A Flow Visualization Experiment for a First Course in Micro-fluidics

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Abstract

Physical intuition developed for fluid flows at the macro-scale can be very misleading when applied to flows in microchannels. The Reynolds number of these flows is typically low, and thus they remain totally laminar. Under microflow conditions, familiar phenomena such as fluid mixing behave counter to the intuition developed by students in a standard engineering curriculum. We present a laboratory project designed to stress this point to students taking a first-year graduate introduction to microsystems. The pilot group found the results surprising and counter-intuitive. It appears that the project was instrumental in clarifying key concepts in microfluidics.

Introduction

After several decades in which microsystems research mainly addressed electromechanical systems [1], the focus has begun to shift to fluidic systems. This shift is driven primarily by potential application of microsystems to chemistry, biology and medicine [2]. An introductory course in microsystems at Texas Tech University (TTU), offered to graduate students and advanced undergraduates, includes several modular projects in photolithography, surface micromachining and bulk micromachining [3]. The course also includes a microfluidics project using "soft lithography" [4]. The microfluidics component has undergone several iterations. This paper describes the most recent version, which requires the design, fabrication and test of a micromixer. It should be stressed that this course is the first of a three-semester sequence with 3 credit hours, and that subsequent projects require integration of valves, pumps and mixers with other components [3]. The main purpose of the module described here is to teach the basic

fabrication techniques. Producing successful devices is a secondary objective. In the version of the project described here, rather than being provided with a predetermined device to build, the class was given an open-ended design problem, and encouraged to experiment. The intent was that, although the number of successful mixers would be reduced, the class would more deeply appreciate the differences between microscale and macroscale devices, and hence would be better prepared to succeed in later lessons.

Ultimately, at the molecular level, all mixing is based on the interdiffusion of the various species. However, most macroscopic mixers exploit features of the flow to enhance the fundamental diffusion process. Of these, the most important is turbulence. Turbulent flows are characterized by eddies and vortices across a large range of length scales [5]. At the interface between two mixing streams, these structures give rise to convective transport at rates typically far in excess of the diffusion velocity. Whether or not a flow will exhibit turbulence is determined by the relative importance of inertial to viscous effects, quantified by the *Reynolds number* (Re). Development of turbulence in internal viscous flows requires Re on the order of 1,000 or higher (as per the classic experiments performed by Reynolds in 1883, in which the laminar nature of the low Reynolds number flow was found to be insensitive to the entrance conditions, no matter how rough and noisy [5]). Re is calculated from a characteristic length of the flow, multiplied by a characteristic velocity, and divided by the (kinematic) viscosity. Because of the very small physical dimensions of microchannels, Reynolds number is typically quite small relative to most common engineering flows—Re on the order of 10^{-2} is not uncommon [2]. As a result, fluid mechanics at the microscale is significantly different from our everyday experiences. For such flows it is impossible to induce turbulence by any known means. In contrast, turbulence is a ubiquitous feature of everyday life, from cream mixing with coffee to dust whirling in the wake of a passing car. It is possible to increase species and momentum transport across an interface without turbulence, by the use of large velocity gradients, leading to layers with high shear rates (consider for example the classic Kelvin-Helmholtz instability [6]). None of the students in the class were aware of this phenomenon, which we attribute in part to the emphasis on integral analysis in the standard fluid dynamics course; shear is inherently a local phenomenon.

In accordance with its importance, turbulence receives a lot of attention in the standard Mechanical Engineering curriculum. Traditional one-semester undergraduate fluid mechanics courses, as taught in most typical Mechanical Engineering departments, must cover so many topics that the student has almost no time to digest the material presented. Looking at two of the most popular texts in fluid mechanics [5, 7], topics presented begin with hydrostatics, followed by an introductory treatment of viscous flows. Internal and external flows are examined next, then potential (inviscid) flows and compressible flows. The books conclude with a chapter on turbomachinery. There is absolutely no way for an instructor to cover this much material with equal thoroughness. Thus choices must be made as to which topics to emphasize. These choices are often made based on the background of the professor, or the perceived career needs of the majority of the students.

Our own experiences are with the curriculum in the Mechanical Engineering Department of Texas Tech University. There the instructors who tend to spend most of their time on the following topics: fluid statics, integral analysis, experimental analysis, internal and external viscous flow from an integral viewpoint, and turbomachinery. Differential analysis is reserved for graduate level courses. Much of the introductory fluid mechanics course is aimed at providing a basic understanding of integral momentum and energy concepts in order to prepare them for entry level fluids engineering positions and for more advanced courses in heat transfer [8]

This emphasis is completely understandable. Graduates of the department go on to design and analyze stationary power plants, gas turbines and jet engines, cooling systems for automobile engines, aircraft systems, and a variety of other traditional careers. Furthermore, these are the areas in which the majority of the faculty have experience. It could well be said that any other choice of emphasis would be irresponsible. Unfortunately, it is also true that students interested in learning about microfluidics enter the field equipped with hard-won engineering intuition that is that can be misleading at the microscale.

