

Passive Mixing in a Microchannel

by

Hengzi Wang
A/Prof. Syed Masood
Dr. Pio Iovenitti
A/Prof. Erol Harvey

Abstract

Mixing of binary or multi-components fluid streams can be difficult in a microchannel, because it relies on diffusion. In the microscopic scale, it is not practical to use mechanical agitation. Therefore, a high performance passive mixing strategy needs to be introduced. In this paper, a study of the influence of a wider range of geometric parameters on passive mixing is reported. In respect to the nature of laminar flow in a microchannel, the geometric parameters were designed to favour lateral convection. Hence, the dispersion of the solutes was not only driven by diffusion, but also, and more importantly, by the convection in the lateral direction. Geometric parameters versus the mixing performance were simulated for T-type mixers using a computational fluid dynamic (CFD) solver for microfluidics. Preliminary experimental results are also presented. The shape of the obstacles used for passive mixing in the microchannels are compatible with current micromachining technology, and therefore, the optimised results can be applied to practical design of microfluidic devices.

1. Introduction

It is well known that the Reynolds number is low in typical microfluidic channels, and the flow is laminar under normal conditions, especially for liquids. Therefore, the mixing of binary or multicomponent fluid streams in a microchannel relies mainly on diffusion. For a typical microfluidic device, the length scale is too large for a rapid diffusion and too small to include mechanical agitation. It is possible to achieve this by dynamic mixing with the assistance of externally forced mass transport, for example Yang *et al.* [16] used ultrasonic waves to enhance mixing, and Knight [8] described fast mixing by forming and controlling nanoscale, submerged fluids jets. However, it is much easier to control mixing in a laminar flow using a static micromixer. The principle of a static micromixer can be categorised into four types. (a). T-shape micromixer. The “T” mixer simply combines two or more fluid streams, which flow parallel to each other in the microchannel, and mixing relies purely on molecular diffusion [3,5-7]. The “T” mixer normally has a small channel width of the order of tens of microns and sufficient channel length. (b). Geometrically splitting and recombining substreams. In this way, large contact surfaces and small diffusion paths are generated (Ehrfeld *et al.* [15], Schwesinger, *et al.* [12], Koch *et al.* [9,10]). (c).

Chaotic Mixer. Stroock *et al.* [13] presented this mixer to stretch and fold the streams by rotating the streamline inside the microchannel. The circulation of the streamlines was due to the transverse pressure component created by the anisotropic resistance to viscous flow. Johnson *et al.* [4] reported similar structures machined by Excimer laser to achieve rapid mixing. However, the obvious drawback for these mixers is the dead volume created by these structures. (d). Altering flow direction laterally. This method tries to create stirring (convective) effects by forcing one fluid stream into another (Liu *et al.*[11], and He *et al.*[2]). Liu's serpentine-shaped micromixer was more favorable to high Reynolds numbers (~ 70), and He's in-situ micromixer could alter the flow direction, shrink the channel and divide the main stream into substreams. However, He's mixer is not likely to be used in a pressure-driven environment, due to the large pressure drop in its packed columns.

In this research, we continued to study the convective effects created by geometric variations. In the authors' previous paper, the results showed that the asymmetric layout of obstacles more favour to mixing performance rather than symmetric ones [14]. We will address the degree of mixing versus various geometric parameters in Section 3., and some preliminary experimental results will be reported in Section 4.

2. Industrial Implications

The nature of microfluidics limits its ability to generate sufficient mixing, which is critical in the development of microfluidic devices, especially for lab-on-a-chip and many other applications. This study uses a passive strategy to enhance mixing in a microscopic scale, and is compatible with the normal micromachining technology. The optimised parameters can be used in the design of such microfluidic devices.

3. Passive Mixing Versus Various Geometric Parameters

3.1 Numbers and Layout of Obstacles

From earlier work, we know the number of obstacles can somehow affect the mixing. We categorise them into two groups, asymmetric group and symmetric group. Then we tested from zero up to 18 square ($80 \times 80 \mu\text{m}$) obstacles. The results are illustrated in *Figure 1*. The results showed that the symmetric arrangement had little effect on the mixing efficiency. On the other hand, the asymmetric arrangement could enhance the mixing performance. The mixing performance for two and three square obstacles were investigated separately for its deviation from the trend. The results are shown in Figure 2. It is quite surprising that two obstacles actually have better performance than three obstacles. The interpretation for this can be the extra obstacle in the mid of the channel blocks the flow, reduces the interface between the two streams of liquids, hence, the maximum velocity towards the transverse direction is reduced, and thus, it has less convection.

