Tunable 3D helical inertial microfluidics constructed with PDMS-Parylene flexible microfluidic system

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ABSTRACT

Simply by bending planar 2D channels into 3D structures, flexible microfluidic systems can be adjusted into 3D channel geometries which will enable tunable inertial separation. We present a poly(dimethylsiloxane) (PDMS)-parylene hybrid thin-film microfluidic system that can provide high flexibility for 3D channel shaping while maintaining the channel cross-sectional shape. The PDMS-parylene hybrid microfluidic channels were fabricated by a molding and bonding technique using initiated chemical vapor deposition (iCVD) bonding.

KEYWORDS: inertial microfluidics; cell separation; flexible microfluidics; 3D microchannel

INTRODUCTION

For inertial microfluidic systems, flow characteristics and inertial particle equilibium positions are highly dependent on channel geometry and structure. Flexible microfluidic channels can create complex 3D channel geometries simply by bending 2D microchannels into 3D structures [1]. However, the low Young's Modulus of typical PDMS channels limits the geometries that can be constructed due to bulging under high pressures [2] and kinks from bending. Parylene microfluidic channels, on the other hand, can provide greater freedom of flexibility due to higher mechanical strength, allowing channels to maintain uniform cross-sections with high internal pressures and micrometer-scale bending radii [1]. We present real-time modulation of inertial focusing with the adjustable 3D structure using hybrid PDMS-parylene flexible microfluidic channels. By bending a 2D channel into a 3D helical structure, we can accomplish a constant bend radius for accurate control of the Dean number, which determines the inertial focusing positions.

EXPERIMENTAL

We developed a fabrication process for a flexible, thin-film microfluidic system using PDMS and parylene (Figure 1). Figure 1a shows a parylene channel with additional PDMS layer on one side (PDMS-parylene hybrid channel). The additional PDMS layer with a thickness similar to the channel height was covered on one side of parylene layer for better handling of the device and simpler fabrication of inlets/outlets ports. Figure 1b shows the comprehensive fabrication process of the PDMS-parylene hybrid channel. First of all, SU-8 negative photoresist channel molds were patterned using conventional photolithography method, (i). Negative PDMS molds were replicated from the SU-8 channel mold (ii). PDMS to glass and PDMS to PDMS bonding were done by plasma bonding using a plasma cleaner (iii). Use of ~30 grams Parylene C dimer was deposited using parylene coater to form of ~15 μm thick film (iv). To release parylene layer from PDMS mold, the surface of the PDMS mold was treated with oxygen plasma using deep reactive-ion-etch (RIE) process before the deposition of parylene because it prevents from fusion of parylene with PDMS.

For the bonding of the parylene microfluidic channels, ~400 nm thick layers of epoxy containing polymer, poly(glycidyl methacrylate) (PGMA) were deposited by iCVD method using glycidyl methacrylate monomer and tert-butyl peroxide initiator (v) [3]. To increase the adhesion between PGMA layer and parylene layer, oxygen plasma was treated on a parylene deposited substrates. After PGMA layer was formed, only one of the parylene deposited substrate was reacted with ethylenediamine (EDA). The substrate and EDA were placed in a glass Petri dish for 5 min on a 75 °C hot plate to make vaporized EDA to react with the epoxy group on PGMA surface. Two substrates were then aligned under a custom-built aligner and compressed together to form a chemical bonding. The substrates were bonded under pressure using a custom-built compressor for 8 h at a temperature of 85 °C. To avoid oxidative damage to the parylene surface by removing oxygen, and to prevent from air bubbles that may be trapped between the substrates vacuum oven was used.