Micromixer design is still an active research area [2, 9, 10, 11]. In this project, to make fabrication complexity manageable, we restrict designs to a single flow layer, and constrain the designs to begin with the two fluids flowing side by side down the stem of a "T." Under these conditions, standard approaches for enhancing diffusion include increasing the interfacial area by maximizing the mixing channel length using a serpentine design. Another approach is to valve the two streams alternately to produce a segmented flow, which also increases interfacial area. We include valves in the design to encourage students to explore this avenue of design. In the pilot group described in this paper, three of the four designs were based on notions from macroscale heat exchangers. These designs performed very badly. The other used serpentine channels to increase residence time. This was slightly more successful. Interestingly, the best mixing at reasonable flow rates was obtained by rapidly pulsing the mixing streams out of phase to create large shear layers. This was discovered not by design, but by experimenting with the device. While the project was highly successful in demonstrating the limits of macroscale techniques, it was less successful in replacing those techniques with a suitable suite of microfluidic tools. Future versions of the project will draw upon this lesson and stress the use of time-varying flows and shear layers.

Design, Fabrication and Test of a Micromixer: A First Project in Microfluidics

The project is carried out in three parts: design, fabrication and test. The fabrication portion is intended to introduce some fundamental processes for producing microfluidic devices. The test

portion is intended to provide hands-on experience in microscopic observation of microflows, and basics of LabView programming for device command and control. We will discuss these briefly below, but our main focus herein is the discrepancy between the students' expectations in the design phase and the results they observe in the test phase. After the project, the students were asked to fill out a questionnaire with the following three questions:

1. Describe your objectives when originally designing your mixer. Sketch the flow pattern that you expected to result from your design, and explain how it would promote mixing.
2. Describe how the actual flow differed from your expectations. Can you account for any discrepancies? How do you think the results would have differed if the device you constructed were 1000 times larger?
3. How would you incorporate the results of this project into a new mixer design?

Design

The students are asked to design a single layer microfluidic device that will mix two aqueous flows. They are presented with the following design constraints: the two flows enter through the arms of a "T." The flow sources are elevated approximately 25 cm above the device, resulting in 2.45 KPa of static head pressure. The pressures driving the two sources are nominally equal, but may be modified through two independently actuated pneumatic valves, one for each source line. These valves are controlled via a LabView program, to be written by the students. The two fluids meet at the stem of the "T," and flow from there into a mixing chamber or structure of the students' design. Students define their devices by using Adobe Illustrator software to draw a black and white full-scale layout. The white areas will comprise the channel and mixer areas. Feature sizes down to 50 microns may be used. All the flow areas are of one uniform depth. The students may choose a depth between 100 and 300 microns.

Fabrication

Masks are made from the students' Illustrator files using a 3000 dpi film printer. The fabrication of the device is done in three layers. The ultra-thick negative photoresist SU8-2075 is spun onto a 10 cm diameter glass wafer to a depth (controllable by varying the spin speed, and selectable by the students) of between 100 and 225 microns. The SU8 is patterned lithographically, by exposure to a UV light source through the student masks. Upon such exposure, and subsequent heating, the SU8 forms extensive cross-links, and becomes extremely chemically resistant. Those areas screened by the black portions of the mask do not cross-link, and are easily dissolved by a chemical *developer*, which does not affect the exposed areas. Thus a negative of the desired device is obtained, with SU8 features defining the desired channels where the original mask was white (that is, clear when printed to film) and blank glass where the original mask was black.

