DESIGN AND SIMULATION STUDY OF OBSTACLE BASED PASSIVE MICROMIXER

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ABSTRACT

Micromixer can be dividing by two categories which are active micromixer and passive micromixer. Due to simple fabrication technology and the easy implementation in a complex microfluidic system, obstacle based passive micromixers will be the focus of this project. Due to laminar flow (Reynold Number < 1) passive micromixer is the best method in fluids mixing. Passive micromixers also depend on the channel geometry for mixing effectiveness. In this study, seven different micromixers were evaluated based on the baseline control Y micromixer. The micromixers are Y shape with obstacle as proposed in PS 1 micromixer, Y shape with internal rib micromixer, Y shape with obstacle design 2, Y shape with obstacle design 3, Y shape with obstacle design 4, and Y shape with obstacle design 5. These micromixers has 237µm channel length, 30µm inlet length, 90^0 between inlets ports, width and depth are 30µm each. The fluids used for mixing were blood which has 3.0 × 10-3 kg/µms of viscosity and glycerin which has high viscosity than blood (1.49 × 10-3 kg/µms). The fluids used to evaluate the differences in term of their visual performance based image's standard deviation by plotting the graph and mixing efficiency by calculation. Based on these evaluations, the Y shape with obstacle design 5 micromixers is the best micromixer design with the highest mixing efficiency of 100% at the outlet of the channel.

ABSTRAK

Micromixer boleh terbahagi kepada dua kategori iaitu *micromixer* aktif dan *micromixer* pasif. Oleh kerana teknologi fabrikasi yang mudah dan mudah disesuaikan dalam sistem *microfluidic* yang kompleks , halangan berasaskan *micromixers* pasif akan menjadi tumpuan projek ini. Oleh kerana aliran lamina (Nombor Reynold <1) *micromixer* pasif adalah kaedah terbaik dalam mencampurkan cecair . *Micromixer* pasif juga bergantung kepada geometri saluran untuk keberkesanan pencampuran. Dalam kajian ini, tujuh *micromixer* yang berbeza telah dinilai berdasarkan bentuk asas Y *micromixer*. *Micromixer* yang dikaji adalah bentuk Y dengan halangan seperti yang dicadangkan dalam PS 1, bentuk Y dengan rusuk dalaman, bentuk Y dengan reka bentuk halangan 2, bentuk Y dengan reka bentuk halangan 3, bentuk Y dengan reka bentuk halangan 4, dan bentuk Y dengan reka bentuk halangan 5. *Micromixer* ini mempunyai panjang saluran 237µm, panjang masuk 30µm, sudut diantara salur masuk 90^0, lebar dan dalam adalah 30µm. Cecair yang digunakan untuk dicampurkan adalah darah yang mempunyai kelikatan 3.0 × 10-3 kg / µms dan gliserin yang mempunyai kelikatan yang tinggi daripada darah (1.49 × 10-3 kg / µms). Penilaian yang digunapakai dalam kajian ini adalah prestasi dari sisihan piawai imej dengan memplot graf dan juga dari segi kecekapan pencampuran yang dilakukan secara pengiraan. Berdasarkan penilaian ini, bentuk Y dengan halangan reka bentuk 5 adalah reka bentuk *micromixer* terbaik dengan keberkesanan pencampuran tertinggi sebanyak 100 % pada keluaran salurannya.

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Symbols / Abbreviation	
LOC	Lab On Chip
CFD	Computational Fluid Dynamics
PDMS	Polydimethylsiloxane
SHM	Staggered Herringbone Mixer
CGM	Connected-Groove Micromixer
SAR	Split And Recombined
ρ	Fluid density
v	Fluid velocity
D	Vessel diameter
µ	Fluid viscosity
C_i^0	The viscosity at the point sample
$\bar{C}_i^0$	The mean or average for the viscosity

CHAPTER 1

INTRODUCTION

1. INTRODUCTION

This chapter will describe about the introduction of the project. In the section of the background of study, the problem in this study is related to biomedical and chemical analysis. A sample solution is often to be tested with a reagent. The two solutions should be well mixed to make the reaction possible. Besides, the more specific problem and method of this study is also been mention for better understanding of this area. Then significant of study, objectives, scopes of study and expected result will be show for the detail of this study.

1.1. BACKGROUND STUDY

In biomedical and chemical analysis, a sample solution is often to be tested with a reagent. The two solutions should be well mixed to make the reaction possible. While in microscale, mixing is achieved with turbulence, mixing in microscale relies mainly on diffusion due to the laminar behavior at low Reynolds numbers.

Micromixers are categorized as passive mixers and active mixers. Passive mixers do not have moving parts. Micropumps or microvalves used to deliver fluids to the mixing area are not considered part of the mixer. In active mixers, moving parts are involved. Moving parts are used to manipulate or control the pressure gradients in the mixing area. Because of the nature of the mixing phenomena, the two mixer types are also called static and dynamic mixers. Because of their simple implementation, passive mixers are a favorable solution for microfluidic systems.

Conventionally, turbulent flows and mechanical agitation make rapid mixing possible by segregating the fluid in small domains, which increase the contact surface and decrease the mixing path. Since the Reynolds numbers in microfluidic devices are on the order of 1 or less, far below the critical Reynolds number, turbulence is not achievable in microscale. All micromixers work in laminar regime and rely entirely on diffusion. General design requirements for micromixers are fast mixing time, small device area, and integration ability in a more complex system.

Micromixers can be categorized as passive micromixers and active micromixers. Passive micromixers do not require external disturbance to improve mixing. The passive mixing process relies entirely on diffusion and chaotic advection. Based on the arrangement of the mixed phases, passive mixing concepts can be further categorized as parallel lamination, serial lamination, injection, chaotic advection, and droplet mixing. Active micromixers use external disturbance for accelerating the mixing process. Based on the types of disturbance, active mixing can be categorized in pressure-driven, temperature-induced, electrohydrodynamic, dielectrophoretic, electrokinetic, magnetohydrodynamic, and acoustic concepts. Because of the integrated components and external power supply for the generation of disturbance fields, the design of active micromixers is often complicated and requires a complex fabrication process. The integration of active mixers in a microfluidic system is therefore both challenging and expensive. The major advantage of passive micromixers is the lack of actuators. The simple passive structures are robust, stable in operation, and easy to be integrated. Figure 1 illustrates the systematic overview of different micromixer types.

