Towards the design of high efficiency, passive microfluidic mixers

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Abstract

Through a combination of computational fluid dynamics and rapid prototyping, we have developed various designs of mixers for millifluidic and microfluidic applications. Two designs will be presented: a mixer based on the Dean vortex, and a groove-based (surface-patterned) mixer. The Dean-based mixer has a low surface area-to-volume ratio, reducing the risk of fouling, but requires a high flow rate to operate. The groove-based mixer has a higher surface area, but operates over a wide range of flow conditions. In the process of developing these mixers, we have gained a deeper understanding of how to control the movement of the fluid streams within the channel. We are developing designs that will improve mixing in shorter path lengths.

1. Introduction.

Since Reynolds number scales with size, biosensors and reaction chambers that use microfluidics are in the laminar flow regime. Fluids in laminar flow follow parallel streamline paths, which remain parallel even in obstructed or tortuous channels. Therefore, two fluids flowing in a microchannel will not mix with each other, except via diffusion at the interface between them. Thus, the goal of a micromixer is to stretch or increase the interface surface area between the two fluids. This has been achieved in passive mixers by redirecting the flow of portions of the fluid flowing in a channel. Diagonal grooves or ridges in the bottom or top of the flow chamber introduce secondary currents that form skew fluid paths, moving portions of one fluid into the other as it flows down the chamber.(1) There are other forces that can redirect flow without the use of grooves. In this paper we describe a mixer that redirects flow without the use of grooves, and we describe an approach to designing an optimized mixer using groove features.

2. Dean vortex-based micromixer

The Dean vortex-based mixer presented here can generate lateral vortices similar to those seen by Stroock (2), but without the need for ridges or troughs.(3) The phenomenon on which these chips are based was first examined by Dean (4, 5) for pressure-driven flows in curved circular tubes. In these geometries, curvature of the channel amplifies a lateral instability that drives a secondary cross-channel flow. The Dean number, defined as

$$D_{\mathrm{n}} = \frac{Gw^3}{\mu v}\left[\frac{2w}{R}\right]^{\frac{1}{2}}$$

characterizes the secondary flow, where G is the centerline pressure gradient driving the primary flow, R is the channel radius of curvature, w is the channel width, *u* is the fluid dynamic viscosity, and *v* is the kinematic viscosity. In a straight channel (Dn ~ 0), the flow develops a parabolic profile with the fluid moving down the center of the channel traveling faster than the fluid traveling along the walls or along the top and bottom. When the flow is through a curved channel (Dn > 0), the fluid moving down the center experiences a higher centrifugal force than the surrounding liquid (see Figure 1). As a result, a pair of counter-rotating vortices forms that sends fluid from this high-speed core toward the outer wall. At higher values of Dn and depending on the aspect ratio of the channel cross-section, other vortices and oscillations can form.(4-8) These secondary flows can be used to mix two segregated inflow streams.

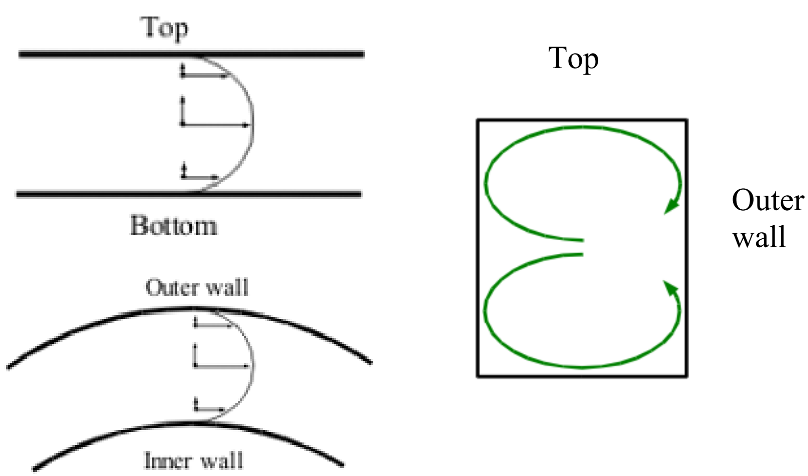

Figure 1. Schematic of the lateral vortices set up in the channel.

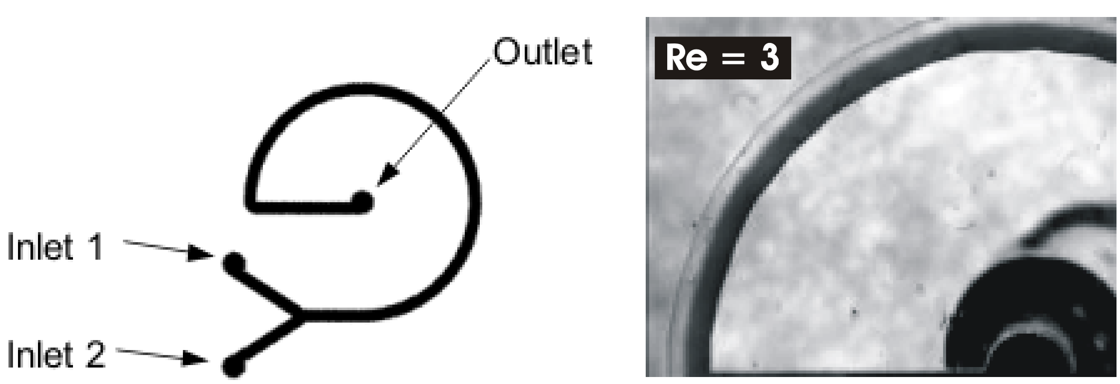

Figure 2. Left – top view of the Dean mixer showing inlets and outlets. Dye solution flowed on inner part of channel. Right - photo of dye and clear solution flowing in channel.

