COMPARISON OF RHOMBIC TYPE MICROMIXER TO IMPROVE MIXING EFFICIENCY IN BIOMEMS APPLICATION

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ABSTRACT

The term lab on chip and micro total analysis system stand synonymous for devices that require handling and processing of small amount of fluid to perform function such as sample preparation, separation, biosensing and detection. Constraint due to the long mixing channel and miniaturized in size but efficiently mixed between fluids. In this project, the three types of rhombic geometry design were studied to characterize mixing performance between the blood sample and reagents. Pure rhombic, branch rhombic and slanted groove rhombic glass based micromixer were proposed to study the mixing performance. The simulation was obtained using CoventorWare 2010. The laminar mixing between blood sample and reagent was simulated at low Reynolds number flow (Re <<1). Reagents used are toluene-low viscosity reagent and carbolic acid- higher viscosity reagent in comparison to blood. The mixing characterization will be optimized based on visualization result of the distribution field in term of viscosity. Image standard deviation (σ) is used to characterize fluid mixing; the lower σ, the better in fluids mixing properties. From this study, it was found that slanted groove rhombic gained the highest mixing efficiency followed by pure rhombic and branch rhombic. This is because grooves structure can improve surface contact area thus stretch and folds the laminar flows.

ABSTRAK

Istilah makmal pada cip dan sistem total analisis mikro berdiri sinonim dengan peranti yang memerlukan pengendalian dan pemrosesan sejumlah kecil cecair untuk melaksanakan fungsi seperti contohnya penyediaan sampel, pengasingan, biosensor dan pengesanan. Kekangan berlaku kerana saiz saluran yang agak panjang diperlukan dan terlalu kecil tetapi perlu menghasilkan percampuran yang efisien antara cecair. Dalam projek ini, tiga jenis reka bentuk geometri rombik dikaji untuk mencirikan prestasi percampuran di antara sampel darah dan reagen. Rombik tulen, rombik bercabang dan rombik alur condong yang berasaskan kaca adalah dicadangkan untuk mengkaji prestasi pencampuran. Simulasi telah diperolehi menggunakan CoventorWare 2010. Percampuran lamina diantara sampel darah dan reagent telah di simulasi pada aliran nombor Reynolds yang rendah (Re << 1). Reagen yang digunakan adalah toluene - mencirikan kelikatan rendah dan asid karbolik- mencirikan kelikatan lebih tinggi dibandingkan dengan kelikatan darah. Pencirian pencampuran antara cecair dapat ditentukan melalui keputusan visualisasi dari segi kelikatan. Imej standard deviasi (σ) digunakan untuk mencirikan prestasi pencampuran antara cecair ; lebih rendah σ menunjukkan pencampuran antara cecair yang lebih baik. Daripada kajian ini, didapati bahawa rombik alur condong memperolehi kecekapan percampuran antara cecair tertinggi diikuti dengan rombik tulen dan rombik bercabang. Ini adalah kerana struktur alur boleh meningkatkan kawasan bersentuhan antara permukaan dimana aliran lamina dapat diregangkan dan dilipat.

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C	-	Concentration coefficient of fluid species
D	-	Diffusion coefficient of fluid species
dS	-	Elemental Surface Area
L	-	Characteristic Length
μ	-	Dynamic Viscosity
$\vec{n}$	-	Unit vector normal to the surface
Q	-	Flow Rate
P	-	Pressure
Re	-	Reynolds Number
t	-	Time
V	-	Mean Fluids Velocity
v	-	Kinematic Viscosity
$\vec{V}$	-	Flow Velocity
W	-	Channel width
σ	-	Standard Deviation
∇	-	Vector differential operator

LIST OF ABBREVIATION

BEM	-	Boundary Element Method
CFD	-	Computational Fluid Dynamics
CDM	-	Circulation-disturbance Micromixer
DNA	-	Deoxyribonucleic Acid
FDM	-	Finite Difference Method
FEM	-	Finite Element Method
FVM	-	Finite Volume Method
IOP	-	Intraocular pressure
LOC	-	Lab-on-a-chip
MEMS	-	Micro-Electromechanical System
µTAS	-	Micro-Total-Analysis Systems
SAM	-	split, split and merge mixer
SHM	-	staggered herringbone mixer

CHAPTER I

INTRODUCTION

1.1 Background Study

BioMEMS are microscopic electro-mechanical systems (MEMS) applied to biomedical applications and life sciences. Classes of BioMEMS devices commonly found including, microsensing, microactuation, microassaying, micromoving and microdelivery. Miniaturization is important in biomedical technology since to aid the usage of sampling procedure from submicron to micron range especially for gene, protein and deoxyribonucleic acid (DNA) application. Derived from the microfabrication technology used to make integrated circuits, BioMEMS is expected to revolutionize the way medicine is practiced and delivered. BioMEMS is typically focused on mechanical parts and microfabrication technologies made suitable for biological applications.