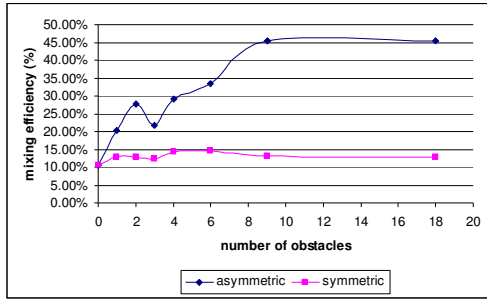


Figure 1 mixing efficiency with number of square obstacles in a H-filter

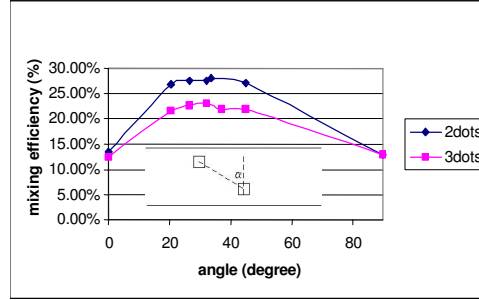


Figure 2 mixing in the channel with 2, and 3 square obstacles in a Hi-filter

3.2 Degree of blockage

While changing the length of the rectangular obstacles, the blockage to the channel increased. In the study, two rectangular blocks were used in the simulation with other parameters fixed. The degree of blockage was defined as the obstacle length b to the width of the channel w . On the one hand, the blockage improved the mixing efficiency, and on the other hand, the fraction of distorted flow dropped when approaching the obstacles.

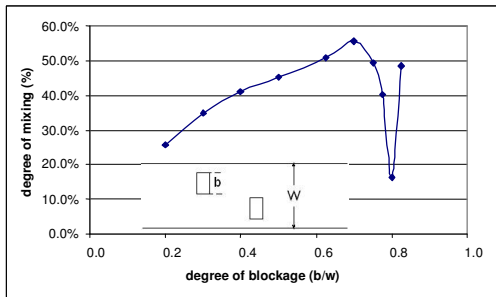


Figure 3 mixing in a T-channel with two rectangular block of obstacles

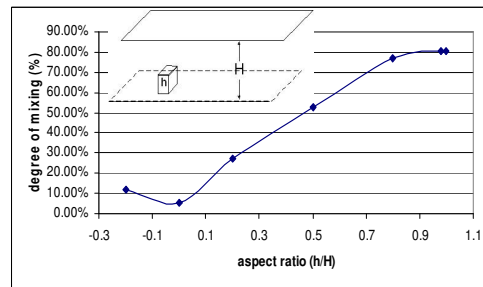


Figure 4 same T-channel with various height to the depth of channel

3.3 Height to depth aspect ratio

In Figure 4, the height of the obstacles to the depth of the channel aspect ratio were investigated. The degree of mixing improved, while the aspect ratio increased. At the zero, which meant that there was no obstacle in the channel, it gave the lowest degree of mixing. However, this ratio became negative, and the obstacles became grooves, and then the degree of mixing turned started to improve again. The asymmetric patterned grooves gave the lateral pressure component created by the anisotropic resistance to viscous flow. So it was expected that some lateral convection occurred to enhance mixing.

3.4 Offset

When two or more obstacles are placed in a microchannel, their relative position needs to be studied. In this paper, this parameters was measured as a to b ratio and ten obstacles were placed in the channel. See Figure 5. When $a/b=1$, it meant that the obstacles lined-up in the centre of the channel symmetrically, which was not improve the mixing performance. When $a/b = 0$, the obstacles were in contact with the wall, which actually formed a serpentine-shaped channel. However, it was preferable to have a gap between the obstacles and the wall, as it could eliminate the dead volume created at the corner.