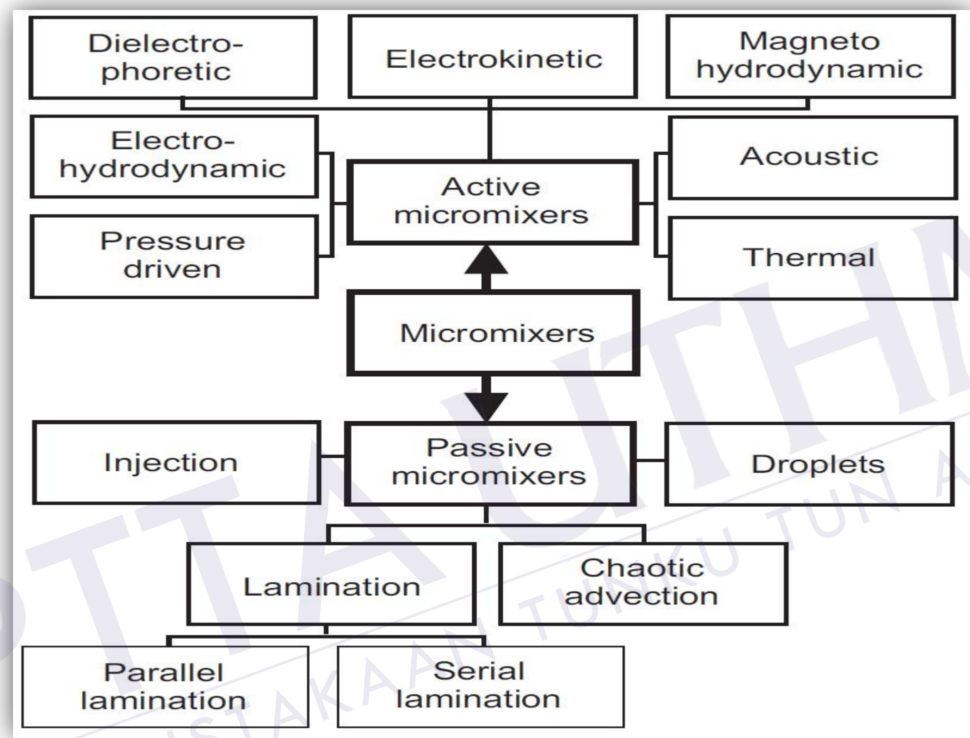

Figure 1.1: Overview of different micromixer types.

1.2. PROBLEM STATEMENT

Generally, active micromixers have higher mixer efficiency. However, the requirement to integrate peripheral devices such as the actuators for the external power source into the microdevice, and the complex and expensive fabrication process, limit the implementation of such devices in practical applications. In addition, in active mixing mechanisms such as ultrasonic waves, high temperature gradients can damage biological fluids. Therefore, active mixers are not a popular choice when applying microfluidics to chemical and biological applications.

Passive mixing devices rely entirely on fluid pumping energy and use special channel designs to restructure the flow in a way that reduces the diffusion length and maximizes the contact surface area. Passive mixers were the first microfluidic device reported, often entail less expense and more convenient fabrication than active micromixers, and can be easily integrated into more complex LOC devices. The reduction in mixing time is generally achieved by splitting the fluid stream using serial or parallel lamination], hydrodynamically focusing mixing streams, introducing bubbles of gas (slug) or liquid (droplet) into the flow, or enhancing chaotic advection using ribs and grooves designed on the channel walls.

There are many different ways to provide mixing in macroscale such as molecular diffusion, eddy diffusion, advection, and Taylor dispersion. Eddy diffusion is the transport of large groups of species and requires a turbulent flow. Because of the dominant viscous effect at the microscale, turbulence is not possible in micromixers. Mixing based on eddy diffusion is therefore not relevant for micromixers.

Thus, the main transport phenomena in micromixers are molecular diffusion, advection and Taylor dispersion. Molecular diffusion is caused by the random motion of molecules. This transport mechanism is characterized by the molecular diffusion coefficient. Advection is the transport phenomenon caused by fluid motion.

A simple Eulerian velocity can lead to a chaotic distribution of the mixed species. A stable and laminar flow can also lead to chaotic advection. Thus, chaotic advection would be ideal for the laminar flow condition in micromixers. Taylor dispersion is advection caused by a velocity gradient. Axial dispersion occurs due to advection and interdiffusion of fluid layers with different velocities. Due to this effect, mixing based on Taylor dispersion can be two or three orders faster than mixing based on pure molecular diffusion.

1.3. SIGNIFICANT STUDY

Due to this project, the new design of micromixer is being study. It helps medical researchers and others to understand the concept and make the comparison which design will get the fastest time for fluids to mix. This design can be applied on LOC and the result can be drawn faster and more efficient. It will help, for example the doctor can give patient suitable treatment based on the result from micromixer test in very short time.

1.4. OBJECTIVE

The following are the objectives of this project:

i. To build a new design of microchannel of passive micromixer using split and recombined technique plus rib technique with single layer structure.
ii. To analyze the fluids mixing performances via color changes, viscosity's standard deviation and mixing efficiency among the selected micromixers
iii. To perform a comparative analysis and to select the optimum design among the selected micromixers

1.5. SCOPE

There is a lot of ground need to cover for this project and there are so many designs in passive micromixer from the basic shaped, parallel lamination micromixer, sequential lamination micromixer, focusing enhanced mixer, chaotic advection micromixer and droplet micromixer. To make the comparison between those designs, will take a lot of time also energy.

Designing micromixers is a completely new engineering discipline, because existing designs in macroscale cannot simply be scaled down for microscale applications. One of the main challenges related to miniaturization is the dominance of surface effects over volume effects. Actuation concepts based on volume forces working well at the macroscale may have problems at the microscale.

Besides surface phenomena, the laminar flow condition is another challenge for designing micromixers. For many applications, the flow velocity in micromixers cannot be too high. The small size of micromixers leads to an extremely large shear stress in mixing devices, even at relatively slow flow velocities. This shear stress may damage cells and other sensitive bioparticles. Advection allows improved mixing in fluid flows at low Reynolds number. In most passive micromixers based on molecular diffusion, advection is parallel to the main flow direction. Thus, transversal transport of species relies entirely on molecular diffusion. Advection with a three-dimensional orbit can cause secondary transversal transport and significantly improve mixing. The basic design concept for the generation of advection is the modification of the channel shape for stretching, folding, and breaking of the laminar flow.

In this project, the new design of passive micromixer is build based on the split and recombined technique plus rib technique structure. The alteration of internal structure and shape of microchannel can increase the interfacial surface areas and then improve the mixing performance. The internal-rib micromixer with a high mixing efficiency and low pressure loss is able to meet the requirement of microfluidic chips.