1.1.1 BioMEMS Application

Applications for bioMEMS devices exist in clinical medicine, environmental, biological and chemical analysis. Applications from one area often overlap with other areas. Applications can be broadly placed into the categories of clinical diagnostics and therapeutics, environmental applications including Homeland Security, food safety, and bioprocessing. Clinical applications of bioMEMS include both diagnostic which utilizing MEMS sensors and transducers, and therapeutic applications such as drug delivery actuators.

1.1.2 Lab on chip (LOC)

Recently, microfluidics and lab on chip (LOC) have been emerging as one of the most promising platforms for better immunoassays due to its distinctive natures which to meet the development of new protocols with rapid turnaround time , high sensitivity and low cost for high throughput drug screening, point-of-care clinical diagnostics, or rapid food safety monitoring(Ahn et al., 2011). Thus it has currently being discussed and emerged as state of the art in the microfluidic world.

Micro total analysis system (μTAS) and its subset devices referred to lab on chip (LOC) is fabrication techniques for manufacturing of miniaturized device that perform all part of biochemical analysis. Micro total analysis systems with the advantages of saving reagents and shortening assay time have been widely developed these decades. The systems also enable sample handling, mixing, dilution, electrophoresis and chromatographic separation, staining and detection on single, micro integrated systems. Good mixing efficiency of micromixers is an important issue for enhancing the

performance of the μTAS and the development of planar micromixers with simple design and low pressure loss are required in μTAS is required compared to 3 dimension micromixer.

As well as μTAS , LOC intergrate multiple laboratories functions on a single chip which capable of handling small fluid volumes. It is also a potential tool allowing simultaneous detection of a large number of disease biomarkers in a single step. LOC has got tremendous advantages in terms of sensitivity, specificity, cost, time, detection limit, sample requirement and simplicity. LOC would be made from an array of few hundred microcantilevers with each one of them immobilized with probe specific for their complementary biomolecules,

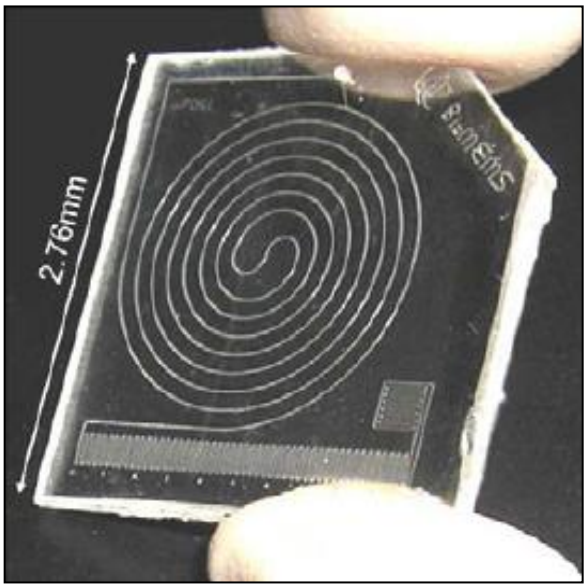

Figure 1.1: Microfluidic systems used for blood separation developed by University of Cincinnati.(Ahn et al., 2011)

Microfluidics is a promising technique to replace the conventional diagnostic systems for diabetes screening(Yao, Liu, Dong, & Tung, 2012) due to its advantages of

low reagent consumption, short analysis time, and multi-process integration. In microfluidic systems, sample pretreatment, reagent transportation, mixing, reaction, separation, detection and product collection can be effectively integrated and accomplished automatically on a single chip. With their portability characteristic, microfluidic systems can be used outside of the hospital, and provide a great opportunity for widespread diabetes screening in the rural environment.