This negative is used to cast a device out of the silicone elastomer poly(dimethyl)siloxane (PDMS) (GE Silicones RTV 615). The glass negative is placed at the bottom of a well milled into an aluminum plate, which is then filled to a depth of 1 mm with PDMS. The plate is carefully leveled using leveling screws, and the PDMS is cured at 80° C for 45 minutes. This is the fluidic layer of the mixer. The process is repeated to produce a pneumatic control layer containing two inflatable air bladders used to valve the flows. In this case two layers of SU8-2075 are spun on the glass blank, to produce bladders 0.5 mm deep. Finally three 0.75 mm holes are drilled into the glass wafer, one inlet for each fluid, and a combined outlet. This glass wafer serves as a support structure, and as an attachment point for fluid tubes. The complete device is then assembled as follows: 1) the PDMS fluidic layer and the glass support plate are oxidized in an oxygen plasma (Trion inductively-coupled plasma chamber, O_2 flow rate 50 sccm, ICP power 250 watts, RIE bias 100 watts, time 30 seconds). 2) Immediately upon removal from the chamber, the two pieces are pressed together with the plasma-activated surfaces in contact. 3) A weight of 6 kg is placed on the stack for 8 hours, after which the PDMS is bonded to the glass. The process is repeated with the exposed PDMS surface of this stack, and the bladder side of the pneumatic control layer. 4) Stainless steel tubes with an outside diameter of 0.3 mm (McMaster-Carr) are inserted into the pneumatic layer to provide attachments to an external compressed nitrogen gas tank. 5) Barbed polycarbonate tubing connecters are epoxied to the outside surface of the glass wafer over the drilled holes to provide access for the mixing streams, and an outlet for the product. 6) The inlet connectors are connected with silicone tubing (McMaster-Carr) to two bottles containing water, one dyed fluorescent green, the other undyed. Silicone tubing carries the outlet liquid to a waste beaker. 7) The pneumatic lines from the two valves are connected, through a LabView-controlled solenoid valve, to a bottle of nitrogen gas, regulated to 15 psig. This completes the experimental set-up.

Testing

Students write drivers to run the flow valves. Typically in this project both valves are either open, when the experiment is running, or closed, between tests. They observe the flow by eye and through a microscope, and take still photos and movies. Flow patterns are observed, and the degree of mixing is, at present, evaluated qualitatively. Future versions of the course will evaluate mixing by microscopically observing the flow, and comparing the intensity of fluorescence downstream of the device as a function of position across the channel.

Results

The students have been told that the Reynolds number is low, and that the flow will remain laminar. However it is clear from their remarks that they do not fully grasp what this implies.

Figure 1 shows one student sketch, the resulting mask for photolithography and the fabricated device.
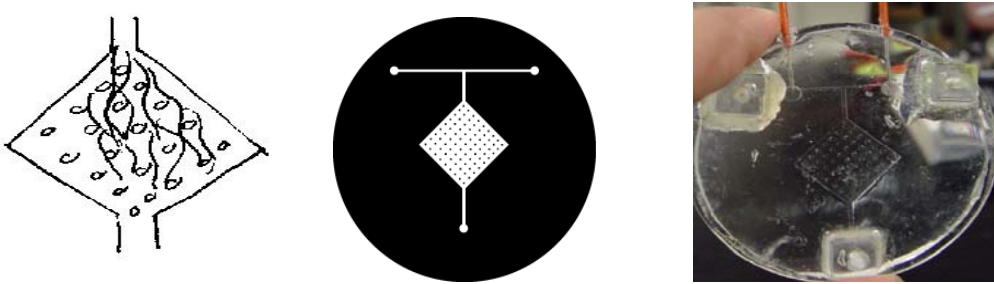

Fig. 1. "Tube Bank" mixer design, photolithography mask and device.

This design was accompanied by the remark, "We hoped a tube bank design would trip the laminar boundary layer and induce mixing." In fact, the sketch provided by the student may well depict the flow pattern. What is missed is that eddies away from the fluid interface do nothing to promote mixing. Figure 2 shows a similar design, which was provided with the comment, "…the discontinuities in the channel allow the proper mixing of the fluids…." Figure 2 also shows the corresponding lithography mask, device and resulting flow pattern. From the flow image it can be clearly seen that little or no mixing results.
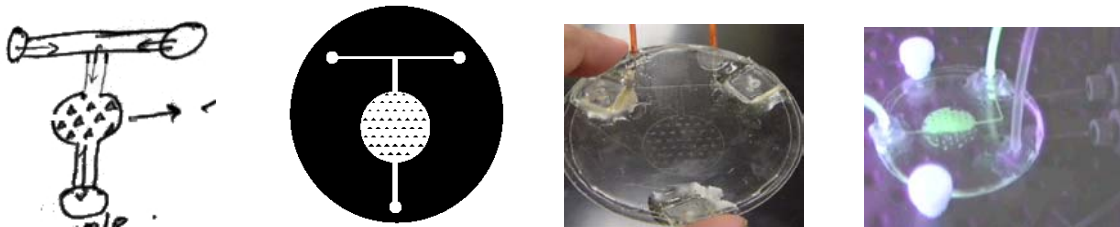

Fig. 2. "Triangles" mixer design, photolithography mask, device and flow.