1.6. REPORT OUTLINE

Chapter 1 has presented a briefly introduction of the thesis project mainly about micromixer which consist of passive and active also microfluidic, the problem that we are facing, the objectives of the project and also the scope or the limitation of the project itself.

Chapter 2 will present more deeply into the related topic of microfluidic for passive and active micromixer. This chapter will also explain more about the fundamental of mixing fluid, the Reynold number and the mathematical background of fluid flow.

Chapter 3 will present the methodology used to complete this project. Using only Autodesk inventor and CFD software, is the method used to compare and analyze the result. But before using this software, all the specifications including the details of the design of the chosen passive micromixer will be included in this chapter. The details are: the Reynold number used the length of the channel, the depth of the channel, the details of the fluid used etc.

Chapter 4 is the result and discussion for all the analysis of the seven micromixers for evaluation. The result and analysis are based on viscosity performances, viscosity's standard deviation and also the mixing efficiency.

Chapter 5 presents the overall conclusions and discussions of this thesis and also the recommended future work. This is followed by references and appendices.

CHAPTER 2

LITERATURE REVIEW

2. INTRODUCTION

In this chapter of literature review, most of the recent related researches had been reviewed as the reference of this study. The references are reviewed based on the micromixers design and the simulation. The parameters and boundary condition of fluid flows is also important for the review in this study, because these information can be obtain for the analysis uses. Finally, the ideas and method of the previous researches are referred for the better understanding of this study.

2.1. LITERATURE REVIEW

Over the past two decades, lab-on-a-chip (LOC) technologies have driven considerable progress in the development of microsystems, particularly for chemical, biological, and medical applications. The exponential increase of research in miniaturization and in microfluidic applications highlights the importance of understanding the theory and the mechanisms that govern mixing at the microscale level. This chapter will review the most recent research and developments in mixing processes within microfluidic devices.

Jayaraj et al. [1] presented a review on the analysis and experiments of fluid flow and mixing in microchannels, but their review was based on the literature published mostly before 2005. Very recently, Falk and Commenge [2] addressed use of the method of performance comparison or evaluation of micromixers by using the Villermaux/Dushman reaction. They combined the order-of magnitude analysis and a phenomenological model to derive relation between the mixing time and other parameters such as the Reynolds number. However, no review paper has been found which addresses key features of various types of micro mixers and evaluates them in terms of their mixing performance, versatility of application and difficulty of fabrication, etc. This review paper summarizes the fundamental ideas behind the mixer designs presented in the papers published in 2005 and thereafter, as well as the application range and the fabrication difficulty of these.

In this paper it will review the various ideas of the microfluidic mixers reported since 2005. Surveying the literature, we have found that many papers treat moderate or high Reynolds-number flows. However, this type of paper will be excluding in this review because such moderate or high Reynolds-number flows are rarely found in microfluidic applications. Moreover, with such flows it may be easy to induce unsteady complex flows that naturally contribute significantly to the fluid mixing. The microfluidic mixers can be classified in various ways. In this paper, the physical mechanism will be used for classification purpose such as hydrodynamic focusing, injection, geometry effect and droplet mixing.

2.2. HYDRODYNAMIC FOCUSING

From previous paper, Floyd et al. [3] fabricated a silicon microchannel with 10 inlets for mixing acid and base solutions (Figure 2.1). Their experimental measurement for the mixing performance was compared with computational fluid dynamics (CFD) results with good agreement in terms of the residence time. Nguyen and Huang [4] presented a comparison between the analytical solution and the experimental measurement of the diffusion of samples in a hydrodynamic focusing means.

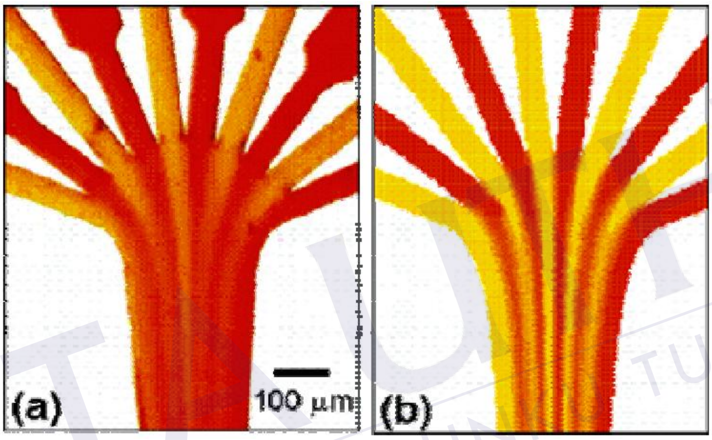

Figure 2.1: (a) Experimental and (b) numerical visualizations of fluid mixing in hydrodynamic focusing channels (from Floyd et al. [3]).

They achieved the focusing by using a pair of inlet channels. Unique to their study is that they employed pulsed addition of solute to the channel to enhance the reaction. In this design, the valves at the inlets are actuated by two piezo discs. It is implied in this paper that the Taylor dispersion can further enhance the mixing. Adeosun and Lawal [5, 6] introduced the so-called multilaminated/elongational micromixers to mix two fluid samples (Figure 2.2). Their design is composed of many mixing structures strategically arranged on the channel floor of the mixing device and blocks arranged in a staggered way at the inlets. It was shown that their mechanism of fluid multilamination and elongation is highly effective in enhancing the mass transfer.

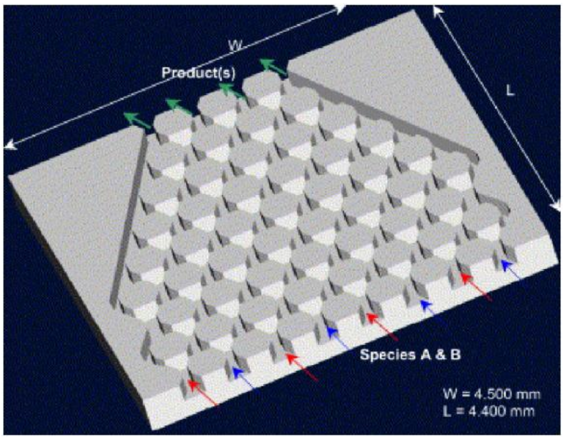

Figure 2.2: A multilaminated/elongational flow micromixer (from Adeosun and Lawal [5, 6]).