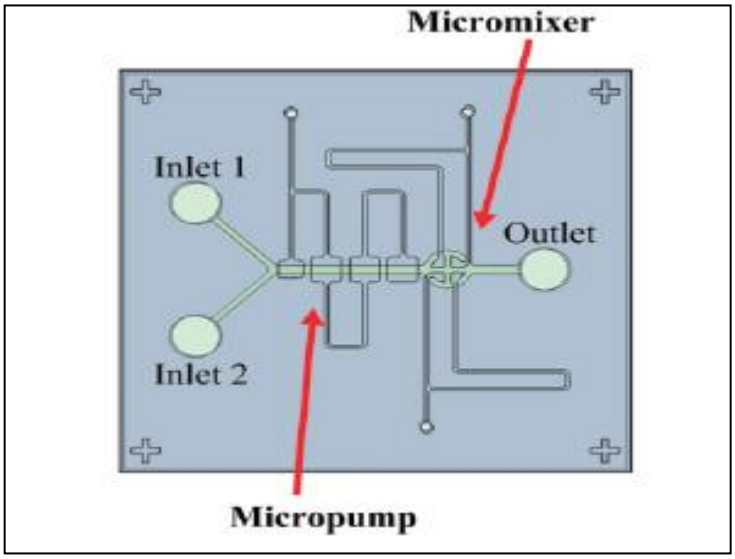

Figure 1.2: Schematic of the integrated microfluidic chip for diabetes screening. (Yao et al., 2012)

1.1.3 Diagnostic Microsystem

In diagnostic microsystems application, biosensors and detectors are the most upcoming technologies. Molecular Recognition Biosensors usually contain selective molecule surfaces onto which an appropriate conjugate molecule selectively binds producing a measurable change in a physical parameter. Biomolecular recognition micro

sensors can potentially provide a cost-effective approach to rapidly and cost-effectively diagnose the human condition. These devices usually contain selective molecule surfaces onto which an appropriate conjugate molecule selectively binds producing a measurable change in a physical parameter.

A miniature mass spectrometer has been designed as a diagnostic microsystem and fabricated for the detection of gas molecules of low molecular weight(Polla, 2001). The device is based on a compact double-focusing mechanism that deflects ions in a 90" cylindrical crossed electric and magnetic field sector analyzer with a radius of 2.0 cm.

The microfabricated impedance spectroscopy flow cytometer permits rapid dielectric characterization of a cell population with a simple microfluidic channel(Cheung & Renaud, 2005). As a non-invasive technique, dielectric spectroscopy is suitable for the characterization of living biological cells. Impedance measurements over a wide frequency range give information on cell size, membrane capacitance, and cytoplasm conductivity as a function of frequency. The amplitude, opacity, and phase information can be used to discriminate between different cell populations without the use of fluorescent, magnetic, or other cell markers.

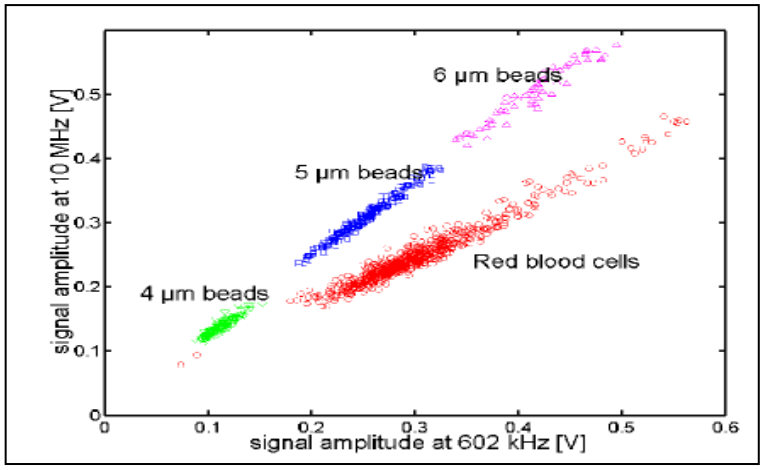

Figure 1.3: Measurement data showing the sub-micron size discrimination between 4, 5, 6 µm beads. (Cheung & Renaud, 2005)

1.1.4 Therapeutic BioMEMs

Therapeutic microsystems offer the potential of autonomous care management and precision delivery of medications. In the case of applanation tonometry which is the standard procedure for measuring intraocular pressure (IOP) does not monitor variations over time. However, increased IOP and wide daily IOP variations indicate risk of glaucoma, and detailed information would be invaluable toward the clinical management of glaucoma. Since changes in IOP are correlated to changes in cornea curvature, a MEMS strain gauge for the measurement of spherical deformation of the cornea due to intraocular pressure changes could provide continuous, minimally invasive monitoring over prolonged periods (Leornardi et al, 2004). This strain gauge is based on the same flexible polyimide technology with embedded Pt- Ti structures. This polyimide device is then embedded in a soft contact lens.

The development of more flexible probes is essential for improving their biocompatibility. Current intracortical recordings are also limited by the number of electrodes (wire bundles) that can be implanted into the cortex. The development of a reliable, microfabricated, multielectrode array for long-term use will provide neuroscientists with a tool of greater functionality. Current work is done by embedding a flexible multielectrode array in the brain to monitor changes in hippocampal theta rhythm by auditory stimulation as in Figure 1.4.