3.5 Gap between obstacles

Another parameter to be studied was the gap between each obstacle. It was surprising that the degree of mixing was actually improved when the gap increased.

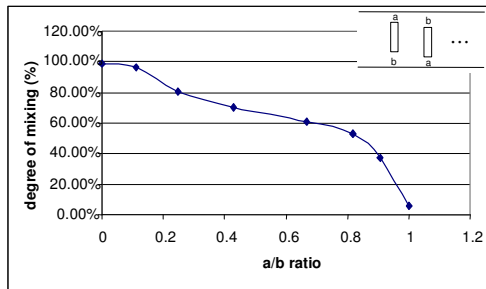


Figure 5 floating rectangular blocks in the channel

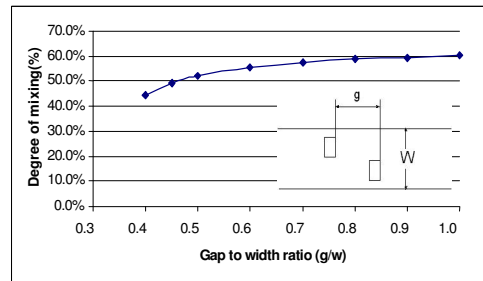


Figure 6 gap between two rectangular blocks

3.6 Degree of bias

For the previous simulation, the rectangular obstacles were placed perpendicular to the flow direction. The rotation of the rectangular obstacles were considered in the study. In Figure 7, shows the optimised region was from 60° to 120° .

3.7 Flow rate

From our previous work [14], we knew that mixing by diffusion alone was a slow process and a low flow rate was necessary for a sufficient mixing. In this paper, we expected that the mixing would still be improved, even in a high flow rate, because of effects of lateral convection. In Figure 8, at a very low flow rate, the mixing was largely due to diffusion. But as the flow rate was increased, the mixing performance dropped to its lowest point at 155nl/sec ($Re \sim 1$). Then, the degree of mixing went up again due to convective effects.

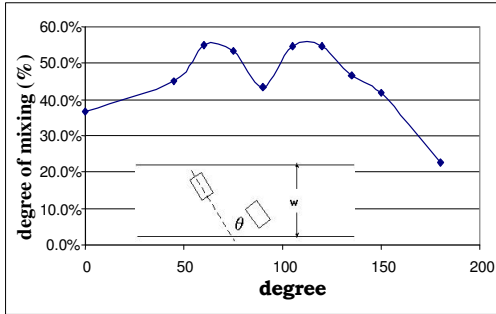


Figure 7 rotation of two rectangular blocks

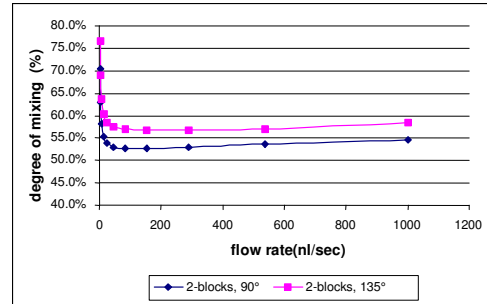


Figure 8 flow rate vs mixing efficiency in a channel with two rectangular blocks: a. 90 degree; b. 135 degree

4. Experimental design

The microfluidic channel was fabricated in the microtechnology laboratory in the Industrial Research Institute Swinburne, using the Excimer Laser to create the channels. The standard operation procedures can be found in early papers of the laboratory [1]. The UV laser beam, with a wavelength of 248nm, projected through the designed features on a chrome-on-quartz mask, and then laser beam is focused to pattern the feature on the substrate (Figure 9). The Excimer laser machined structures have a depth resolution of the order of $0.1\mu\text{m}$ and spatial resolutions of the order of $1\mu\text{m}$ or better. Figure 10 shows the laser ablated Y-channel on a polycarbonate substrate.