A high aspect-ratio flow channel was constructed to show the Dean effect. Figure 2 shows a view from the top. Figure 3 shows a side view. Dye solution flowed near the inner surface, while clear solution flowed on the outside of the curve. The top of Figure 3 shows no Dean effect. At higher Reynolds numbers, the clear solution appears at the top and bottom of the channel (Figure 3. bottom) because of the fluid rotation due to the Dean effect. Details of this experiment are described in Howell et. al.(3)

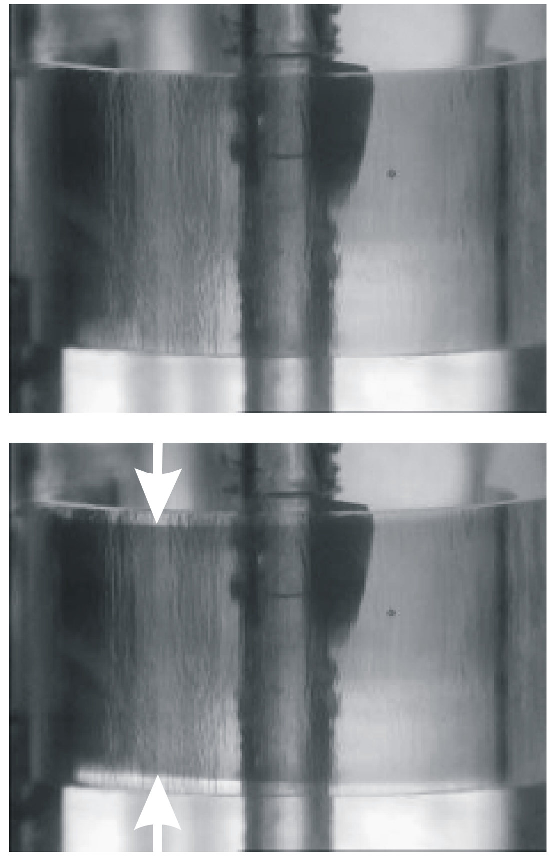

Figure 3. Side view of a high aspect ratio channel. The channel is 500 um deep and 5.3 mm tall. The inner radius of the curve is 4 mm. The solution is introduced on the inside of the curve. Flow is from right to left. The vertical structure seen in the middle is a registry hole placed at the center of the curve. Top: Re ~ 0.9. Bottom: Re ~ 17.

3. Making and modeling mixers

There are several features that are desirable for a flow chamber mixing device. A low surface area to volume ratio decreases flow-through resistance and also decreases the likelihood of debris in the sample clogging the flow chamber. For ease of manufacturing and cost, the mixing method should be passive; active elements are prone to failure, fouling and require application of external energy.

An optimal design would provide complete mixing within a reasonable distance. Inserting diagonal grooves into the surface of the flow chamber redirect the flow and introduce folding, as in the Baker's transformation, into the flow stream. This approach has a low surface area to volume ratio, is passive and is relatively easy to manufacture. However, this pattern requires some distance for complete mixing. Introducing directional grooves on both the top and bottom of the flow channel forms more aggressive flow redirection, and reduces the mixing distance.

An important aspect of our approach is how we develop the micromixer design. As part of a microfluidics collaboration at NRL, we have combined CAD machining and microfabrication, biosensor experience and computational physics facilities into one interactive project. Designs are tested and optimized computationally before they are fabricated, and results from manufactured mixers are used to modify and correct the computational designs.

We use a new computational fluid dynamics (CFD) program, TINY3D, interactively in the design and optimization of the micromixer. The basis of TINY3D is a workstation-based, single-processor version of FAST3D, which is now being used by other DARPA programs. FAST3D performs full, three-dimensional reactive-flow Navier-Stokes computations with complex geometries, all on a Mac G4. Novel features of this code include the ease of changing the geometry and the speed at which it can be done, and it is fully integrated with existing graphics packages. The combination of fast computational design and analysis along with rapid prototyping is a powerful tool for producing an optimal micromixer.

Figure 4 shows an example of computational analysis of flow through a channel with groove features on the top and bottom of the channel.