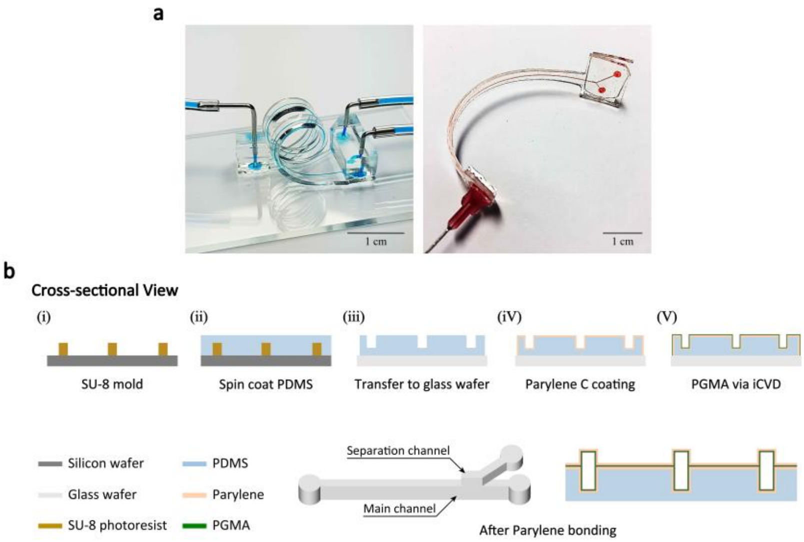

Figure 1. Flexible, thin-film channels based on parylene microfluidics (a) Poly(dimethylsiloxane) (PDMS)-parylene hybrid channel. One of the parylene layers is combined with supportive PDMS layer. Inlet constructed with a piece of PDMS block bonded to supportive PDMS layer. (b) Schematics of device fabrication (for PDMS-parylene hybrid channel). The parylene layer is fused with the PDMS layer for the main channel while it is detached from the separation channel mold after initiated chemical vapor deposition (iCVD) bonding.

We used various size polystyrene microparticles to observe inertial focusing in flexible microfluidic systems and particle separation demonstration. Green fluorescent particles of size 4.8, 9.9, and 15.45 μm, and red fluorescent particles of size 26 μm were used. The densities of suspension all microparticles are 1.05 g/cm3. NaCl was added to match the densities of the liquid and the particles. In addition, to prevent from particle aggregation 1% of non-ionic surfactant was added to the particle suspension. The particle concentration was in the range of 0.05−0.25 w/v%.

RESULTS AND DISCUSSION

Figure 2a represents the schematic image of the helically coiled Parylene channel as well as the illustration of particle migration mechanism inside the microfluidic channel. In a curved channel, the secondary flows, namely, Dean flows are generated by the uneven fluid inertia due to the difference in fluid velocity between the center and wall of the channel. The magnitude of the Dean flow is known to be characterized by the dimensionless Dean number (De) and Dean drag force (F_D). The Dean drag force in addition to inertial lift forces (shear gradient lift force and wall effect lift force) is known to enhance efficiency and throughput for size-based microparticle separations in spiral channels. To easily adjust the radius of curvature of the 3D microfluidic channels, the flexible, thin-film microfluidic devices are coiled around rods with varying diameter. To easily adjust the radius of curvature of the 3D microfluidic channels devices are coiled around aluminum rods with a varying diameter (Figure 2b). Two types of Al rods: one with multiple stages with different diameter and another one with a continuously changing diameter. The Al rod with multiple stages has six different diameters; 2, 3, 4, 5, 6, and 7 mm. For a demonstration of the real-time tuning of the focusing position, the rod with continuously changing diameter was used.

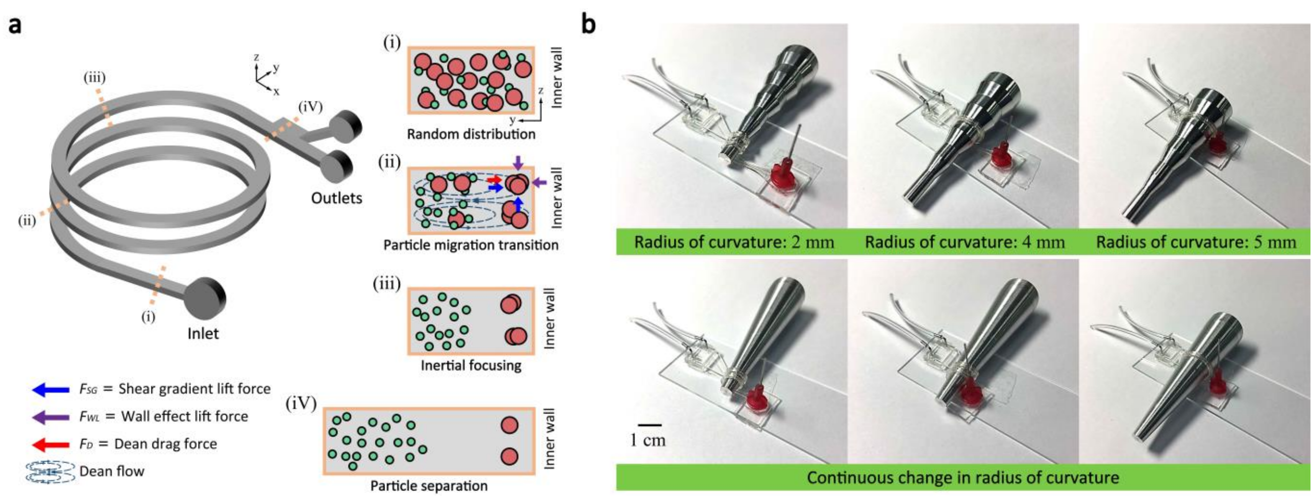

Figure 2. Flexible 3D helical inertial microfluidics operations. (a) Schematic illustration of inertial focusing in a helical microchannel. (b) Control of radius of curvature, R. PDMS-parylene hybrid channels are coiled on aluminum rods, with stages of distinct diameters and continuously changing diameter.

