COMPLEX 3D SHAPED PARTICLE FABRICATION VIA INERTIAL FLOW DEFORMATION AND UV POLYMERIZATION

A.J. Chung*[1,2], **C.-Y. Wu**[1], **D.E. Go**[1], **J.C. Oka**[1], **O.H. Paydar**[1], **R. Candler**[1,3], **D. Di Carlo****[1]

[1]*Department of Bioengineering, University of California, Los Angeles, USA*

[2]*Department of Mechanical, Aerospace, and Nuclear Engineering, Rensselaer Polytechnic Institute, USA*

[3]*Department of Electrical Engineering, University of California, Los Angeles, USA*

ABSTRACT

At finite Reynolds number, sequences of structures (*i.e.* pillars or columns) in a channel create a combined secondary flow enabling the precise control of flow cross sectional shape. Using an inertial flow deformation control scheme and previously reported UV polymerization techniques used to fabricate 2D extruded particles, we present a novel fabrication process to create complex 3D-shaped particles. A shaped stream of polymer-precursor and photoinitiator is exposed to orthogonal masked UV light, creating 3D shapes consisting of the extrusion of two 2D shapes. We present the results from numerical and experimental studies on the flow deformation physics and possible shapes achievable.

KEYWORDS: Optofluidics, Inertial microfluidics, 3D particles, Particle synthesis, Particle fabrication

INTRODUCTION

Although difficult to manufacture, complex shaped particles could provide unique properties in a variety of settings, including in photonic devices, self-assembling systems, engineered tissues, and construction materials. Novel methods to create shaped particles were previously reported [1, 2] though the possible shapes achievable are fundamentally limited to simple extrusions of two dimensional shapes. Multilayer polydimethylsiloxane (PDMS) microfluidic chambers [3, 4] were used to synthesize three dimensional (3D) particles but only limited shapes can be created and a relatively complicated fabrication process is needed. To address these limitations, our unique approach makes use of inertial flow deformations [5] with stop flow lithography (SFL) [1, 2] to fabricate complex 3D shaped particles (see Fig. 1).

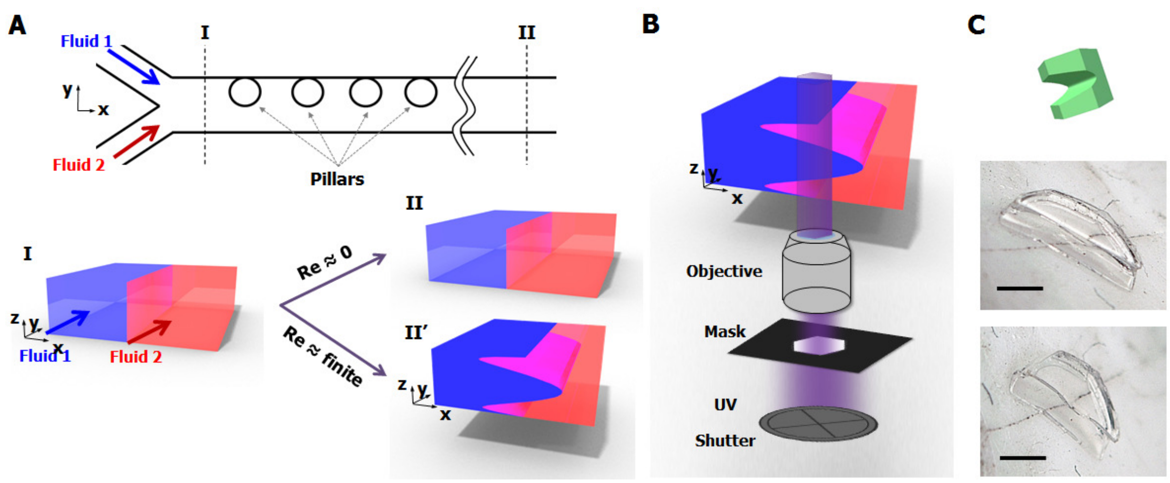

Figure 1: Schematic of three dimensional particle synthesis process. A. Design and operating principles for inertial flow deformation. B. Stop flow lithography under flow deformation (only red fluid contains photoinitiator). C. Three dimensionally fabricated particles (Scale bars represent 600 µm)

THEORY

The presented method is based on a two-step process. First, we use sequences of pillars to engineer the cross-sectional shape of a polymer precursor stream. As compared to Stokes flow, at finite Reynolds numbers each pillar (or column) creates a discrete lateral net secondary flow pattern (see Fig. 1A and 2). Importantly, the local secondary flow pattern is not a random process, and by having different combinations of pillars we can precisely control the cross-sectional shape of fluids [5]. Detailed numerical analysis for two conditions (*e.g.* Stokes and Inertial flows), and two-dimensional cross-section views of the flow deformation are presented in Fig. 2.