Cha et al. [7] proposed a 3D micromixer combining the focusing and split-and-recombination (SAR) functions called the chessboard mixer (Figure 2.3). For the flow rate of 12.7 μL/min, 90% of mixing occurs only within the length of 1.4 mm. Park et al. [8] demonstrated the use of sheath flows from the hydrodynamic focusing as an effective method in controlling the reaction of samples. They fabricated five inlet channels: the center for an analyte solution, the two sides for the solution B and the two diagonals for the solution A. In this way, they could prevent the undesired premixing of solutions before the focusing was completed. Mimicking the geometrical properties of a vascular system, Cieslicki and Piechna [9] designed a branched channel and numerically investigated the mixing performance, particularly focusing on the effect of the number of branches.

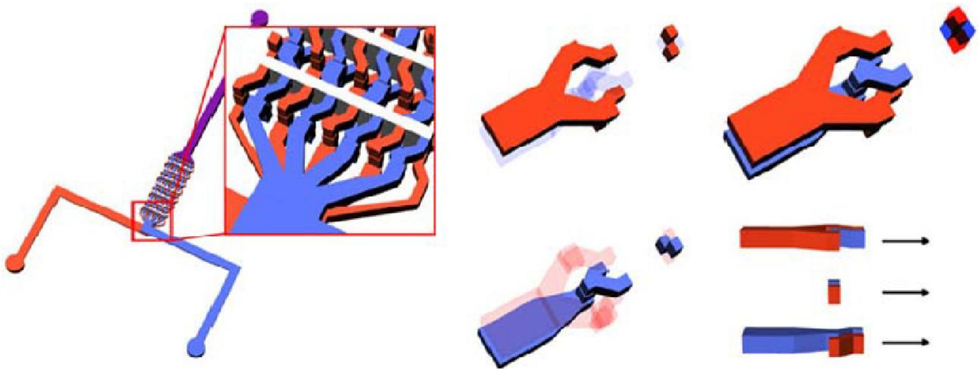

Figure 2.3: A schematic illustrating the structure of the chessboard mixer (from Cha et al. [7]).

All the papers investigating the hydrodynamic focusing principle indeed show its highly effective mixing performance, such as short mixing length or fast mixing time. The main problem in the hydrodynamic focusing, however, lies in how to distribute the fluids to the multiple inlet channels. Typically, for the mixing of two samples, each sample is stored in one of the two different reservoirs while multiple channels used for the focusing are usually arranged in a staggered way. Then the fabrication of the inlets must be of a two-layer structure, which adds to the complexity in the overall device design.

2.3. INJECTION

Another popular method for enhancing the mixing performance is to inject samples of different species at the inlet in an alternating way; in view of each sample, the resulting flow is similar to a pulsed flow. Compared with the hydrodynamic focusing case, the alternate injection design does not require complex channel fabrication. MacInnes et al. [10] conducted a numerical and analytical study on the mixing performance for a case in which two different samples are introduced into the channel via a pulsating pressure. Such alternate injection increases the interfacial area, leading to a fast mixing. Goullet et al. [11] studied the effect of the geometry of the inlet channel (i.e., "T" and "Y", etc.) as well as the phase difference between the two injected samples on the mixing performance of the pulsed-flow mixer. They also introduced ribs in the main channel and demonstrated significant improvement in the degree of mixing.

As the driving force for the sample injection, electroosmosis is sometimes more beneficial than pressure. The research group of Sinton [12, 13] conducted an experimental study on the mixing effect in a channel design composed of a cross inlet channel and a larger mixing chamber (Figure 2.4), where samples are sequentially injected via electroosmotic force. The decelerating flow in the expansion channel connected to the chamber makes the striation thinner and thinner, thus promoting the diffusion. It was shown that the optimum frequency for the best mixing in their specific parameter settings is in the range 1–2 Hz. Similar designs have also been proposed by Leong et al. [14] and Sun and Sie [15].

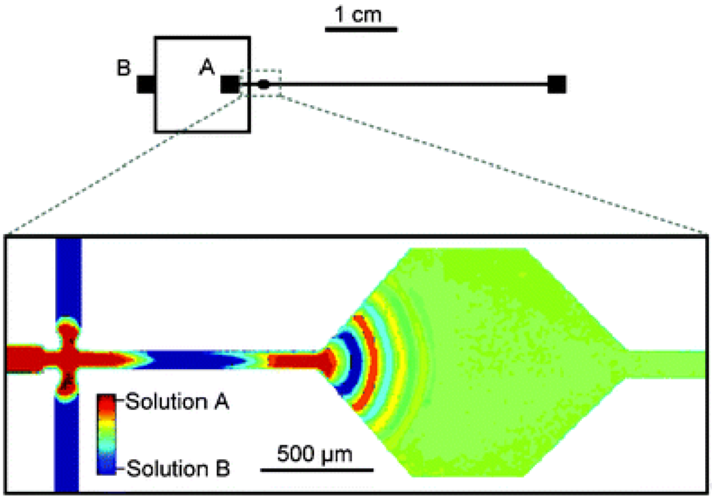

Figure 2.4: An alternate-injection mixer composed of an inlet cross channel and a larger chamber (from Coleman et al. [13]).

The concept of the simple alternate injection can be further improved or altered for better mixing. Fu and Tsai [16] conducted a numerical simulation on the dispersion of concentration caused by alternately driven fluid through the simple "T" and double "T" channels. They showed that the double "T" channels provide a faster mixing effect compared with the single "T" design (Figure 2.5). In the work of Lee et al. [17], a detailed analysis of the chaotic advection in an alternate-injection mixer was presented in terms of the non-linear dynamical terms, such as Lyapunov exponent and Poincare section. For the case with fluid injection through the side channels, they showed the existence of an optimum frequency of fluid injection for the best mixing. In the work of Chen and Cho [18], in addition to the pulsating fluid injection through the inlet channels, the main channel walls are also designed in a wavy form so that each isolated slug of sample undergoes the stretching-folding process, which further enhances the mixing (Figure 2.6).

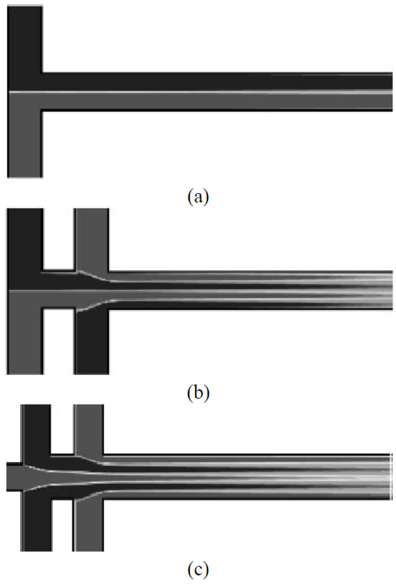

Figure 2.5: Three types of inlet channels; (a) single “T”, (b) double “T” and (c) double cross channel (from Fu and Tsai [16]).