As shown in Figure 3, inertial focusing of microparticles in the 3D helical channel was investigated with four different sized particles while varying the radius of curvature and flow rate, i.e. Re (Figure 3). The measurement was performed with six different radius of curvatures (2, 3, 4, 5, 6, and 7 mm) and four different combinations of flow rates (Re = 20, 60, 100 and 200). The 26 and 15 µm particles' equilibrium positions were mostly located near the center of the channel (in *y*-direction) instead of the position close to the inner wall which normally observed in 2D spiral channels. We believe such focusing near the channel center is due to relatively small channel dimensions. In a spiral channel with a small cross section, inertial lift forces can completely dominate over Dean drag force and the focusing near the center of long channel faces is expected, similar to the case of low aspect ratio straight channels. The relative strength of the Dean drag compared to inertial lift force increases in a channel with larger cross-sectional dimensions, and the focusing positions for similar conditions (Re, R and a_p) were observed shifting towards the inner wall, which more closely resembles the focusing in 2D spiral channels. In general, Dean flow effects seem weak at low Re and, with the increase of Re, the focusing position shifted towards the inner wall showing the Dean drag become strong enough to change the focusing positions. Inertial lift forces are strong function of particle size and it is expected that focusing to a narrow stream becomes difficult with the smaller 10

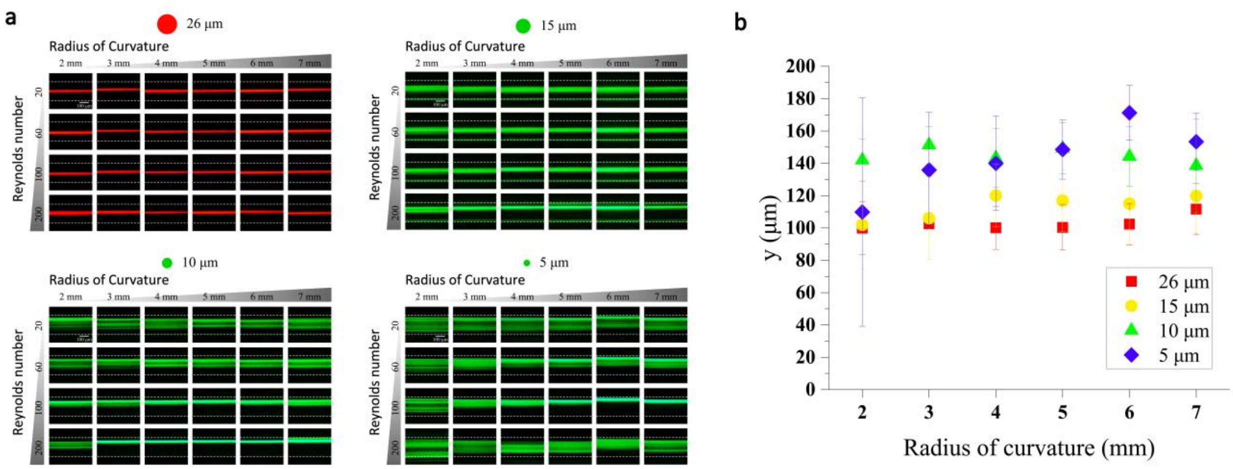

Figure 3. Inertial focusing in the 3D helical channel and real-time tuning. (a) Inertial focusing of particles with 4 different sizes (ap = 5, 10, 15, and 26 µm). The fluorescent images of particle streaks collected with a varying radius of curvature and flow rate (Re). (b) full width at half maximum (FWHM) of the fluorescent streak images vs. radius of curvature is plotted for Re = 100.

