ENGINEERING FLOW CROSS-SECTION *VIA* PROGRAMMED PILLARS

Hamed Amini[1,2], Mahdokht Masaeli[1,2], Elodie Sollier[1,2], Yu Xie[3], Baskar Ganapathysubramanian[3], Howard A. Stone[4], Dino Di Carlo[1,2]

[1] University of California, Los Angeles (USA), [2] California NanoSystems Institute (USA)
[3] Iowa State University (USA), [4] Princeton University (USA)

ABSTRACT

We introduce the ability to engineer the cross-sectional shape of a fluid using the integrated inertial flow deformations induced by sequences of simple microstructures (i.e. pillars). Discretization of single pillar operations followed by their programmed superposition allows the hierarchical assembly of complex flow programs. The introduction of a general strategy to program fluid streams in which the complexity of the nonlinear equations of fluid motion are abstracted from the user can impact biological, chemical and materials automation in the same way that abstraction of semiconductor physics from computer programmers enabled a revolution in computation.

KEYWORDS

Inertial microfluidics, Flow control, Sequential programming, Flow deformation, Mass transport

INTRODUCTION

Control of fluid streams is useful in biological processing [1], chemical reaction engineering [2], and creating structured materials [3]. However, general strategies to engineer the cross-sectional form and motion of fluid streams have been limited. Strategies to mix fluid [4] and control particles [5] using engineered systems exist, often relying on chaotic fluid transformations to disrupt sustained regions of order in the flow. Rather than apply flow transformations to prevent order, here we develop a hierarchical approach to engineer fluid streams into a broad class of complex configurations.

EXPERIMENT, RESULTS AND DISCUSSION

We use cylindrical pillars to induce significant deformations in laminar flow. Numerical simulations predict that as fluid passes centrally positioned pillars in a straight microchannel, the fluid parcels near the channel centerline move towards the side walls, while fluid parcels near the top and bottom walls move towards the channel center. This phenomenon, validated experimentally, effectively creates a set of *net* rotational secondary flows within the microchannel (Figure 1A). Hence, the flow is irreversibly twisted near the pillar, leading to a significant final flow deformation (Figure 1B). The lateral position of the pillar can be used to tune the lateral position of the net recirculating flow (Figure 1C).

Hierarchical flow deformation operations can be integrated to execute sophisticated programs and render complex flow-shapes. We can numerically predict the deformation near a single pillar with high precision and accordingly, predict the total transformation function of any potential program (Figure 2A). Consequently, a user can use a library of pre-simulated motions and engineer a flow-shape of interest quickly, at a low cost, and with high accuracy. Systematic discretization of the pillar positions (Figure 2B) enables each program to be simply communicated using the inlet condition and the sequence of pillar positions (Figure 2C). Therefore, analogous to programming of software, a designer can build upon previously demonstrated functions and integrate them in new ways to create more complex and useful outcomes. For instance, controlling the cross-sectional shape of a monomer stream enables manufacture of new classes of polymerized fibers with engineered interactions (e.g. interlocking or self-assembling fiber materials) [6].

We apply inertial flow deformation to several example practical applications. We demonstrate fast and simple extraction of particles from a fluid stream (Figure 3A) and particle separation and sorting by size (Figure 3B). More sophisticated programs enable cross-stream translation of a fluid stream and solution exchange around particles in which both the particles and fluid stream stay focused (Figure 3C). We can also split a single stream at the inlet into multiple streams, which can be useful in parallelization of screening applications (Figure 3D). Finally, the strong deformations create a semi-helical motion in the flow which can enhance mixing at high Peclet numbers dramatically (Figure 3E).

The introduction of a general strategy to program fluid streams in which the complexity of the nonlinear equations of fluid motion are abstracted from the user can impact biological, chemical and materials automation in the same way that abstraction of semiconductor physics from computer programmers enabled a revolution in computation.