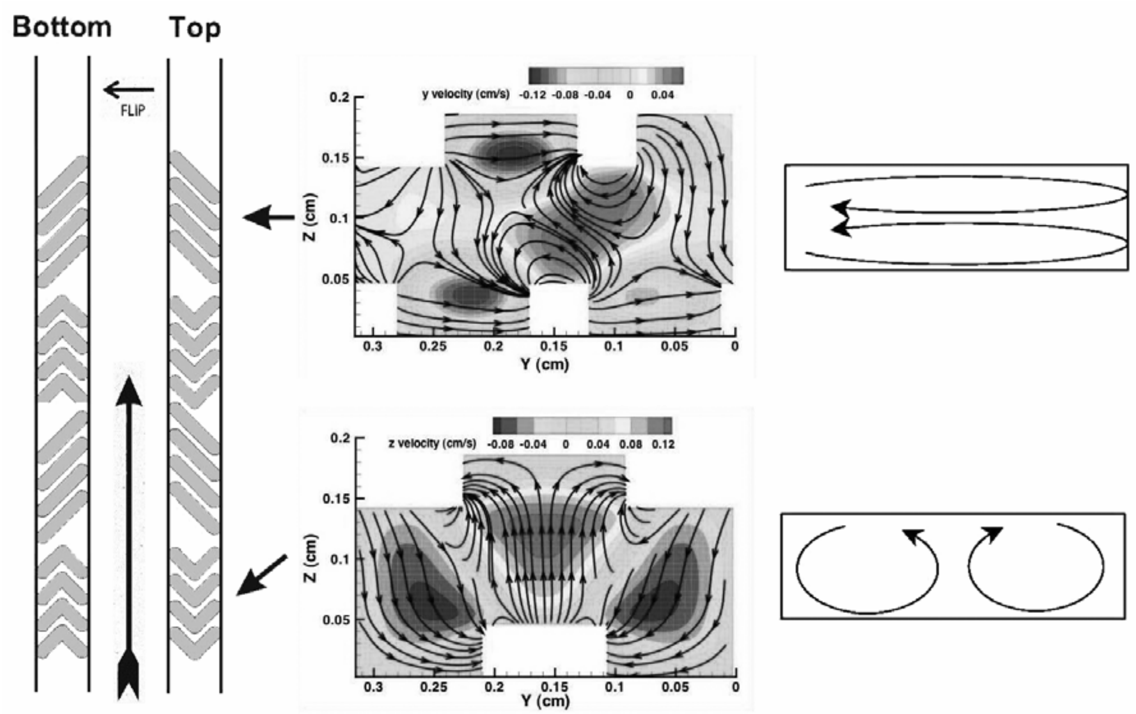

Figure 4. Computational flow analysis of a mixing channel with groove features on the top and bottom of the channel. Streamlines indicate direction of flow and color (grayscale) indicates velocity of flow. Diagrams on the right are simplified drawings of the vortices generated by the features.

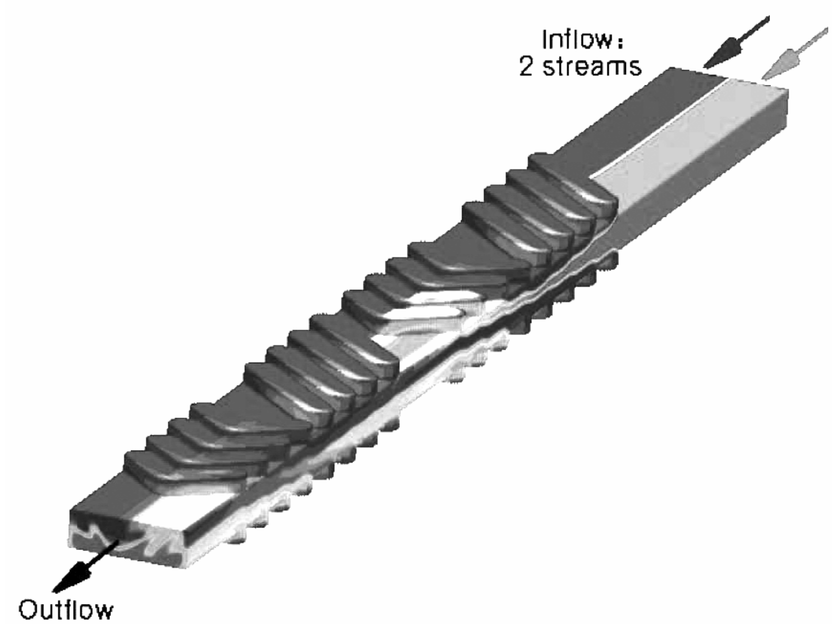

Figure 5. Simulation of mixing of 2 fluids in channel with groove features on top and bottom of the channel.

Figure 5 shows a computational simulation of mixing of 2 fluids in a flow channel with groove features on the top and bottom of the channel. Results from simulations such as this are used to optimize the design of the mixing chambers made in the microfabrication facility.

4. Conclusions

We have developed several different flow devices that enhance the mixing of fluids in low Reynolds number regimes. The synergy of design simulation, fabrication and testing the designs has proven to be a very effective method for developing an optimized microchannel mixer. In the near future we will show results from this design process.

5. Acknowledgments

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6. References

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