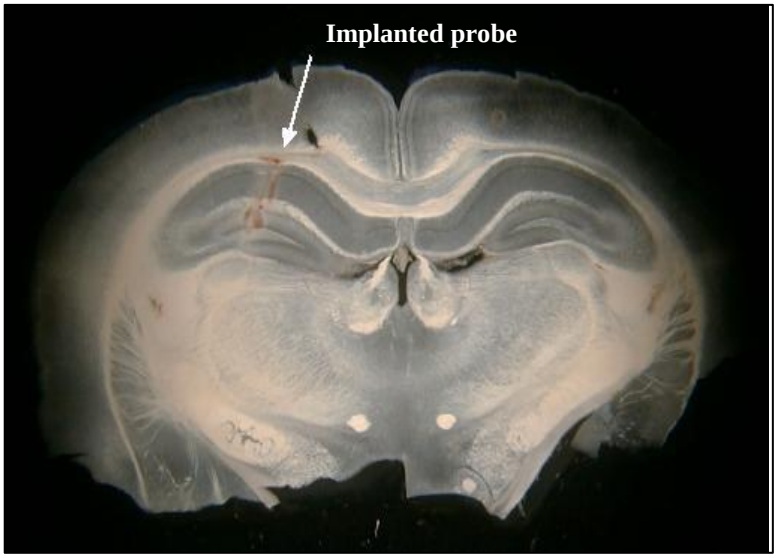

Figure 1.4: Implanted probe penetrates easily into brain tissue at the hippocampus. (Leornardi et al, 2004)

1.2 Objectives of the study

Objectives of the research are as follows;

i. To compare and simulate 3 types of rhombic micromixer for laminar fluid mixing of two types of fluids with various viscosity using CoventorWare2010 software.

ii. To characterize diffusion properties in the micromixer between low and high viscosity reagent compared to blood.

1.3 Scope/Limitation of the study

The scope areas for this study are limited to;

i. Design rhombic types micromixer using CoventorWare2010 software.
ii. Simulate 3 types of rhombic-type micromixer and characterize properties involved in micromixer.
iii. Study the mixing performance of blood-reagent using the rhombic-type micromixers.

1.4 Problem statement

Fluid mixing is an essential process in microfluidic devices. The efficiency of its performance depends on effective and rapid mixing of sample and reagent. Problem arises when minituarized mixer need a long channel to provide good mixing between blood and reagent. Fluid mixing only base on diffusion and need long microchannel to mixed completely.

The project is chosen based on the below criteria;

1. This project is significant to study the effect of different geometries to aid in mixing performance between two types of fluids in the microchannel.
2. The simulation is done to study the effect of planar and groove geometries to improve mixing efficiency.

CHAPTER II

BASIC AND FUNDAMENTALS

2.1 Introduction

This chapter will discuss basic and fundamental of fluid mechanics and micofluidic theory. Basic geometry design of micromixer will be discuss in the later section. Previous study were studied to summaries the effect of various geometry to improved micromixer performance and formation of channel that may induced chaotic flow.

2.2 Basic of fluid mechanics

To understand microscopic fluid properties, fluid mechanics properties must be well understood such as flow pattern, viscosity and Reynolds number as discussed in subsection below.

2.2.1 Fluid Flow pattern

For laminar flow pattern, the flow is gentle and at low speeds liquid flow is smooth. The flow occurs in parallel layers, with minimal disruption between these layers. The flow is greatest at the centre and diminishes towards the periphery. Turbulence flow is characterized by recirculation and randomness. The flow occurs at higher flow rates, not streamlined and has a lot of swirling of the fluid. The fluid pattern discussed is as Figure 2.1.

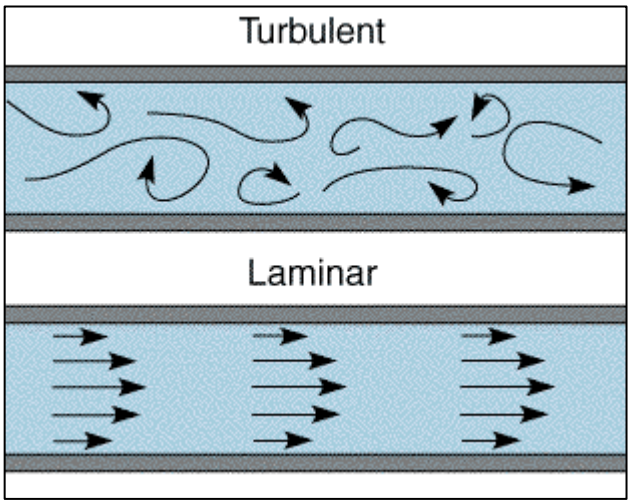

Figure 2.1: Laminar and turbulent flow pattern.