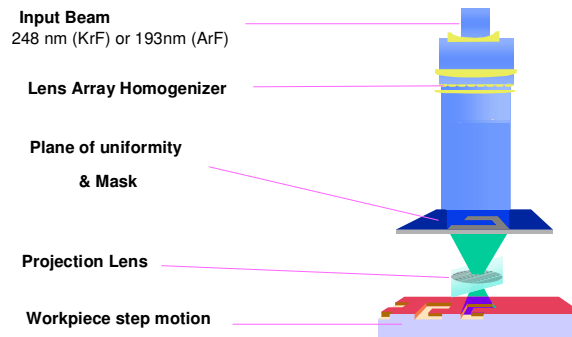


Figure 9 Excimer Micromachining (reproduced with permission)

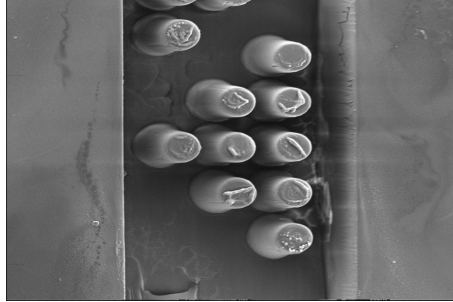


Figure 10 Section of Y-channel machined by Excimer laser

The microchannel was made using a lamination process in which a thin PET foil coated with a melting adhesive layer is pressed by a heated lamination roller onto the structure as the lid. Melinex® Polyester film type 301 (Dupont Teijin films), 30 μ m in thickness was used in our fabrication, and the lamination equipment was MEGA dry film laminator model 305 (Mega Electronics).

The aqueous solutions, one was a mixture of water, 2.4% food dye E102 and E122 (Yellow), and another one was a mixture of water and 2.1% food dye E133 (blue) (made by Queen Fine Foods Pty Ltd, Australia), were introduced to the channel by capillary effects. Flow rates were measured by weighing the fluid collected at the outlet of the channel. The viscosity of the food dye/water solution was assumed the same as water.

The preliminary results are illustrated in Figure 11. One figure is missing. In Figure 11, the mixing of two food colouring dyes (one yellow and one blue) in a Y-channel is shown. The mixed fluid is shown as a part showed green colour. It was clear that there was little green region before the blockage of obstacles, but it showed significant broadening of green region after the obstacles. This indicated the improvement to mixing by placing obstacles in the channel, which qualitatively agreed with the simulation results published earlier [14].

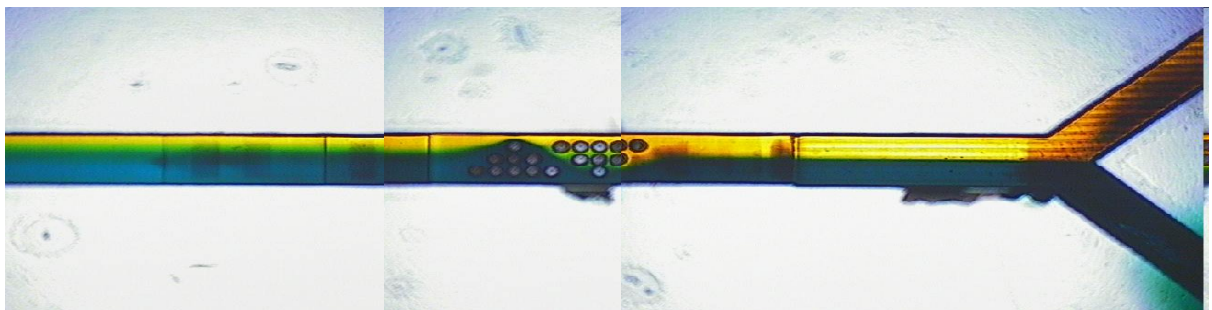


Figure 11 - Mixing two colouring dyes in a Y-channel

5. Conclusion

In this paper, the results showed that asymmetric placement of obstacles can improve mixing significantly due to the convective effects. The complexity of the mixing problem and the variations of geometry make it impossible for a general analytical solution to be derived. However, the computational fluid dynamic (CFD) tool illustrated its ability to analyse the mixing problem, even the full-scale of simulation was not achievable due to lack of computer resource. Preliminary experimental results were also presented, and it demonstrated the similarity with the CFD simulation results.

The shape of the obstacles used for passive mixing in the microchannels are compatible with current micromachining technology, and therefore, the optimised results can be applied to practical design of microfluidic devices.

6. Acknowledgments

The authors wish to express their gratitude to the Cooperative Research Centre (CRC) for Microtechnology for the support in this research project. Dr. Rowan Deam also provided very helpful discussions with the authors.