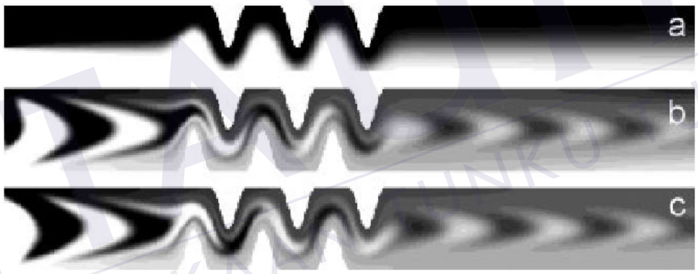

Figure 2.6: Distribution of species concentration in wavy-wall channels by (a) continuous injection, (b) pulsed injection with a certain period and (c) pulsed injection with the period double that for (b) (from Chen and Cho [18]).

Like the hydrodynamic focusing method, the alternate-injection method also suffers from a fundamental drawback; the stirring occurs only in the inlet region of the channel. Although the larger chamber attached to the inlet channel proposed by Sinton’s group [12, 13], Leong et al. [14] and Sun and Sie [15] promotes the mixing via the stretching of the slug, it is not like chaotic advection since the stretching occurs only linearly in time. Further, when elctroosmotic force is used for the fluid injection due to its feasibility in the injection control, bubble generation from the electrodes or the electrode degradation can cause another problem. For practical applications, therefore, those problems must be tackled.

2.4. GEOMETRY EFFECT

Apparently, the simplest way to enhance mixing in a microchannel is to make the channel geometry complex, e.g., a serpentine structure [19], or with grooves [20] or blocks [21] on the bottom wall. Kim et al. [22] proposed a two-layer microchannel composed of a series of F-shaped channel units (Figure 2.8), which was shown to bring chaotic advection via the stretching-folding mechanism. Xia et al. [23] compared three kinds of two-layer crossing channels in terms of the mixing effect including the basic serpentine mixer proposed by Liu et al. [19].

Their two types of design (Figures 2.8a and 2.8b) revealed much better mixing performance than the basic serpentine structure (Figure 2.8c) at low Reynolds numbers, implying that the basic serpentine microchannel is not suitable for low Reynolds-number flows. Further support for this argument was given by the numerical simulation of Ansari and Kim [24]. The two-layer structures proposed by Kim et al. [22] and Xia et al. [23] are shown to provide chaotic advection, but again the main disadvantage of those structures is that the fabrication of the two layers separately should increase the device price.

Howell et al. [25] also proposed a two-layer design, where not only the bottom but also the top walls carry grooves of stripes and chevrons. Their design brings faster mixing compared with the case with bottom grooves only [20], but here again fabrication difficulty must be overcome to be useful for practical applications. Similarly, Yang et al. [26] proposed to build partitioning plates on the top wall in addition to the bottom grooves to stir the fluid in the region near the top wall, but the fabrication of such a channel may not be so simple.

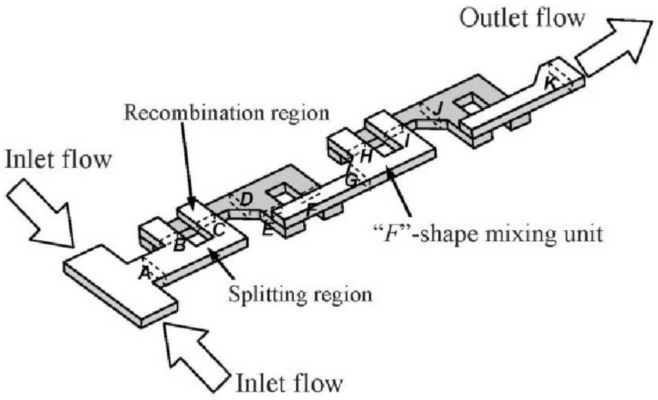

Figure 2.7: A serpentine laminating micromixer composed of a series of F-shaped channel units (from Kim et al. [22]).

As a single layer structure, the mixer proposed by Simonnet and Groisman [27] deserves our attention. Their design is composed of a complex but single layer of PDMS (polydimethylsiloxane) attached to a top planar wall (Figure 2.9). Visualization of a dye of very low diffusivity indeed demonstrated chaotic advection inside the channel, as shown in Figure 2.10. The proposed design is shown to provide excellent mixing when two samples are introduced in the upper and lower domains of the channel section, but it is implied that no stirring occurs when they are introduced in the left and right domains, the latter corresponding to the most common situations. To shorten the mixing length, Camesasca et al. [28] proposed fractal patterning of grooves on the bottom of the channel (Figure 2.11).

The Weierstrass function was used in the design of the pattern with the fractal dimension D as one of the key parameters. It was found that, depending on D, the mixing can be enhanced compared with the original staggered herringbone mixer of Stroock et al. [20]. However, it is still questionable if the upper region of the channel may also show chaotic mixing because the flow in the region near the top wall is less disturbed by the bottom grooves. Various modifications of the grooved channel design have been tested. Yang et al. [29] designed side grooves in addition to the bottom grooves of Stroock et al. [20] so that secondary flows can be promoted (Figure 2.12). It was found that the existence of side grooves brings a 10–50% increased mixing performance.

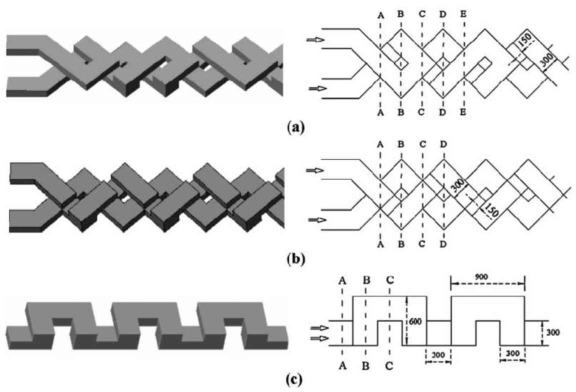

Figure 2.8: Three kinds of two-layer microchannels (from Xia et al. [23]).