2.2.2 Reynolds number

In fluid mechanics, the Reynolds number gives a measure of the ratio of inertial forces to viscous forces and quantifies the relative importance of these two types of forces for given flow conditions. Therefore Reynolds number can be formulated as below

$$\mathrm{Re} = \frac{\rho L V}{\mu} \tag{2.1}$$

Where is ρ is fluid density, V mean fluid velocity and μ is kinematic viscosity. The characteristics of dimension L is the dimension that is principle factor that relates to the flow.

Reynolds number is affected by laminar and turbulent flow. It characterizes the tendency of a flowing liquid phase to develop turbulence. The lower the velocity and density with higher viscosity of the liquid gaining lower Reynolds number. In microfluidic system, Reynolds number affect flows in three different region of behavior which are Re<<1; viscous effect dominate inertial effect (completely laminar flow), Re≈1; viscous effect comparable inertial effect (vortices begin to appear) and Re>>1; inertial effect dominates viscous effect (turbulence flow). If the Reynolds number is very small (Re ~ 1), this is an indication that the viscous forces are and it may be possible to neglect the inertial effects.

In almost MEMS and nanodevice applications, fluid flows are always in laminar flow region. In all typical microfluidic channel, Reynolds number is very low therefore fluid streams relies mainly on diffusion. Rapid diffusion is constraint by large microchannel length yet too small to include mechanical agitation.

2.2.3 Viscosity

Viscosity is a measure of the resistance of a fluid which is being deformed by either shear stress or tensile stress. Viscosity is fluid thickness or fluid internal friction. For example, water has a lower viscosity while blood has a higher viscosity. Viscosity effect on fluid movement. Thus the less viscous the fluid is, the greater its ease of

movement. Viscosity also describes a fluid's internal resistance to flow and may be thought of as a measure of fluid friction. It also has significant effects on the fluid motion and therefore Reynolds number which can be used to evaluate level of fluid's viscous.

Consider the motion of a fluid between two parallel plates shown in Figure 2.2. The bottom plate is stationary, and the top plate moves with constant velocity μ. The fluid in contact with each surface has the same velocity as that surface. The flow speeds of intermediate layers of fluid increase uniformly from one surface to the other, as shown by the arrows, so the fluid layers slide smoothly over one another; the flow is laminar. A portion of the fluid that has the rectangular shape at some instant has thebecomes more and more distorted as the motion continues. That is, the fluid is in a state of continuously increasing shear strain. In a fluid the shear strain increases continuously and without limit as long as the stress is applied. The stress depends not on the shear strain, but on its rate of change.

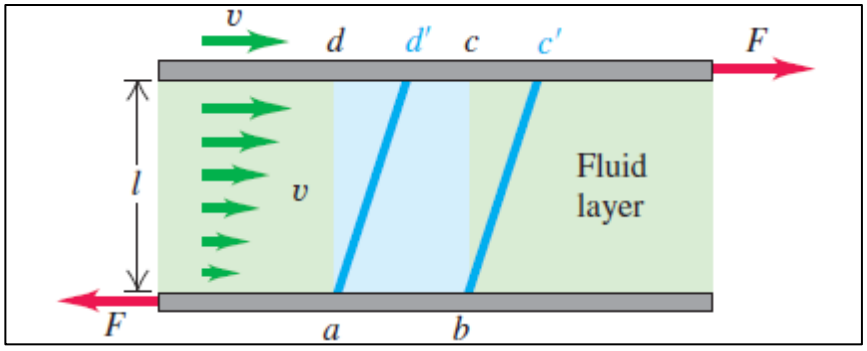

Figure 2.2 Laminar flow of a viscous fluid.

2.2.4 Governing equations

In fluid dynamics, the continuity equation states that, in any steady state process, the rate at which mass enters a system is equal to the rate at which mass leaves the system. The differential form of the continuity equation is

$$\frac{\partial p}{\partial t} + \nabla.(\rho u) = 0 \tag{2.2}$$

The vector differential operator del is defined as

$$\nabla = i_x \frac{\partial}{\partial x} + i_y \frac{\partial}{\partial y} + i_z \frac{\partial}{\partial z} \tag{2.3}$$

Where ρ is fluid density, t is time,u is the flow velocity vector field.

The Navier-Stokes equations form a vector continuity equation describing the conservation of linear momentum. If ρ is a constant, as in the case of incompressible flow, the mass continuity equation simplifies to a volume continuity equation:

$$\nabla \bullet V = 0 \tag{2.4}$$

Which means that the divergence of velocity field is zero everywhere.

