passive Contraction Expansion Straight Channels

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***Abstract*—Particle separation in passive micro fluidic channels has been investigated in straight channels with contracting and expanding geometry is studied. The angles in the entrance of contacting part of the channel are varied and the influence of the forces on the particle focusing is studied at various fluid flow rates. Single focusing position could be achieved for a certain flow rate and an angle of inclination at the entrance of a contracting part in the direction of flow.**

Keywords- microparticle; separation; wall effect; focusing.

I. INTRODUCTION

Microparticle separation techniques have attracted extensive attention for their importance in clinical diagnostics, treatment, and various biomedical applications. Most common separation techniques involve centrifugation and membrane based filtration on macro scale systems. Microfluidics based particle separation systems have advantages over these techniques due to small amounts of sample and reagent, less time consumption, lower cost and high throughput. In general, separation techniques could be categorized as passive and active with respect to any available applied external forces. Active separation systems require external forces such as ultrasound, magnetic field, and dielectric field for controlling the behavior of the particles suspended in fluid [1–2]. Passive separation techniques do not require external forces; the separation relies entirely on the hydrodynamic effects, which are mainly caused by channel geometry. However, most of the passive separation systems suffer from low throughput and filtration efficiency due to low channel Re numbers [1–2].

The first experiment about inertial forces was accomplished by Segre and Silberberg [3] in which particles migrate to a radial equilibrium position at the pipe radius of 0.62 from the axis of the pipe, which is known as "Tubular Pinch Effect". Working with a wide range of Re numbers, Matas et al. [4] experimentally confirmed the tubular pinch effect and found that the equilibrium positions shift towards the wall with increasing Re. Kim et al. [5] observed that particles focused to a narrow band along the perimeter, which is about 0.2 D_h (hydraulic diameter) in low Re number (Re < 20). On the other hand, Di Carlo et al. [6] investigated the inertial focusing in a straight microchannel and proved that uniformly distributed particles in rectangular channels migrate across the streamlines of four symmetric equilibrium positions at the centers of the sides and move closer to the walls as particle Re number increases. Lateral migration of particles mainly depends on the ratio of the particle diameter to the channel hydraulic diameter (a_p/D_h). Inertial effects are significantly large and particle focusing occurs in short distances in $a_p/D_h > 0.07$ criterion. They also point out that the focusing positions that occur in the straight channels can be determined by the fold symmetry of the channel's cross section. In a rectangular channel the flow will have two focusing positions [7]. Di Carlo et al. [8] also studied the equilibrium positions of cells with comparing the expanding channel types. It was determined that the equilibrium positions moved closer to the channel centerline in rapid expanding channel while they were closer to the channel wall in the gradual expanding channel. Recently, Asgar et al. [9] discovered that the inertial focusing positions of particles in a straight microchannel also depend on the channel aspect ratio. They found that particles converge to an equilibrium in two focused streams along the longer sidewalls for both H/W > 1 and W/H > 1 (H: Height, W: Width) at the same channel Re number. Shear gradient induced lift force is linked to the flow velocity profile at the location of the particle. Due to its larger weight and size, the particle moves a little more slowly than the fluid and relative velocity is larger on the wall side, a pressure difference acts on the particle to push it towards to the wall. The second lift force where induced lift force is linked to the vicinity of the solid surface is called as wall effect. The relative velocity closed to the wall side of the particle is reduced by the presence of the wall, and the pressure on the wall side is larger than that on the centerline side. A lift force is exerted on the particle towards the channel center.

In this study, straight microfluidic channels with contracting and expanding geometry are studied. The angles in the entrance of contacting part of the channel are varied and the influence of the forces on the particle focusing is measured at various fluid flow rates.

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II. MICROCHANNEL DESIGN

The angle of the entrance to contraction part was varied while other parameters were kept constant. Schematic view of the designed channel geometry is shown in Fig. 1, and dimensions are given in Table 1.