7. References

- [1] Harvey, E., Hayes, J., Dempster, B., Mackin, T., and Scholten, R., "Excimer laser ablation used for the fabrication of micro-optic phase and diffraction elements," Proceedings of SPIE - The International Society for Optical Engineering: Micro-Opto-Electro-Mechanical System, Glasgow. UK, pp. 152-158, 2000.
- [2] He, B., Burke, B. J., Zhang, X., Zhang, R., and Regnier, F. E., A picoliter volume mixer for microfluidic analytical systems Analytical Chemistry, vol. 73, pp. 1942-7, May 1, 2001.
- [3] Jacobson, S. C., Mcknight, T. E., and Ramsey, J. M., Microfluidic Devices for Electrokinetically Driven Parallel and Serial Mixing Analytical Chemistry, vol. 71, pp. 4455-4459, Oct 15, 1999.
- [4] Johnson, T. J., Ross, D., and Locascio, L. E., Rapid Microfluidic Mixing Analytical Chemistry, vol. 74, pp. 45-51, Jan 1, 2002.
- [5] Kamholz, A. E., Schilling, E. A., and Yager, P., Optical Measurement of Transverse Molecular Diffusion in a Microchannel Biophysical Journal, vol. 80, pp. 1967-1972, Apr, 2001.

- [6] Kamholz, A. E., Weigl, B. H., Finlayson, B. A., and Yager, P., Quantitative Analysis of Molecular Interaction in a Microfluidic Channel: the T-Sensor Analytical Chemistry, vol. 71, pp. 5340-5347, Dec 1, 1999.
- [7] Kamholz, A. e. and Yager, P., Theoretical analysis of molecular diffusion in pressure driven laminar flow in microfluidic channels. Biophysical Journal, vol. 80, no. 1, pp. 155-160, Jan, 2001.
- [8] Knight JB, Vishwanath A, Brody JP, and Austin RH, Hydrodynamic Focusing on A Silicon Chip – Mixing Nanoliters in Microseconds, Physical Review Letters, vol. no. 17, pp. 3863-3866, Apr 27, 1998.
- [9] Koch, M., Chatelain, D., Evans, A. G. R., and Brunnschweiler, A., Two simple micromixers based on silicon Journal of Micromechanics and Microengineering, vol. 8, no. 2, pp. 123-126, Jun, 1998.
- [10] Koch, M., Witt, H., Evans, A. G. R., and Brunnschweiler, A., Improved characterization technique for micromixers Journal of Micromechanics and Microengineering, vol. 9, no. 2, pp. 156-158, 1999.
- [11] Liu, R. H., Stremmer, M. A., Sharp, K. V., Olsen, M. G., Santiago, J. G., Adrian, R. J., Aref, H., and Beebe, D. J., Passive Mixing in a Three-Dimensional Serpentine Microchannel Journal of Microelectromechanical Systems, vol. 9, pp. 190-197, Jun, 2000.
- [12] Schwesinger, N., Frank, T., and Wurmus, H., Modular microfluid system with an integrated micromixer Journal of Micromechanics and Microengineering, vol. 6, no. 1, pp. 99-102, 1996.
- [13] Stroock, A. D., Dertinger, S. K. W., Ajdari, A., Mezic, I., Stone, H. A., and Whitesides, G. M., Chaotic Mixer for Microchannels Science, vol. 295, pp. 647-651, Jan 25, 2002.
- [14] Wang, H., Iovenitti, P., Harvey, E., and Masood, S., Mixing of liquids using obstacles in microchannels Proceedings SPIE, BioMEMS and Smart Nanostructures, vol. 4590, pp. 204-212, 2001.
- [15] V.H.H.L. Wolfgang Ehrfeld, Microreactors: New Technology for Modern Chemistry, John Wiley & Sons, 2000.
- [16] Yang, Z., Goto, H., Matsumoto, M., and Maeda, R., Active Micromixer for Microfluidic Systems Using Lead- Zirconate-Titanate(Pzt)-Generated Ultrasonic Vibration Electrophoresis, vol. 21, pp. 116-119, Jan, 2000.