As a second step, we employ SFL as a particle polymerization process. Briefly, streams of Polyethylene Glycol-Diacrylate (PEG-DA) solution with a photoinitiator (2,2-Dimethoxy-2-phenylacetophenone) and Polyethylene Glycol (PEG) were injected. The fluid cross-section that is established is deformed by fluid inertia interacting with pillars. Then, UV light was selectively illuminated through a transparency mask with a conventional mercury fluorescent light source as can be seen in Fig. 1B.

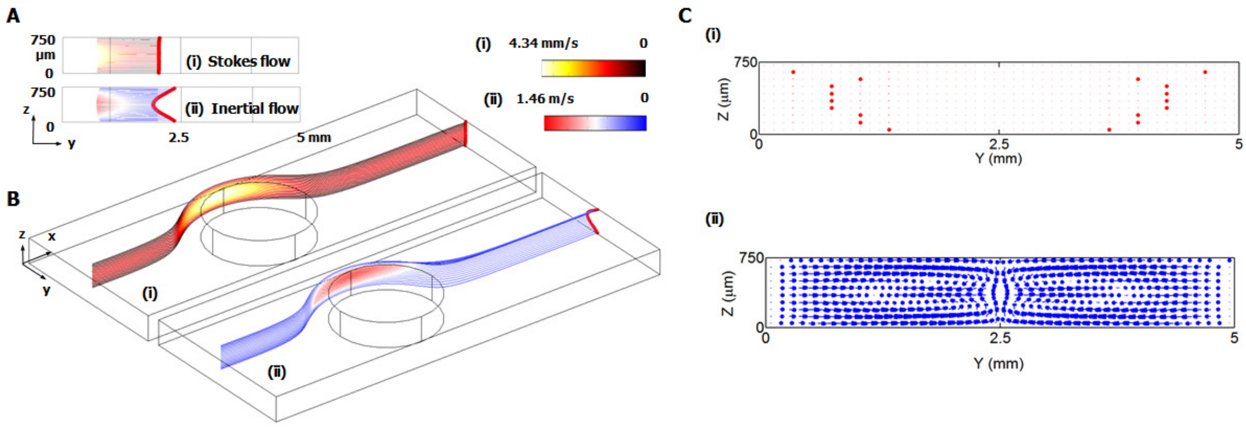

Figure 2: Finite element analysis of the net secondary flows around a pillar. A. and B. Streamline displacements as they flow around a single pillar for (i) Stokes flow and (ii) inertial regimes. C. Vector plots of net lateral velocity fields for (i) Stokes and (ii) inertial flow.

EXPERIMENTAL

All channels were fabricated by bonding PDMS replicas to glass slides coated with a thin PDMS layer. Molds for PDMS were made using a 3D printer [6]. PEG/PEG-DA solutions with microspheres (flow visualization purpose) were pumped into the channel using pressurized air and pressure lines controlled via a customized LabVIEW software. Numerical simulations were performed in COMSOL Multiphysics. All 3D shaped particles were imaged using a Hirox 3D High-Scope System.

RESULTS AND DISCUSSION

In order to understand the secondary flow motion more in detail, numerically calculated net lateral velocity field [7] is plotted in Fig. 2C. Generally speaking, for inertial flow, fluid elements close to the channel center move outwards, while fluid elements near the top and bottom of the channel are transported to the center (Fig. 2C(ii)). Experimentally, various polymer-precursors and photoinitiators under different light and flow conditions were investigated. A rectangular channel (*W*: 5 mm x *H*: 750 µm) containing various combinations and numbers of pillars was used. Each pillar has a diameter of 2 mm and is spaced out 7.5 mm apart with a total number of 9 pillars. The inertial flow deformation around pillars between the numerical and experimental results showed a very good agreement. Preliminary results of three-dimensional particles are shown in Fig. 1C. Furthermore, the particle shapes can be easily tuned by having a new combinations of pillars (numbers and locations of pillars in the channel), mask patterns, and inlet fluid conditions (*i.e.* sheath flow). Figure 3 shows examples of various three-dimensional particles that were fabricated using a range of flow and polymerization conditions.