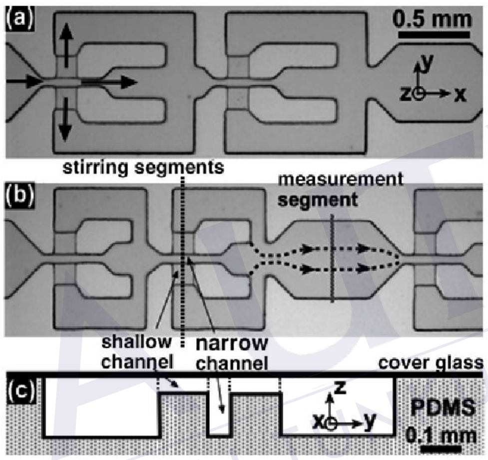

Figure 2.9: (a, b) Sketch of the two kinds of channel mixer with a single-layer structure and (c) the cross-sectional view of the plane cut by a dotted line in (b) (from Simonnet and Groisman [27]).

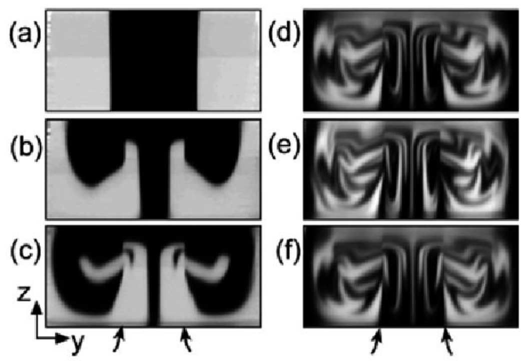

Figure 2.10: Development of the striation pattern inside the channel (from a to f) showing chaotic advection (from Simonnet and Groisman [27]).

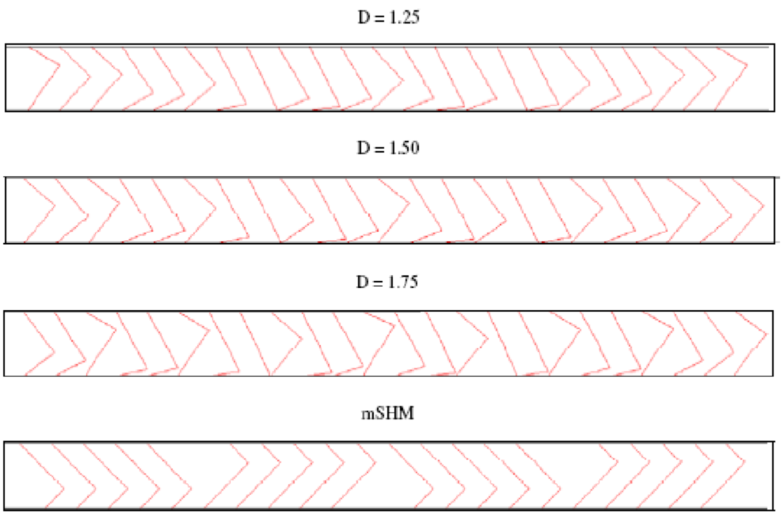

Figure 2.11: Top view of the channel designs with different fractal patterning of bottom grooves and SHM (modified staggered herringbone mixer) (from Camesasca et al. [28]).

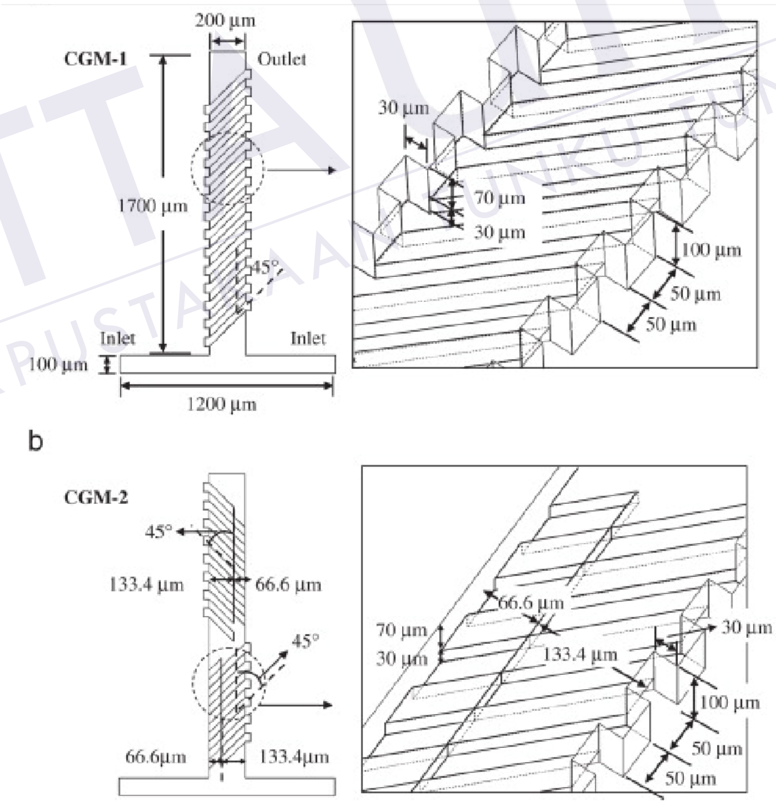

Figure 2.12 Schematic of the two channel designs of CGM (connected-groove micromixer) with not only bottom but also side grooves: (a) CGM-1 design; (b) CGM-2 design (from Yang et al. [29]).

The design concept of SAR comes directly from the stretching-folding mechanism of chaotic advection. Hardt et al. [30] reported experimental and numerical results on the mixing performance with the SAR design mimicking the original concept of the stretching-folding scenario in the chaotic advection (Figure 2.13). Compared with the design with grooves on the bottom wall, this design guarantees almost uniform mixing characteristics over the whole cross section of the channel. A problem, of course, lies in the difficulty of fabrication. Lee et al. [31] proposed to use steps and partition blocks on the bottom wall of the channel (Figure 2.14) to establish the split-and-recombination function without fundamental difficulty in the fabrication process. Suh et al. [32] also presented a new channel design composed of a series of cross baffles. Clear evidence of stretching-folding action was revealed from both numerical and experimental visualizations (Figure 2.15).