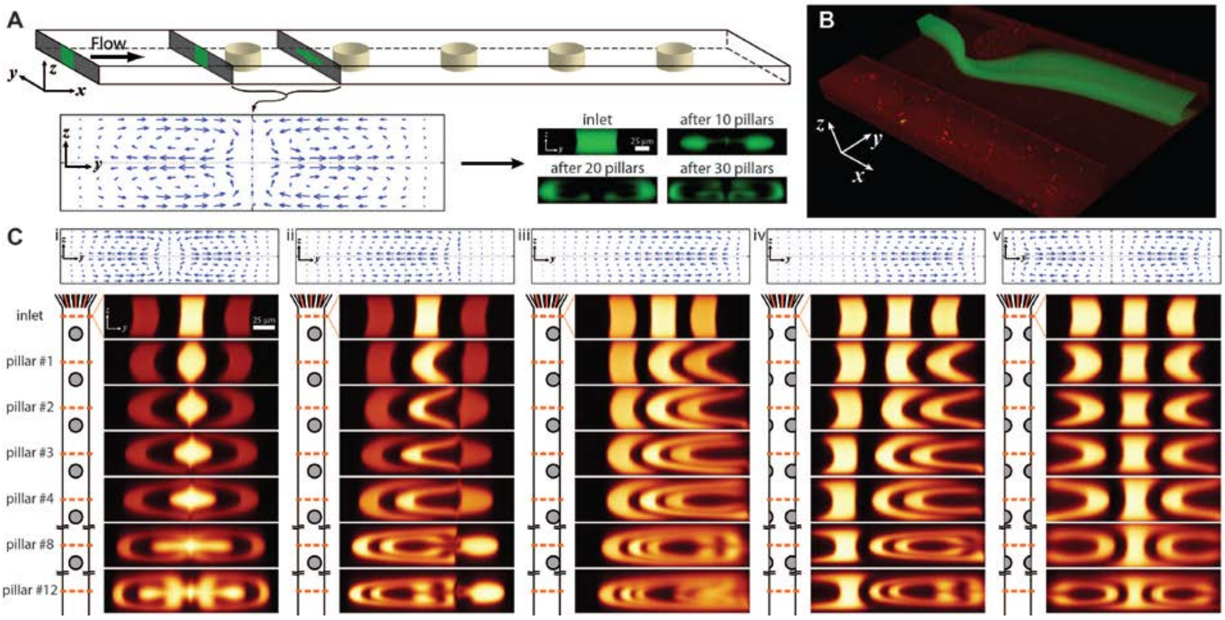

Figure 1. Local inertial flow deformation induced by microstructures. A. Flow passing a microstructure deforms significantly creating a net recirculating secondary flow in the channel. The arrow plot shows the average lateral velocity field as fluid parcels travel from input cross-section (upstream) to output cross-section (downstream). The numerical prediction is confirmed experimentally. B. A 3D confocal microscopy image of a fluorescent stream deforming around a single pillar in the channel clearly shows how the stream of fluid (sandwiched between two streams of unlabeled fluid) is irreversibly twisted losing fore-aft symmetry around the pillar. The PDMS surface of the channel is labeled red for a more vivid observation. C. Position of the net circulation is controlled by pillar location. The top row shows the net deformation arrow plots for different pillar locations as predicted by numerical simulations. Below are the confocal images of channel cross-sections for each of the sequenced configurations. The lateral placement of pillar sequences is shown in the schematic. Three labeled streams are tracked for a more detailed observation. By displacing the pillar center from the middle to the side of the channel (from i to v), the lateral position of the net recirculating flow is similarly displaced.

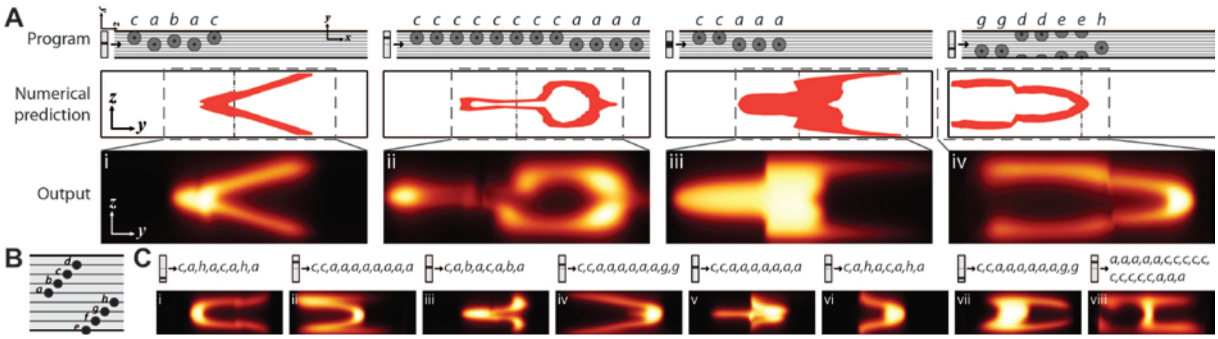

Figure 2. Engineering fluid flow using programmed sequences of pillars. A. Accurate numerical prediction of inertial flow deformation allows programming the cross-section of the flow. Each program consists of 1) a sequence of pillars positioned at different locations across the channel, and 2) an initial condition, i.e. inlet position and width of the fluid stream. The numerical predictions based on sequencing operations from a library of single-pillar flow transformation maps match very well with the experimental results. A user can use a library of pre-simulated motions and place these in series to engineer a flow shape of interest. B. The systematic discretization of the pillar positions, similar to discretization of musical notes, facilitates the communication and reproducibility of different designs. C. Demonstration of a variety of cross-sectional flow patterns created using simple programs. The images show the wide range of interesting shapes that can be created using the simplest form of programming, using only different pillar positions while maintaining the channel geometry, pillar shape and size, and flow conditions.

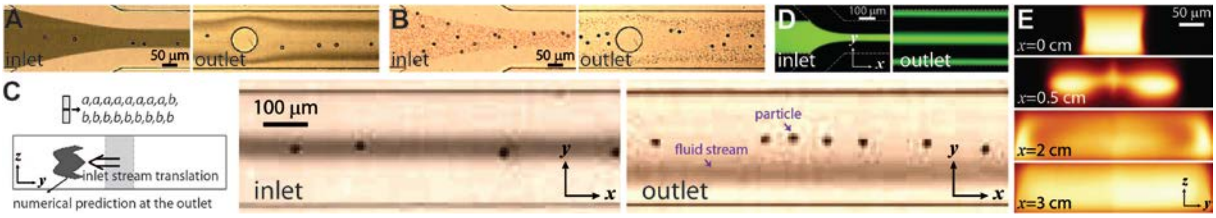

Figure 3. Applications of inertial flow deformation. A. Extraction of particles from a fluid stream. While the fluid moves away from the channel center due to inertial effects, particles are maintained at the channel centerline due to inertial focusing. B. Separation of particles by size using a similar geometry (10 µm particles remain focused while 1 µm particles follow fluid streams). C. Moving fluid streams and solution exchange. D. Stream splitting. E. Microfluidic mixing.

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CONTACT

Dino Di Carlo: (+1) 310-983-3235 or dicarlo@seas.ucla.edu