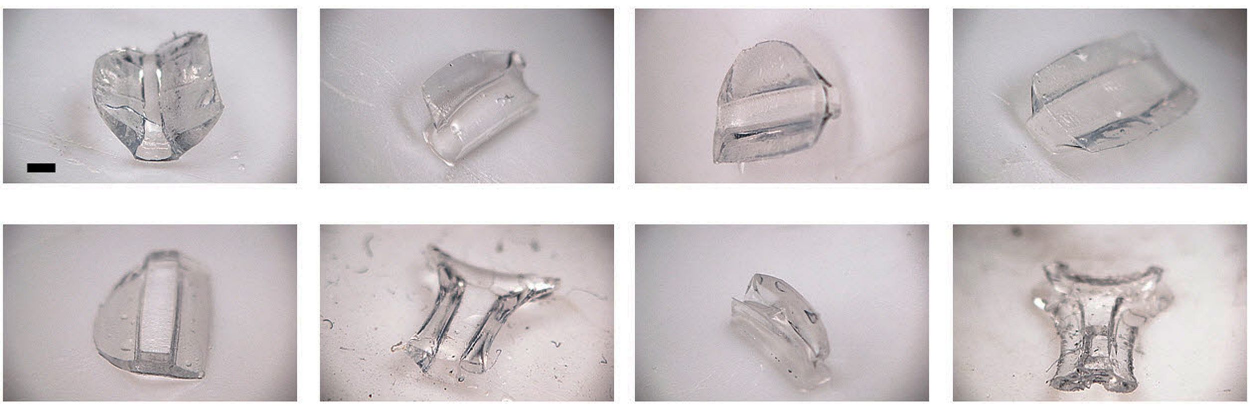

Figure 3: Gallery of complex 3D shaped particles. By having different pillar locations in the channel more complex flow patterns and shapes can be generated. (Scale bar represents 600µm)

CONCLUSION

To conclude, we present a novel 3D particle shape fabrication process that combines inertial flow deformation of a polymer feed with patterned UV polymerization. The entire process can be considered a polymerization of an intersection of two extrusion bodies: a horizontal extrusion of flow field by pillars and a vertical extrusion of light defined by the mask. In future work, more complicated particle shapes will be presented in a high-throughput manner via full automation.

ACKNOWLEDGEMENTS

Authors would like to thank to Mr. Daniel Membreno and Professor Bruce Dunn at UCLA for their technical support.

REFERENCES

[1] F. Dendukuri, D. C. Pregibon, J. Collins, T.A. Hatton and P. S. Doyle, "Continuous Flow Lithography for High-Throughput Microparticle Synthesis", *Nat. Mater.*, vol. 5, pp. 365-369, May. (2006).

[2] S. E. Chung, W. Park, S. Shin, S. A. Lee and S. Kwon, "Guided and fluidic self-assembly of microstructures using railed microfluidic channels", *Nat. Mater.*, vol. 7, pp581-587, Jul. (2008).

[3] K. W. Bong, K. T. Bong, D. C. Pregibon and P. S. Doyle, "Hydrodynamic Focusing Lithography", *Angew. Chem. Int. Ed.*, vol. 49, pp. 87-90, Jan. (2010).

[4] S. A. Chung, S. E. Chng, W. Park, S. H. Lee and S. Kwon, "Three-dimensional fabrication of heterogeneous micro-structures using soft membrane deformation and optofluidic maskless lithography," *Lab Chip*, vol. 9, pp. 1670-1675, Jun. (2009).

[5] H. Amini H, E. Sollier, M. Masaeli, Y. Xie, B. Ganapathysubramanian, H. A. Stone and D. Di Carlo, "Engineering fluid flow using sequenced microstructures", *Nature Commun.* doi:10.1038/ncomms2841. (2013).

[6] O. H. Paydar, C. N. Paredes and R. N. Candler, "Three Dimensionally-Printed (3DP) Microfluidic Devices", Proc. Solid-State Sensors, Actuators, and Microsystems Workshop (Hilton Head), Hilton Head Island, SC, (2012).

[7] H. Amini, E. Sollier, W. M. Weaver and D. Di Carlo, "Intrinsic particle-induced lateral transport in microchannel", *Proc. Natl. Acad. Sci.*, vol. 109, pp. 11593-11598, Jul. (2012).

CONTACT

*A.J. Chung, chunga6@rpi.edu, http://www.chungresearch.com

**D. Di Carlo, dicarlo@seas.ucla.edu, http://biomicrofluidics.com