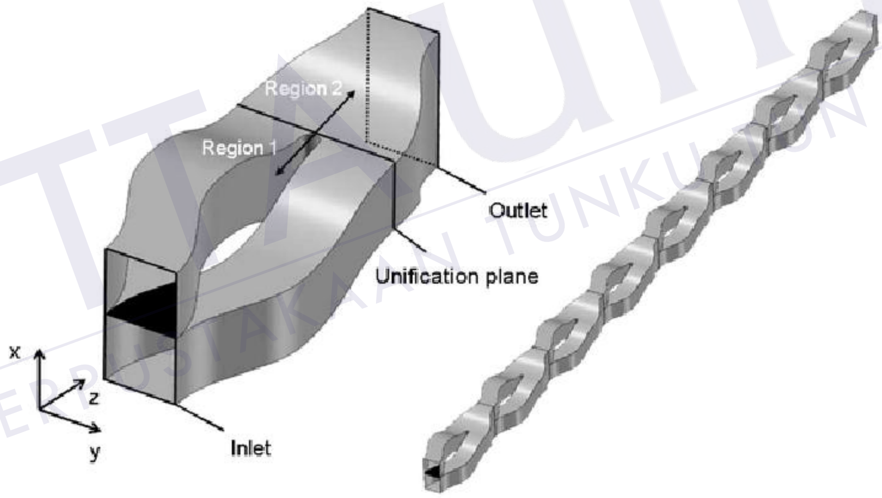

Figure 2.13: Enlarged view of the SAR unit (left) composing the 8-unit mixer (from Hardt et al. [30]).

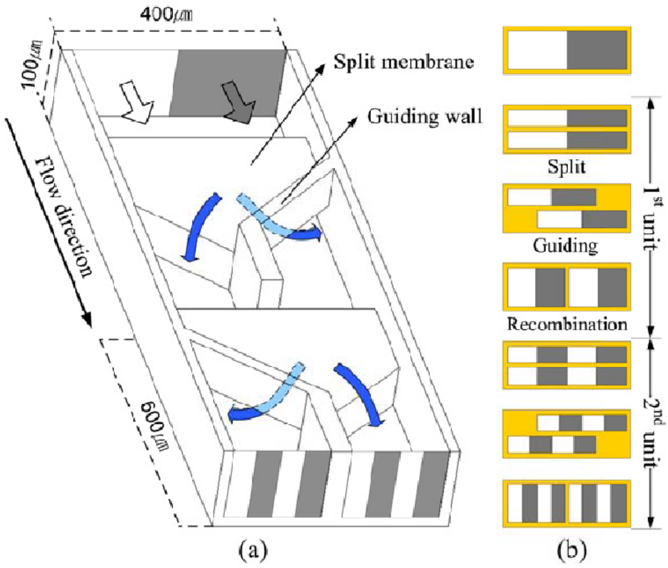

Figure 2.14: (a) Perspective view of SAR mixer with steps and partitioning blocks on the bottom wall and (b) schematic illustration of mixing principle (from Lee et al. [31]).

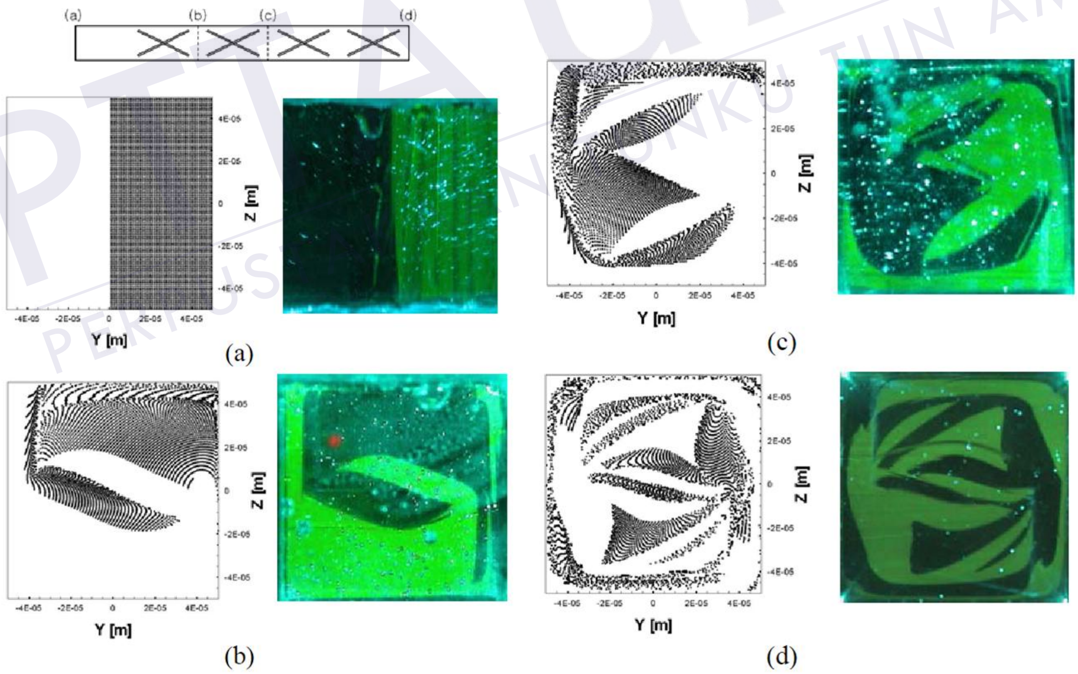

Figure 2.15: (a) comparison of the mixing patterns from numerical (left) and experimental (right) results for each section of the channel (denoted as (a), (b), (c) and (d) shown on the top) of a cross-baffle mixer (from Suh et al. [32]).

2.5. DROPLETS

The pressure-driven flow employed in most continuous-flow mixers, such as hydrodynamic focusing, alternate injection or the geometry-modification technique, inevitably suffers from a broad distribution in the residence time due to the parabolic velocity profile. The method of droplet or slug mixing has been developed to overcome this problem. Due to a strong surface-tension effect at the interface between the sample (occupying the droplet) and the carrier fluid (usually oil), the droplet always takes an isolated form such as a sphere or finite cylinder, and thus every fluid particle within the droplet must experience almost the same residence time. Another advantage in the droplet mixing is that the internal flow required for the mixing can be relatively easily created by a meandering channel.

Liau et al. [33] designed a meandering channel whose curved part has bumps on the outer side (Figure 2.16). This design makes the droplet's internal flow more asymmetric than the case without bumps, because the oil film effectively becomes thinner on the bump side than the other smooth side resulting in higher shear stress acting on the fluid on the bump side. Muradoglu and Stone [34] performed two-dimensional numerical simulations for the mixing inside a droplet flowing in a wavy channel. It was shown that the best mixing can be obtained when the drop size is comparable to the channel width. The effect of the capillary number is significant; the smaller the capillary number the better the mixing effect. The ratio of the viscosity of the drop to that of the ambient fluid must be as small as possible for better mixing. The effect of the channel geometry on the droplet mixing has been further studied by Tung et al. [35] for a serpentine microchannel with oil as the carrier fluid, and by Dogan et al. [36] for a meandering channel with a gas as the carrier fluid. In the latter study, when the contact angle is less than 90 degrees the gas rather than the liquid takes a blunt-cylinder form. What these two studies and the other studies on this issue have in common is that they imply that there exists an optimum configuration of the channel for the fastest mixing rate in each design.