Another group based its design on the notion of splitting and recombining the flow, as shown in Fig. 3. The comment that accompanied this sketch was, "I thought that splitting the flow apart and bringing it back together would result in mixing." Again, examination of the flow pattern indicates little or no mixing.
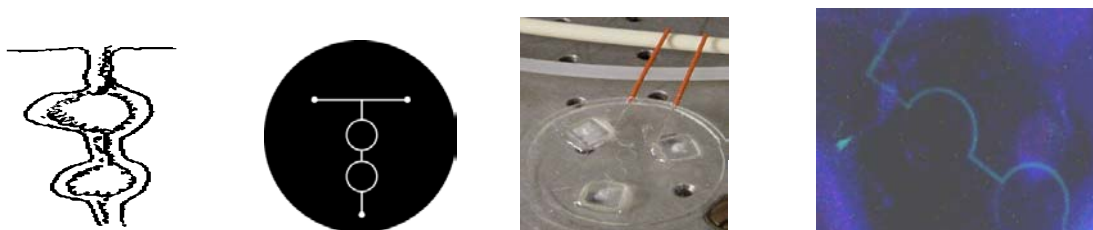

Fig. 3. "Figure Eight" mixer design, photolithography mask, device and flow.

The final design was a fairly standard serpentine mixer that maximizes residence time by maximizing the flow channel length. The mask and completed device are shown in Fig. 4. In this case there was slight mixing at exit. Table 1 summarizes these results.
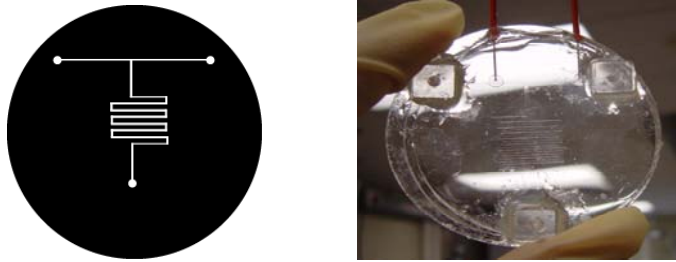

Fig. 4. "Serpentine" photolithography mask and device.

Table 1. Summary of results for three groups.

| Group | Average flow rate | | Wetted area to perimeter ratio | Re=(vW)/ | Flow Result | | Interaction length x interaction time |
	Volume flow (ml/min)	Velocity (mm/sec)			Mixed	Did not mix	
1	5.2	2.84	.00074	1.86E–03		X	145.29
2	6.8	3.97	.00074	2.59E–03		X	91.50
	4.3	7.52	.00073	4.84E–03	X		2984.83
3	1.5	9.37	.00069	5.69E–03		X	45.93

In the "Triangles" mixer design as the 2 inlets are valved mixing occurs due to shear between the layers at the interface between the streams.(Fig.5)
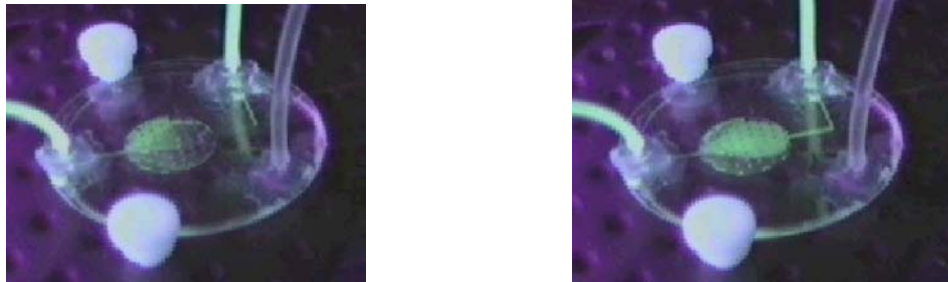

Fig. 5. Mixing due to shear between the layers.

Summary and Conclusion

Microfluidics presents challenges for conventional macroscopic thinking. The design problem presented in this paper illustrates that physical intuition derived from undergraduate thermal-fluids courses is not always sufficient to solve problems outside of the flow regimes that the professors had in mind when developing their curricula. It is clearly evident that the students' background in mixing was primarily based on their understanding of macroscopic fluid mixing in heat exchangers. There fluid mixing is always presented in the context of heat exchangers as a choice between staggered or aligned tubes. The extremely low Reynolds number was not factored into the students' thinking, as flows in this regime never occur in the courses they take as undergraduates. Even a professor in the department who was shown the designs predicted that the flows would mix. This shows the need for dedicated training in microflows for those students planning to pursue research in the area. The results of this project successfully demonstrated the limitations of the current training, but revisions are required to replace that flawed intuition with something better. These revisions will be applied in the next iteration of this project. We conclude with the remark that an excellent textbook is now available dedicated solely to design, fabrication and test of microfluidics [2]. This is the text we are now using for the later courses in our sequence.

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