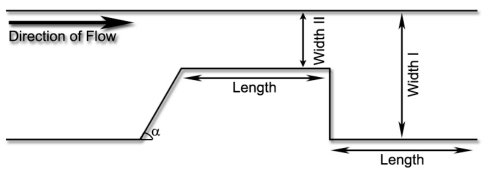

Figure 1. Schematic view of designed channel geometry

III. METHODS

A. Fabrication

SU – 8 3050 (MicroChem Corp.) was spun on the 4 inch Si wafer at 500 rpm for 10 s with 100 rpm/s acceleration and then 3000 rpm for 30 s with 300 rpm/s acceleration. A soft bake process was done at 95 °C for 15 min. After lithography, SU–8 coated wafer was post baked at 65 °C for 1 min. following at 95 °C for 5 min, and developed. Then it was placed in a petri dish for PDMS casting. Vacuum oven was used for degassing the PDMS and kept at the curing temperature of 150 °C for 2 hours. After curing, PDMS was peeled off the mold and placed in oxygen plasma furnace with a glass substrate side by side for the surface treatment to improve the adhesion between PDMS and glass, then both pieces were bonded together for the final construction of the microfluidic device.

TABLE 1. Design parameters of the channel geometry

Width I	100 μm
Width II	40 μm
Length	200 μm
α	30,45,60,90

B. Characterization

A mixture of 0.04 ml solution containing 1% of 9.9μm diameter green fluorescent particles and 70 mL DI water was prepared. Flow rates were determined with respect to the particle Re numbers (Re_P). It has been shown that particle inertial lift forces are dominant when $Re_p > 1$, causing the particles to migrate laterally inside the channels [10]. Flow rates and particle Re numbers used in this study are given in Table 2.

For obtaining a stable image from green fluorescent particles, exposure rate and color were adjusted with respect to red, green and blue. Exposure rates were varied between the values of 80 μs to 160 μs in which microchannel borders are not visible so that the particle images could easily be viewed. For obtaining an image over time, accumulation settings were set at 40 frames, meaning each image taken contains accumulated 40 frames.

TABLE 2. Flow rates and particle Reynolds numbers in expanding/ contracting part of channel

Flow rate (μl/min)	Re_P (expansion part)	Re_P (contraction part)
105	0,38	1,49
120	0,44	1,70
140	0,51	1,99
160	0,58	2,27
180	0,65	2,55

IV. RESULTS AND DISCUSSION

A. Focusing Positions

Using the line profile option of the DP72 microscope camera software, the positions of the accumulated particle flows images were obtained. The line profile system depends on the RGB color value of the points along the chosen line. From the RGB values focusing width and position were determined. The obtained images showing the focusing positions of the micro channels are given in Fig. 2. It can be seen from the figure highly concentrated single focusing can be obtained at certain flow rates for angled designs (30° - 45° - 60°) at the upper side of the channel for certain flow rates while this could not be possible for 90° degree design.

B. Intensity Analysis

The brightness of the color image can be obtained with using the line profile option of the microscope. By using color intensity values it can be determined whether a certain flow rate can produce a single focus or a dual focus positions. While the intensity values give the value of the brightness of the focusing, that value needs to be adjusted with respect to the width of the focus in order to normalize the intensity value. Single focusing could be categorized as high intensity over low width values. In other words, in order to define a single focusing position for a certain flow rate, its intensity/width value must be much higher than that of its second focusing position value. Furthermore, for the single focusing position determination at different flow rates intensity/width value is divided by the flow rate values to normalize the color intensity with respect to flow rate. The obtained results are shown in Fig. 3. Left side of each graph corresponds to expansion region of the channel while the right side corresponds to contraction part of the channel. From the graphs, for a certain Re_P value whether a focusing position is single or double is seen. Mark x shows the single focusing positions. For 45 and 60 degree designs have single focusing for two different flow rates in the contraction part of the channel while 30 degree design has only one and 90 degree design has none.