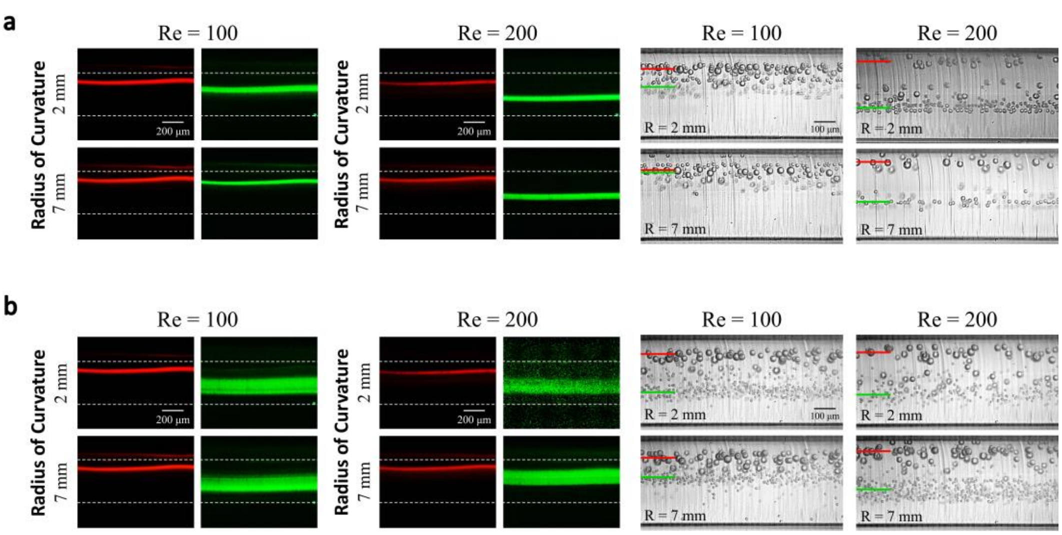

Figure 4. Demonstration of particle separation. The mixed particle suspension flowed and particle distributions were observed near the outlet for particle mixture of (a) 26 and 15 µm and (b) 26 and 10 µm. Fluorescent streak images on the left and the stacked high-speed images (200 images) on the right. The inertial focusing and the separation distance can be controlled with the flow rate and the radius of curvature.

and 5 μm particles. On the other hand, the Dean drag effects become more evident with smaller size particles, therefore the focusing positions shift towards the inner wall and the peaks broaden. Figure 3b summarizes the representative focusing trend at Re = 100; the center and the full width at half maximum (FWHM) of the fluorescent streaks are shown with varying *R*.

As shown in Figure 4, we demonstrated the real-time tunability of the inertial focusing by physically adjusting the radius of curvature, which can allow easy modulation of the separation threshold and optimization of separation efficiency. By adjusting the radius of curvature from 2 mm to 7 mm, the separation distance between two different size particles has increased. Most dramatic change of a focusing position appeared to be at a flow rate at Re = 100. On the other hand, at a flow rate of Re = 200, the gap distance between two different sized particles was maintained, but there was no significant difference when the radius of curvature was changed.

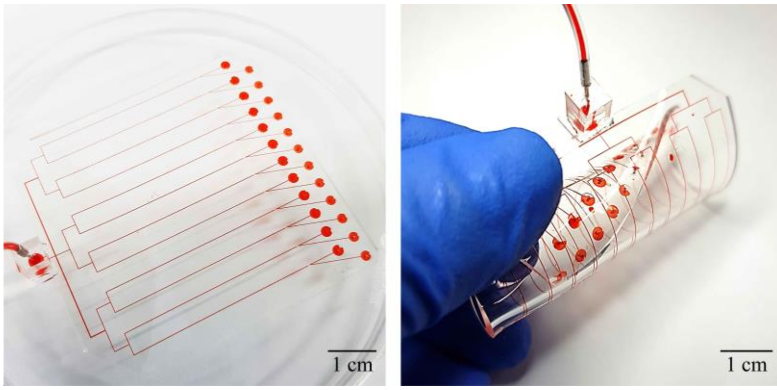

Figure 5. Parallelization of the 3D spiral channel can be achieved easily by rolling the 2D parallel channels.

As shown in Figure 5, flexible microfluidics allows simple, straightforward parallelization of spiral channels; a row of spiral channels connected to a single inlet can be constructed from 2D parallel channels. The parallelized device has 12 identical channels in the current design. It may be designed to have different channel dimensions for different separation threshold or efficiency. This novel method of 3D parallelization would inspire new approaches for compact 3D microfluidic systems for large-scale integration.

CONCLUSION

We observed the inertial focusing in the 3D helical channel while varying the radius of curvature and flow rate using a single device. We also demonstrate the real-time tuning of the inertial focusing and feasibility of microparticle separation in a 3D helical channel. In addition, the flexible microfluidic system can provide a simple method of parallelization of the spiral channels in 3D. We anticipate the flexible, thin-film microfluidic system will lead to diverse methods for constructing unconventional 3D structures that may allow novel functionality with real-time tunability.

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