The volume flow rate which is defined as the volume of fluid flowing per unit time can be determined by the following equation;

$$Q = \iint \vec{V}.\vec{n}\, dS \tag{2.5}$$

Where $\vec{V}$ is the velocity vector, $\vec{n}$ is unit vector normal to the surface and dS is the elemental surface area.

The finite volume method and the structured grid were employed to solve the governing equations, consisting of continuity equation, momentum (Navier-Stokes) equation and convection-diffusion equation.

$$\rho\left[\frac{\partial V}{\partial t}+V\bullet\nabla V\right]=-\nabla p+\eta\nabla^2 V \tag{2.6}$$

Where p and η are the density and the viscosity of the fluid, respectively. V and P are velocity vectors and the pressure, respectively.

$$\frac{\partial C}{\partial t}+V\bullet\nabla C=D\nabla^2 C \tag{2.7}$$

Where C and D are the concentration and diffusion coefficient of fluid species, respectively (Guo, Zhang, Cheng, & Song, 2009).

2.3 Classification of micromixer

Miniaturization is the recent trend in analytical chemistry and life sciences. Microfluidic applications which cover micro arrays, DNA sequencing, sample preparation and analysis, cell separation and detection, as well as environmental monitoring attracts interest from both industry and academics field. This is because of its potentials and advantages which use small amounts of sample and reagent causing less time consumption, lower cost and higher throughput. Rapid mixing is essential in many

of the microfluidic systems used in biochemistry analysis, drug delivery and sequencing or synthesis of nucleic acids. Micromixers can be integrated in a microfluidic system or work as stand-alone devices.

In general, micromixers can be categorized as passive micromixers and active micromixers as in Figure 2.3 (Nguyen & Wu, 2005). Passive micromixers do not require external energy; the mixing process relies entirely on diffusion or chaotic advection. Passive mixers can be further categorized by the arrangement of the mixed phases that is parallel lamination, serial lamination, injection, chaotic advection and droplet. Active micromixers use the disturbance generated by an external field for the mixing process. Thus, active mixers can be categorized by the types of external disturbance effects such as pressure, temperature, electrohydrodynamics, dielectrophoretics, electrokinetics, magnetohydrodynamics and acoustics. With external fields and the corresponding integrated components, the structures of active micromixers are often complicated and require complex fabrication processes. Furthermore, external power sources are needed for the operation of active micromixers. Thus, the integration of active mixers in a microfluidic system is both challenging and expensive. In contrast, passive micromixers do not require external actuators except those for fluid delivery. The often simple passive structures are robust, stable in operation and easily integrated in a more complex system. Active micromixer will not be discussed furthermore in this section since this study focused on passive micromixer.

