EXPERIMENTAL STUDY ON PASSIVE MICROMIXERS: OPTIMIZATION OF COUNTERCURRENT MIXING.

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ABSTRACT

In this work, a planar passive micromixer with small microstructured elements (SME) was studied under laminar flow conditions. The influence of the flow rate, the size and the number of elements per repeating unit on mixing was investigated. A novel 3D mixer of this type was subsequently developed and studied. Its countercurrent properties increased mixing performance compared to other mixers with SME.

KEYWORDS: Passive mixing, countercurrent flow, lamination, chaotic advection, planar, 3D.

INTRODUCTION

Passive micromixers with SME display a chaotic advection type of mixing: this includes splitting, stretching, folding and breaking of the flow. They are most effective at high Reynolds number [1]. In previous work from our group [2] the shape of SME from symmetrically placed elements was studied, demonstrating their potential to distribute the flow, but also the lack of contacting and the concomitant poor overall mixing when working at lower Reynolds numbers. To enhance contacting of the fluids a design was developed were fluids are forced to move laterally from one side to the other side as studied by Melin *et al.* for a droplet in a silicon chip [3]. The pores between the elements allow for lamination and shorter diffusion distances. The chips applied in the current study were milled in PMMA and were operated under continuous flow conditions.

THEORY

Micromixing can be either active or passive. Active mixing requires an external input (pressure, temperature,…) whereas passive mixing relies solely (next to the flow generating input) on channel geometries to mix fluids. Passive mixing occurs either by diffusion or by chaotic advection.

When working with a diffusion based mixer, one usually tries to generate small fluids layers to ensure short diffusion times. Parallel and serial lamination mixers generate these layers by splitting and recombining the flow [1].

Advection is the movement of a particle with the fluid in which it is submerged [4]. When one takes a look at the equations governing the movement of such a particle in a fluid, it can be concluded that they can be nonintegrable and produce chaotic dynamics. The particle can thus exhibit chaotic trajectories. This enhances stretching and folding of the material interfaces, increasing the interfacial area which of course enhances mass transfer. It can be shown that even in laminar flows, particle movement can exhibit chaotic behavior [5]. Liu *et al.* [6] demonstrated that by comparing a square-wave (planar) and a serpentine mixer, 3D flow causes extra chaotic advection and increased mixing performance.

When the pores of a SME based mixer are narrowed to the point where the pressure drop between them is vastly increased, the mixer can display serial lamination properties. This effect along with chaotic advection at the bends was studied for planar and 3D designs.

EXPERIMENTAL

The channels were milled and sealed by thermal bonding (130°C, 30 min) on a PMMA cover sheet. A schematic design and a picture of a generic planar serial lamination mixer are shown in figure 1. Note that the inlet section is not put in axial configuration as it would be for regular SME mixers.

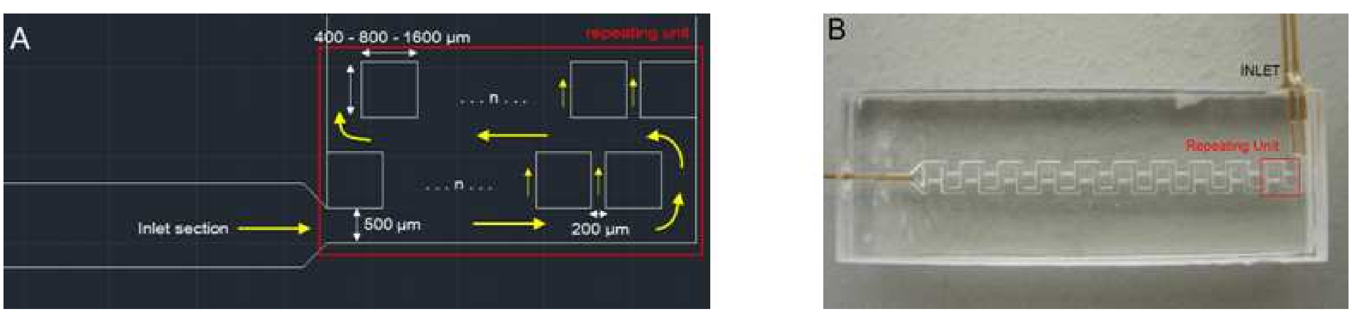

Figure 1. Schematic design of one repeating unit of a generic planar serial lamination mixer. Due to the larger diameter of the lateral channel and the inherent lower pressure drop, only a fraction of the flow goes through the pores. The size and number of the pores was varied to study the effect on mixing. A picture of a mixer with 1 pore (B)

In this work, dilution experiments of 7-amino-4-methylcoumarin (10^{-4} M in methanol) with methanol were performed and detected using a fluorescence microscope equipped with a CCD camera. Pictures were taken at several key points downstream the mixing zone and the mixing performance was evaluated by comparing the standard deviation of the fluorescence signal.