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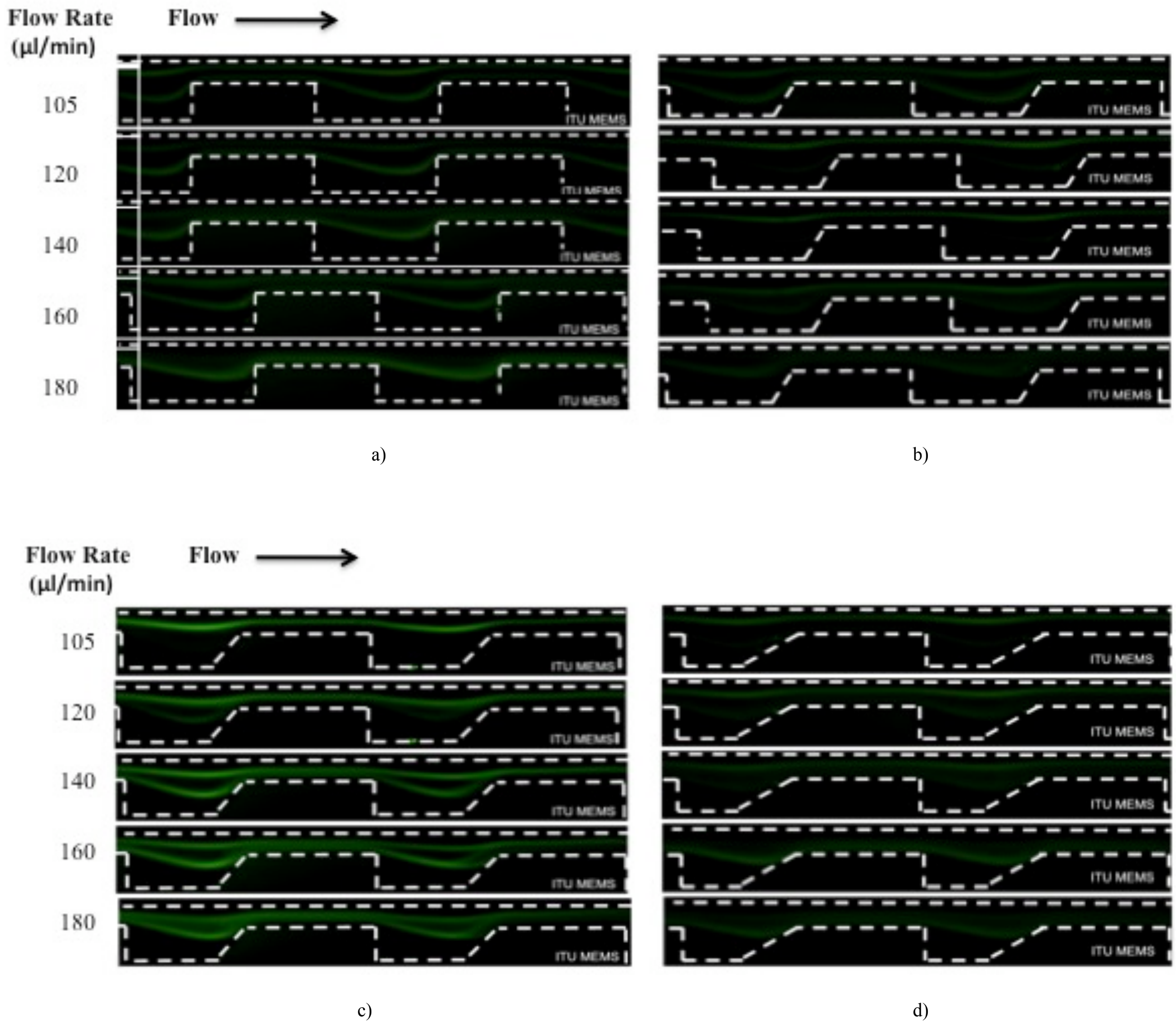

Figure 2. Particle flow with different angle of entrance at contraction part a) 90^o b) 60^o c) 45^o d) 30^o

V. CONCLUSIONS

Single focusing position could be achieved for a certain flow rate and an angle of inclination at the entrance of a contracting part in the direction of flow. This result can be explained with the vortex forces prior to the contraction part and the wall effect at the proposed angle. Fig. 4 illustrates these forces affecting the particle in the channel. From this figure, the x component of the vortex force will be decreasing with decreasing angle. This force is in the direction of the flow causing an increase in the flow rate. But that effect will not have significant effect at low angle values causing no change in the flow rate. In 60°, 45° and 30° channel designs there exists a wall induced inertial lift force which affects prior to the contracting part. This lift force is perpendicular to the angled wall so that its x and y components are not same for different angle values. It has lower x component in lower angled designs. The x component of this wall induced inertial lift force has a decelerating effect for the fluid and particle flow and the y component of this wall induced inertial lift force is the main driving force for obtaining the single focusing position. The x component of the wall induced lift force of 60° design is higher than that of 45° or 30° design, at which the fluid flow will be affected more and its flow rate will be lower than those designs. As a result, a single focus was obtained in even expansion part of the channel at certain flow rates for 60° design.

