CONTROLLING THE SHAPE OF A HYDRODYNAMICALLY FOCUSED STREAM

Mansoor Nasir* and Frances S. Ligler

Center for Bio/Molecular Science and Engineering, Naval Research Lab (NRL)
Washington, DC, USA 20375-5348

ABSTRACT

Control over the shape of a focused stream is important in many biosensors and lab-on-a-chip devices that rely on hydrodynamic focusing for increased detection sensitivity. We found that the introduction of a sheath fluid into a microfluidic channel could have undesirable consequences in terms of the shape of the focused stream and thus examined the parameters influencing deviations from a flat interface between the two streams. Theoretical and experimental approaches revealed Reynolds numbers *Re* and the angle of confluence between sheath and focused streams as two major factors impacting the shape of the focused stream [1].

KEYWORDS: Flow focusing, Angle of confluence, Converging channels, Inertial effects, Laminar flow

INTRODUCTION

Parallel laminar flow of two or more liquid streams in microchannels has been studied extensively over the past decade for use in microfluidic and biomedical applications. The simplest version of this experiment is a Y-junction channel into which two fluids enter through separate inlets, converge and then flow in parallel laminar streams down a main microchannel. An important subset of Y-junction channels is the T-junction channel where the junction angle between the two inlet channels is 90º and the main channel is aligned with one of the inflow streams. If one fluid is flowing at a faster flow rate than the other, it causes the slower fluid to be focused along the channel wall. This is generally termed as hydrodynamic focusing and this technique has been used in a variety of cytometers [2], coulter counters [3] and impedance-based sensors [4]. Here we discuss some of the pertinent factors that can affect the shape of the interface between the focused and sheath streams.

EXPERIMENTAL

Y-junctions with different confluence angles (α) were micromachined out of PMMA substrate using precision micromachining techniques (Fig 1). Since angled inlets are difficult to machine accurately in a top down assembly, the junction and the channels were rotated. Devices where the angles between merging (sheath and sample) streams and the main channel were the same were referred to as *symmetric*, while the devices where the angles between merging streams and the main channel were not equal were denoted as *asymmetric*. The channel width and height were measured to be 600µm and 380µm, respectively. Precision machining techniques ensured that the variation in channel dimensions of any of the designs was not more than 10µm. Confocal microscopy was used to visualize the shape of the focused stream containing a fluorescent dye. Syringe pumps were used for sheath and sample flows.

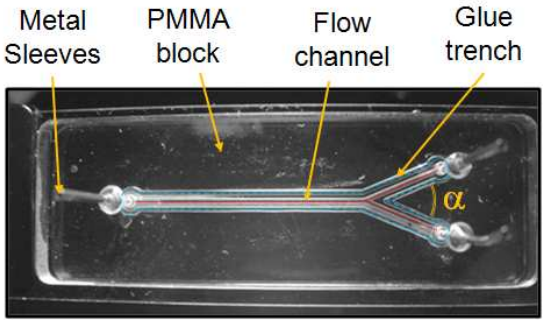

Figure 1: Microchannels were fabricated from PMMA and attached to a glass slide using UV-curable glue. A trench around the boundary of the main channel prevented the glue from running into the channel. All channels were 600µm wide and 400µm deep (±10 µm).

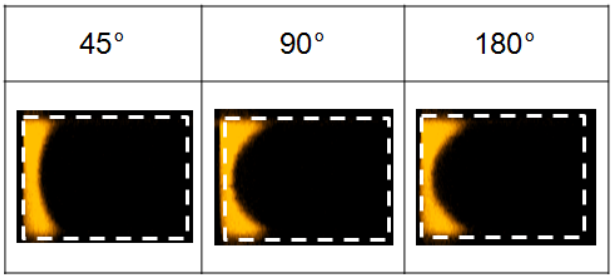

Figure 2: Confocal cross-sections of the main channel show the focused region for three angles of confluence (α). Flow-rate ratios for the sheath and focused streams were 720 and 29 µL/min, respectively (Re ≈25). Deionized water was used for both streams with Rhodamine dye added to the focused stream only.