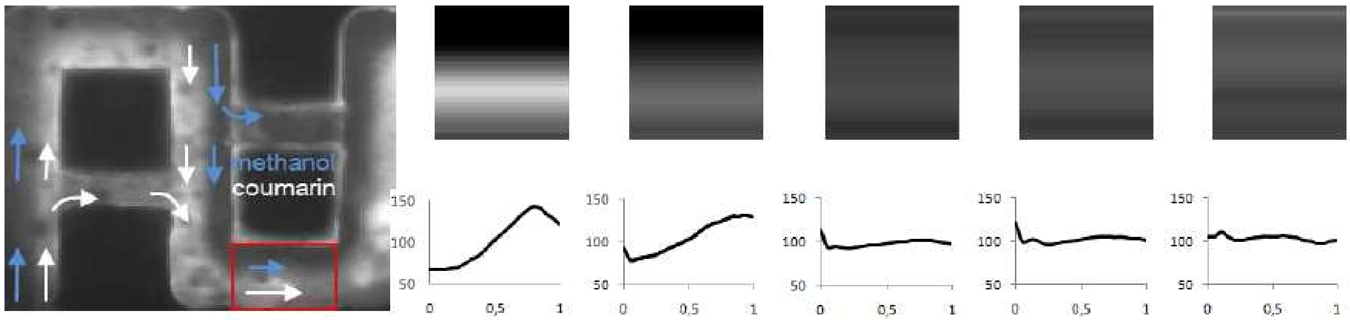

Figure 2. Dilution experiments on chip. Picture of one repeating unit from a planar mixer with serial lamination properties. The flows of methanol and coumarin are pointed out by the white and blue arrows (left). Pictures (right top) are taken at key points (shown in red on the left picture) and their corresponding fluorescent signal is shown (right bottom).

RESULTS AND DISCUSSION

The influence of the flow rate (laminar conditions) on mixing was studied for mixers with elements of 400, 600 and 800 µm (figure 3). An increase in flow rate leads to a small increase of mixing, most noticeable in the first part of the mixer, despite a reduction of the residence time. The effect is more pronounced for mixers with smaller elements (not shown). This could be explained by the higher pressure drops due to narrowing (localized pressure loss scales with velocity squared) of the channel when entering the pore and concomitant smaller fluid layers. Larger pores perhaps already exhibit a substantial pressure drop trough the pore (longer pore section) leading to small lamina. Another factor that could explain this increased mixing is the increased chaotic advection for the short U-turns of the smallest elements.

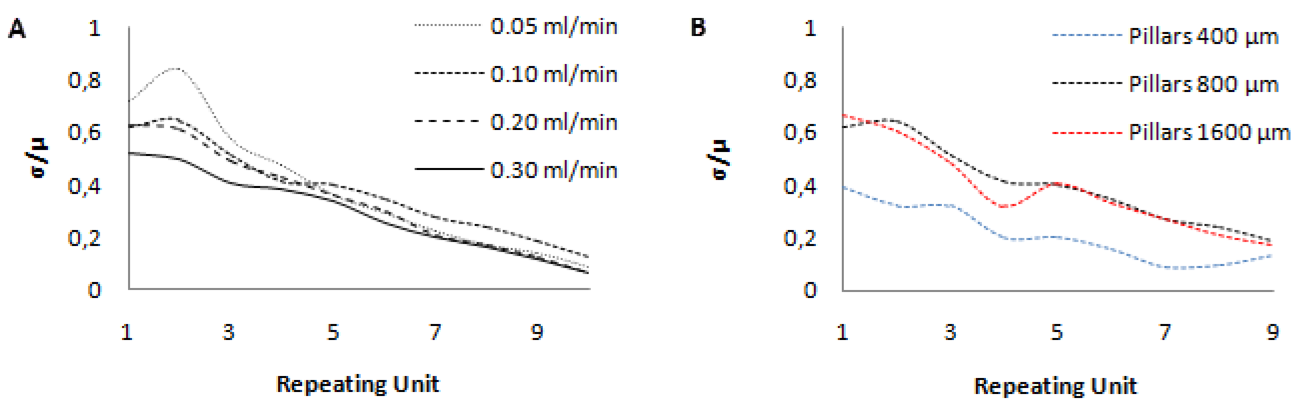

Figure 3. Effect of the flow rate on mixing for a mixer with 800 µm elements.The standard deviation decreases due to the mixing so that the value on the y-axis approaches 0.1 (equilibrium value, complete mixing). Mixing increases at higher flow rates, this is most noticeable in the first section of the mixer (A). Effect of the pillar size on mixing performance (flow rate 0.1 ml/min). The best mixing was seen for the smallest pillars. This effect can probably be explained by an altered flow distribution due to a higher pressure drop at the pores accompanied by increased chaotic advection at the short U-bends (B).

When increasing the number of pillars, the mixing deteriorated rapidly. The two fluids were divided over the 2 sides of the chip and contacting occurred only in the middle, as was the case for previous SME mixers (for low Reynolds numbers).