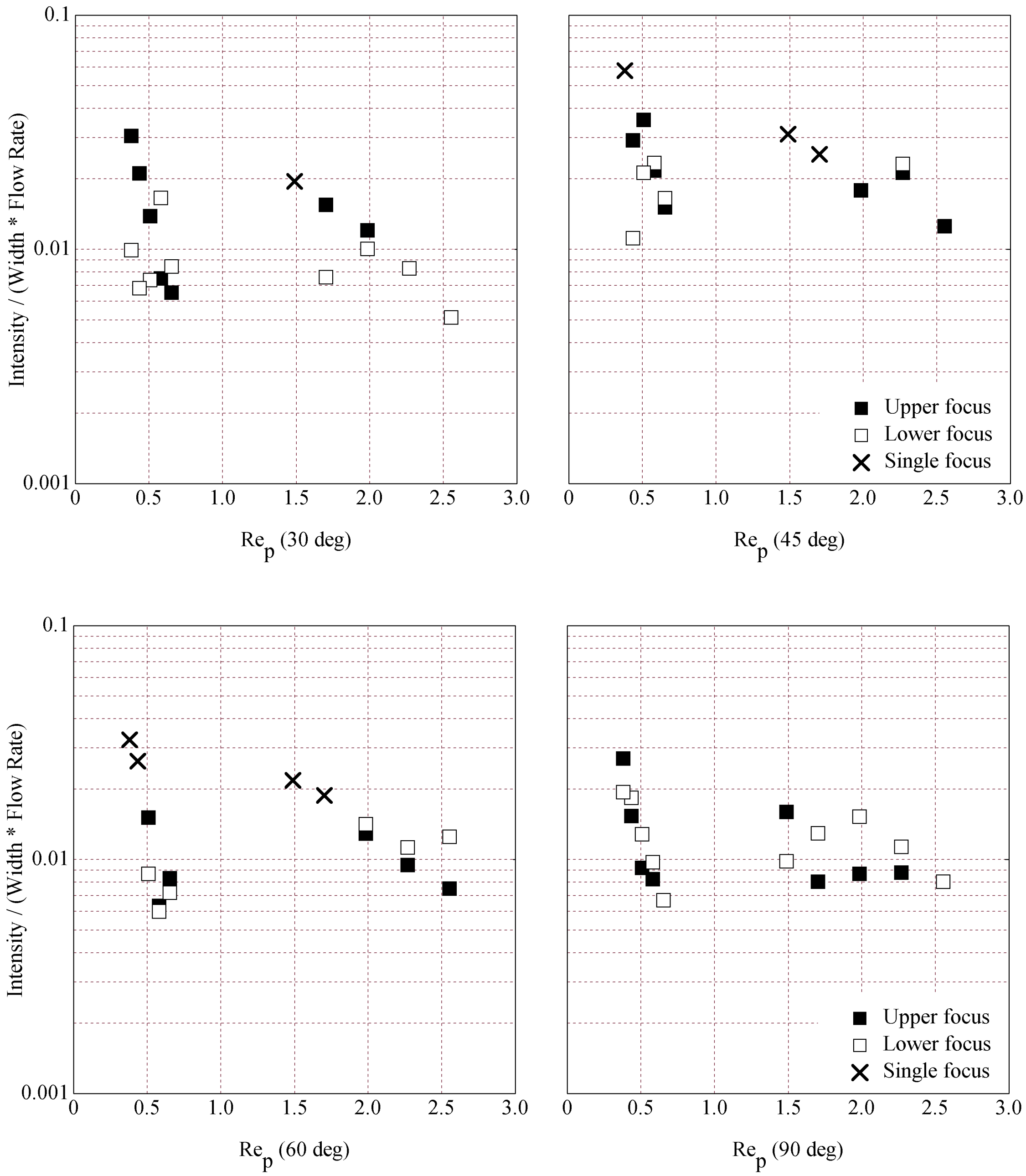

Figure 3. Normalized intensity vs. Particle Reynols number for channels with different angle of entrance at contraction part

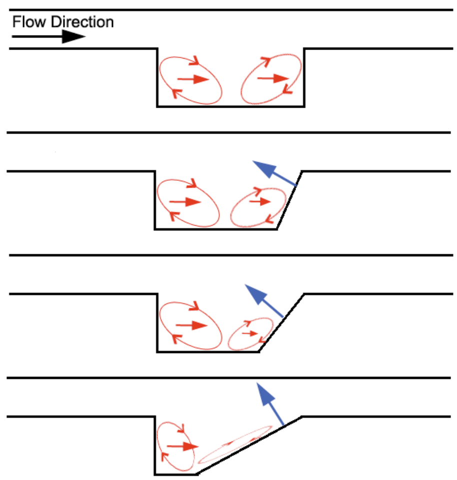

Figure 4. Geometry effects on the focusing mechanism

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