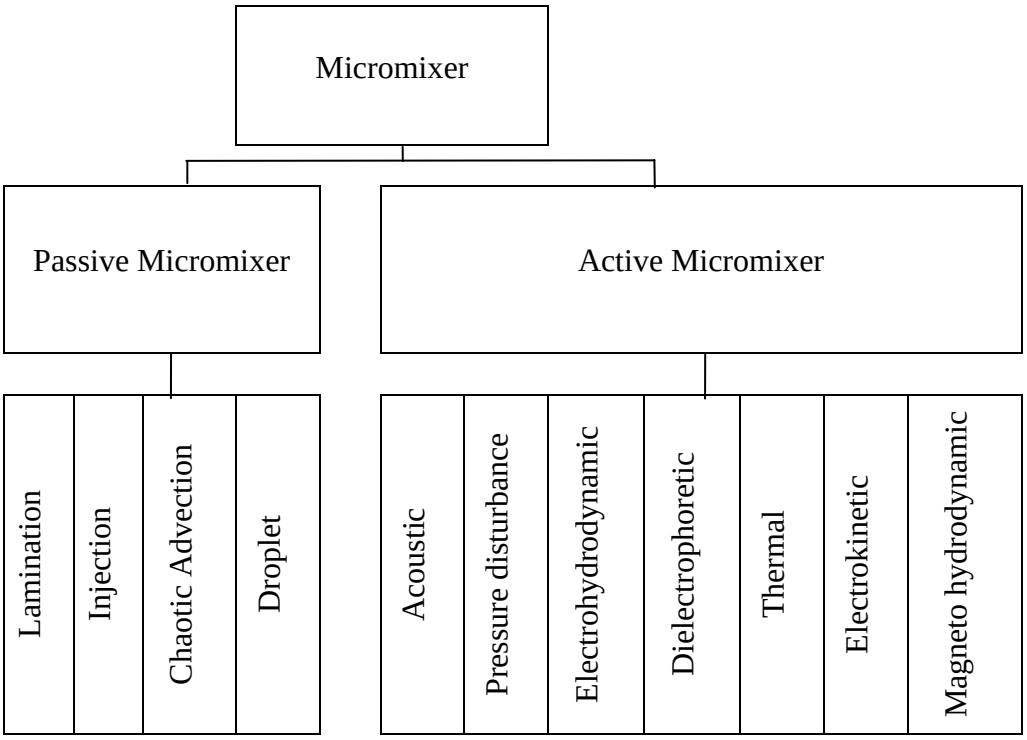

Figure 2.3 Classifications of micromixer

In parallel lamination, fast mixing can be achieved by decreasing the mixing path and increasing the contact surface between the two phases. Parallel lamination splits the inlet streams into multi substreams, and then join them into one stream as laminae which often called T mixer or Y mixer as in Figure 2.4 . Mixing of fluid are entirely depends on molecular diffusion, therefore a long mixing channel is needed. Short channel does not help for this type of micromixer unless for high Reynolds number. However for serial lamination micromixers as in Figure 2.5, enhance mixing can be done through splitting and later joining the streams. The inlet streams are first joined horizontally and then in the next stage vertically.

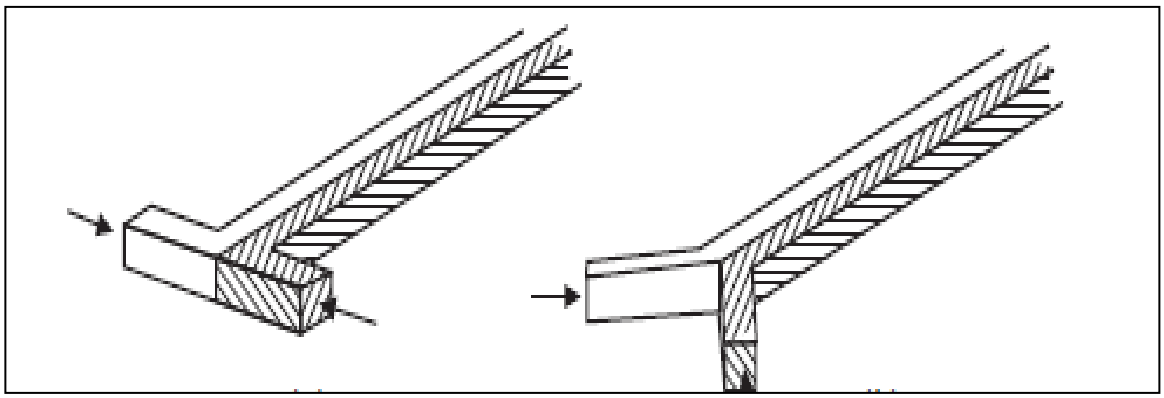

Figure 2.4: Parallel lamination technique for improve fluid mixing.

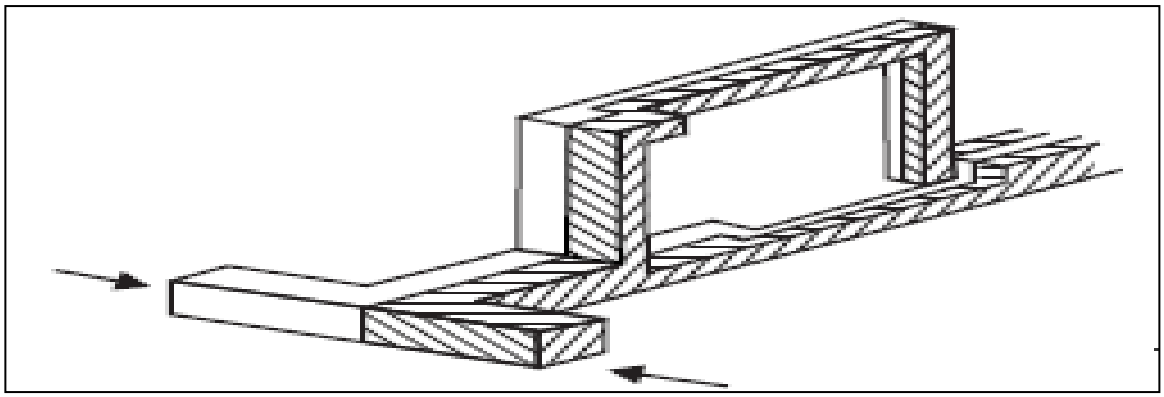

Figure 2.5: Serial lamination technique for passive micromixer.