Finite element modeling using COMSOL multiphysics and the Navier–Stokes solver HYTIDE [5] were used to simulate the effects of different merge angles (α = 45º, 90º, 180º), geometries (symmetric, asymmetric) and Reynolds numbers (1, 10, 25) on the concentration profile of the focused stream. A square geometry (500µm x 500µm) was used for the sheath and sample inlet channels as well as the main channel.

RESULTS AND DISCUSSION

Since the sheath fluid was flowing at a higher flow rate than the sample fluid, it focused the sample fluid along the sidewall of the main channel (Fig. 2). Results from finite element models (FEMs) were consistent with the experimental data and indicated that the initial interaction between the sheath and sample streams at the merging point of the two streams was critical in determining the final shape of the focused stream.

Decreasing the angle of confluence between sheath and sample stream inlets flattened the interface between sheath and focused fluids (Fig 2). The effect of *Re* was studied by changing the flow rates of the sheath and sample streams to maintain a constant ratio of the two at each merge angle. As the *Re* increased, the curvature of the interface increased (Fig. 3). The interface became flatter as *Re* was decreased, but this flattening was accompanied with increased diffusive mixing between sheath and sample streams due to longer residence times. Thus if a flatter flow profile is desired while maintaining the separation of sheath and focused streams, then the preferred approach is to reduce the merge angle between the two streams.

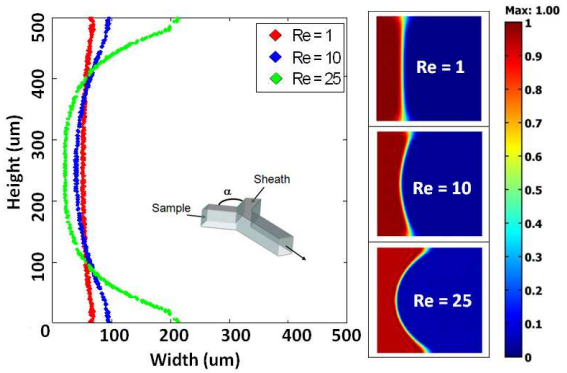

Figure 3: Finite element modeling (COMSOL) was done using a 500μm square microchannel with angle of confluence, α = 90º. Flow velocities for the sheath and focused streams were increased to vary the Re. The mass transport data was imported into MATLAB and plotted for the three cases using a concentration threshold of 0.5.

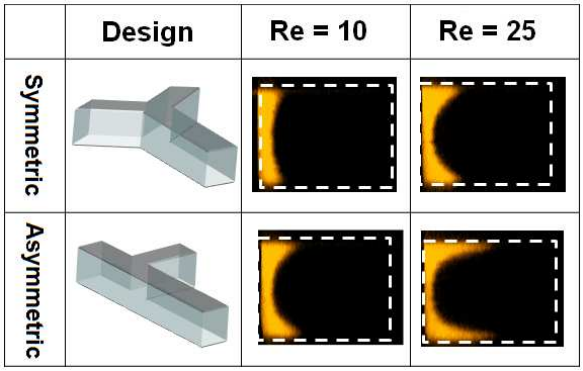

Figure 4: Focusing with a flow-rate ratio of 25 and Re ≈ 10 and 25 was compared for symmetric and asymmetric channel with α = 90º. The sample and sheath flow rates, respectively, were 11and 283μl/min for Re=10 and 28 and 707μl/min for Re=25. The cross-sections of the main channels show the resulting concentration distribution.

At a set flow rate, the sheath velocity component perpendicular to the flow in the main channel increased as the merge angle increased. Thus the fluid momentum caused the sheath stream to penetrate deeper into the main channel and pushed the focused stream into the corners. This analysis was further verified by comparing the concentrations profiles symmetric and for an asymmetric channel (Fig. 4). The interface curvature was always greater for the asymmetric designs for any Re. Asymmetric designs maximized the perpendicular component of the sheath velocity. When flowing at high relative velocity, the fluid momentum caused the sheath stream to penetrate almost all the way to the opposite wall and nearly caused the sample stream to be split into two.