As shown in figure 2, contacting trough the pores happens between fluids of the same type and thus does not lead to increased mixing. Since part of the flow is separated, a smaller layer of one fluid type is bent around the corner along with the other fluid type (if less than 50% of the flow goes through the pore). Chaotic advection and a shorter diffusion distance will realize mixing. By defining how much of the flow is separated over the pore, one could fine tune the layer of fluid moving around the bend. A schematic design of optimization of the planar serial lamination is shown in figure 4, note that the design for 1 pore is shown, multiple pores lead to distribution of the two fluid types.

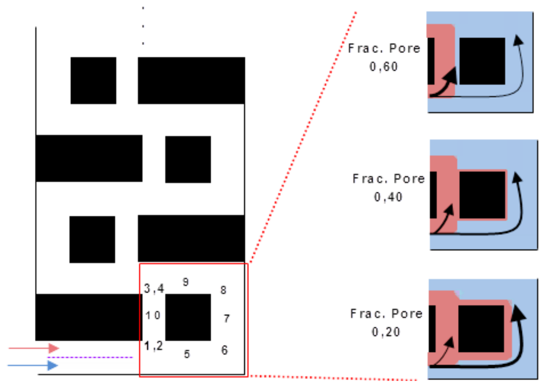

Figure 4. Schematic design of the planar serial micromixer. By designing the pore size (and thus the local and shared pressure loss (the numbers left)), one could fine tune the fraction of the fluid that enters the pore to ensure complete mixing in the bend.

A downside to the planar design is the limited lamination and the dependence of the mixing on chaotic advection. To resolve these limitations, a third dimension was implemented, allowing for countercurrent contacting between different fluid types and increased chaotic advection in the bends. Mixing was almost instantaneous (figure 5).

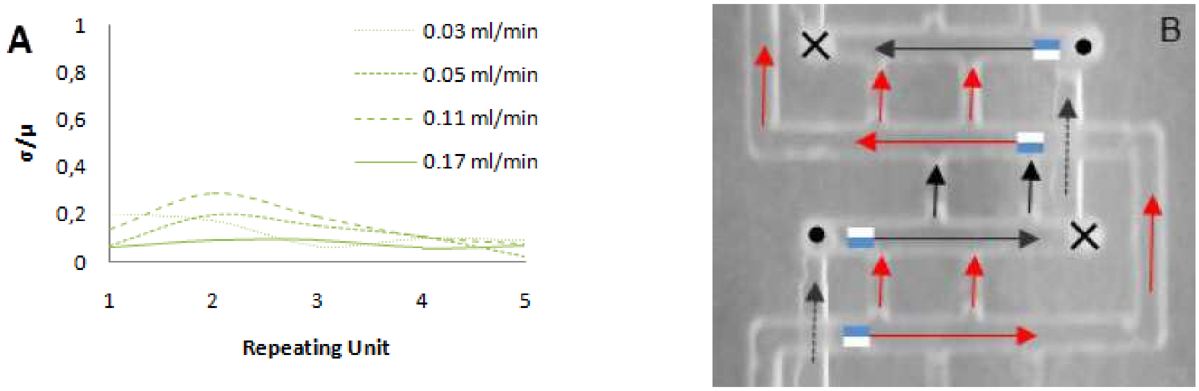

Figure 5. Mixing performance of a 3D mixer with 800 µm elements. Almost instantaneous mixing is seen for every flow rate (A). Photograph of the 3D mixer with arrows (red, black) indicating flow directions. Crosses and dots indicate flow going in and out of the plane. In white and blue is shown at what side of the channel the fluid types are flowing, notice the alternating co-and countercurrent flow (B).

CONCLUSION

While the planar lamination mixer shows good mixing performance, planar improvements to the design are limited. When adding a third dimension, chaotic advection based mixing is improved and the countercurrent flow allows for multiple pores. Improvements in the design are bound to follow.

REFERENCES

[1] N.-T. Nguyen, Z. Wu, Micromixers – a review, *J. Micromech. Microeng*., 15, R1-R16 (2005).

[2] R. Goovaerts, W. De Malsche, N. De Meirleir, G. Desmet, J. Denayer, Improving Crystal Size Distribution using Microreactor Mixing Units, Proceedings of µTAS 2010, 14th International Conference on Miniaturized Systems in Chemistry and Life Sciences, November 1-5, 2010, Groningen, The Netherlands.

[3] G. Melin, N. Giménez, N. Roxhed, W. Van der Wijngaart, G. Stemme, A fast passive and planar liquid sample micromixer, *Lab Chip,* 4, 214-219 (2004).

[4] H. Aref, The development of chaotic advection, *Physics of fluids*, 14, 1315-1325 (2002).

[5] A. M. Stremler, F. R. Haselton, H. Aref, Designing for chaos: application of chaotic advection at microscale, *Philosophical transactions of the royal society A*, 362, 1019-1036 (2004).

[6] R. H. Liu, M. A. Stremler, K.V. Sharp, M.G. Olsen, J. G. Santiago, R. J. Adrian, H. Aref, D. J. Beebe, Passive mixing in a three-dimensional serpentine micro channel, *Journal of microelectromechanical systems*, 9, 190-197 (2000).

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