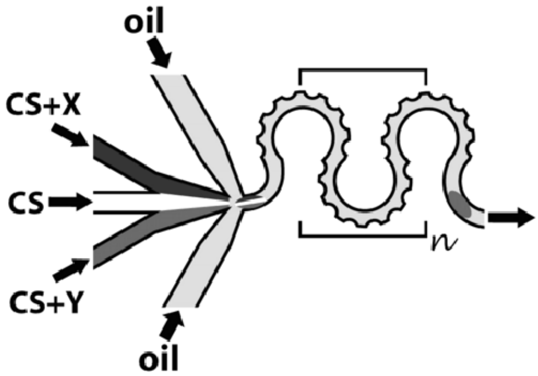

Figure 2.16: A meandering channel with bumps on the outer side for use in mixing three kinds of liquids (from Liau et al. [33]).

When estimating the mixing performance in terms of the distribution of species concentration, care must be given to the initial condition concentration distribution. Tanthapanichakoon et al. [37] numerically revealed that the initial concentrations is the most dominant parameter affecting the mixing rate, which was also addressed in the work of Wang et al. [38]. This means that the given flow field inside the droplet keeps a symmetric property. In order to investigate such a problem, Sarazin et al. [39] considered two kinds of methods in coalescing two droplets of different species subjected to mixing, i.e., coalescing in a longitudinal arrangement and in a side-by-side arrangement. As shown in Figure 2.17, coalescence of droplets in a longitudinal arrangement provides a much better mixing effect, which is in line with the studies of Tanthapanichakoon et al. [37] and Wang et al. [38]. As a carrier, fluid oil is most frequently used. On the other hand, Rhee and Burns [40] used the air as the carrier fluid (Figure 2.18). They managed to produce isolated droplets inside a microchannel and utilized the internal flow driven by the relative motion of the channel wall for better mixing. The droplets were reported to move through the channel without sticking to the side walls.

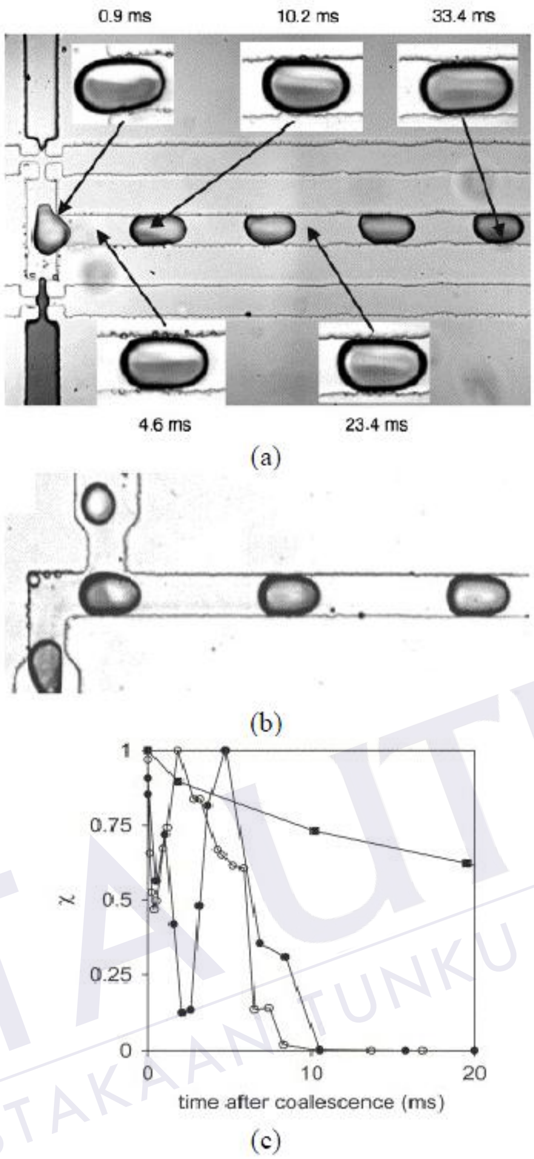

Figure 2.17: Coalescing of two droplets in a (a) side-by-side and (b) longitudinal arrangement. Mixing performance is plotted in (c): ■, mixing of dye and water in a side-by-side coalescence configuration; ●, mixing of dye and water in a longitudinal coalescence configuration; ○, bleaching reaction in a longitudinal coalescence configuration. Here a low level of χ means a better mixing effect (from Sarazin et al. [39]).

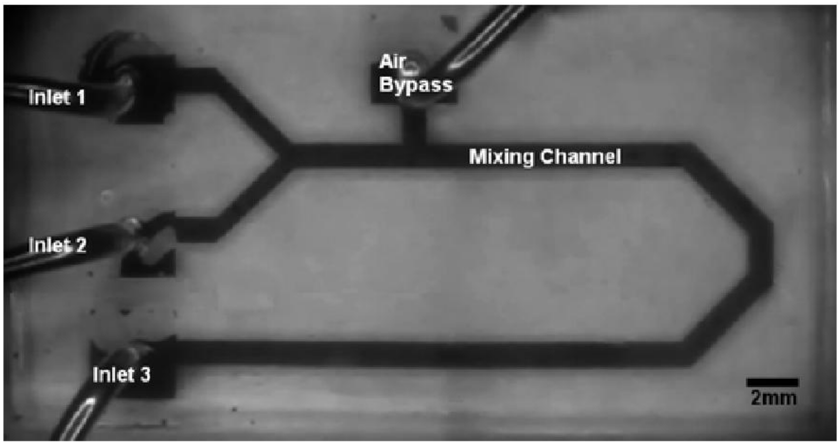

Figure 2.18: A microchannel mixer with an air-inlet port to produce isolated droplets for better mixing (from Rhee and Burns [40]).

The requirement for the application of droplet mixing is that the carrier fluid and the target samples should be immiscible. Usually the samples are aqueous and thus we can easily find a carrier fluid, such as oil. The reaction results can also be easily observed without image deterioration if the droplet interface fully touches the channel wall so that the interface remains planar; in this case, the droplet is called "slug". Momentarily, no serious disadvantage can be found in the method of droplet mixing.

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