Switching the inlets for sheath and focused streams resulted in focused streams with vastly different shapes. When the faster flowing sheath fluid inlet was aligned with the main channel, the focused stream was very flat, even at higher *Re* (Fig. 5). The focused stream was flowing much slower than the sheath stream, and therefore its momentum was not sufficient to penetrate the sheath stream before turning the corner at the junction.

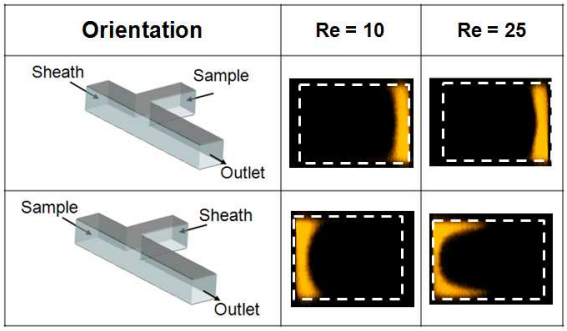

Figure 5: Channel cross-sections from confocal microscopy show the concentration profiles for an asymmetric channel design (α = 90º). The sheath and focused streams were switched for each case of the Re (10, 25). The first row shows the case in which the sheath stream was aligned with the main channel. The second row shows the results in which the focused stream was aligned with the main channel. The channel was 380 μm x 600 μm (height x width).

The described behavior only deviated for channels with extreme aspect ratios where shallow channel approximations were applicable (i.e., 2D flow dynamics can be used for 3D geometry). Simulations were also repeated for square channels with smaller cross-sectional areas and the results followed the same pattern seen here as long as the Reynolds and Peclet numbers were matched to larger channels [1]. The findings of this study can be directly applied to the design of flow focusing micro-channels, especially for microflow cytometers (Fig. 6a & 6b) where the particles must be confined to narrow and uniform cross-section for accurate counting [2] as well as accurate control of the curvature for optofluidic lenses (Fig. 6c) [6].

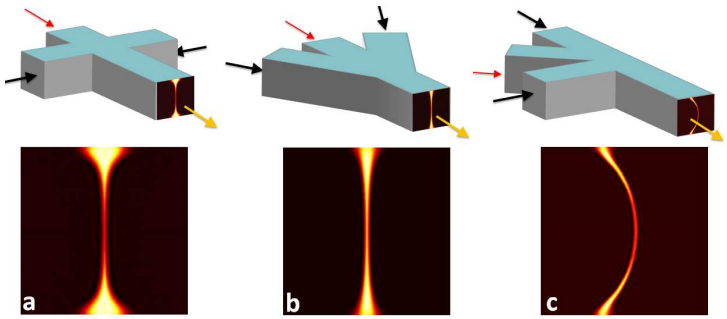

Figure 6: Concentration profiles from FEM of three horizontally focused channels (500μm square). The flow rates of the sheath (black arrows) and focused (red arrows) streams were 360 and 29 μL/min, respectively, resulting in Re ≈ 25 in each case. For cytometer type applications a narrow focused stream (b) is preferred over an hour-glass shape (a). The choice of inlet angles can also be used to control the focal length of a fluidic lens.

CONCLUSION

The findings of this theoretical and experimental investigation reinforce the importance of inertial forces in flow focusing channels and can serve as a benchmark for choosing the optimal design of many microfluidic devices. The confluence angle of the merging streams has a strong impact on the shape of the focused stream. While most microfluidic channels operate within the laminar flow regime, the design of the channel can have unintended consequences by exaggerating the effects of the inertial component of the faster flowing stream. For a flat interface between the sheath and the focused stream, the angle of confluence should be as small as possible within fabrication constraints. Even for 2D flow focusing channels, the side channels should merge at shallow angles as opposed to entering the channel at right angles. Decreasing the Re also helps to produce a focused fluid layer that is very flat across the height of the channel. Whenever possible, the faster flowing sheath fluid should be aligned with the main channel since this reduces the inertial effects and produces a focused stream with a flat concentration profile.

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CONTACT

*Mansoor Nasir, Tel: +1-202-767-2052; mansoor.nasir@nrl.navy.mil