The concept of the injection mixer is similar to the parallel lamination mixer which splits the solute flow into many streams and injects them into the solvent flow. On top of one stream is an array of nozzles, which create a number of microplumes of the solute. These plumes increase the contact surface and decrease the mixing path. Mixing efficiency can be improved significantly.

Besides diffusion, advection is another important form of mass transfer in flows with a low Reynolds number. However, advection is often parallel to the main flow direction, and is not useful for the transversal mixing process. Generally, chaotic

advection can be generated by special geometries in the mixing channel or induced by an external force. The basic idea is the modification of the channel shape for splitting, stretching, folding and breaking of the flow. Ribs or grooves on the channel wall can produce chaotic advection. The chaotic advection mixing can improved mixing significantly (Sabotin, Tristo, Junkar, & Valentinčič, 2013). Figure 2.6 illustrate geometry modification that caused chaotic advection to the mixing fluid.

The study on chaotic advection by micromixers rely on placing micro structured objects within the flow passage on one side of the micro channels was pioneered by Stroock et al 2002. By this means, flow circulations are generated which lead to an exponential increase of specific interface, hence to fast mixing. Typical for such chaotic flows are circulating fluids with large interfaces besides quiescent zones with less improved mixing. One of the pioneering descriptions presents a staggered herringbone mixer (SHM). The SHM mixing is superior to similar microchannels without internal structures or with straight ridges only. Whereas the basic T-mixer requires mixing lengths of about 1m and 10m, the SHM mixer performs the same task within 1 and 1.5 cm only, respectively.

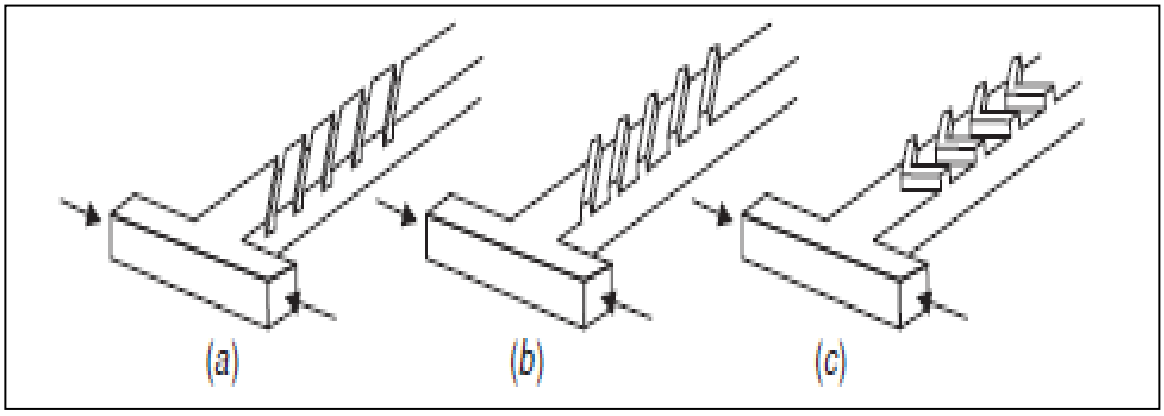

Figure 2.6: Modification of mixing channel for chaotic advection at low Reynolds numbers: (a) slanted ribs, (b) slanted grooves (c) staggered-herringbone grooves.

The last passive mixer discussed here is droplet type. It is the other solution for reducing the mixing path by forming droplets in the mixing liquid. The movement of a droplet causes an internal flow field and makes mixing inside the droplet possible. In general, droplets can be generated and transported individually using pressure or capillary effects such as thermocapillary and electrowetting.

2.4 Selection and design of micromixer

Microfluidic systems are now widely used in biology and biotechnology. These applications include chemical reactions, analysis of DNA and proteins, sorting of cells, high-throughput screening . Typical uses of microfluidic require that these systems be inexpensive and simple to operate. In typical microfluidic systems, pressure flow is laminar and uniaxial because of low Reynolds numbers. In order to decrease the length and time for mixing, micro-mixer is an indispensable element of microfluidic system to make high efficiency chemical reaction . The diffusion time is proportional to the square of the mixing path; the velocity is inversely proportional to the channel width. Thus, one way to achieve faster mixing utilizes a smaller mixing path and larger contact surface. The mixing rate is determined by the flux of diffusion.

Passive micromixers have the advantages of simple fabrication and operation, and are generally divided into two types. One is the 3D microchannels for chaotic-enhanced mixing and the other is the planar micromixers with curved microchannels or obstacles for vortices-enhanced mixing. The fluid mixing in the curved microchannel is attributed to Dean vortices enhanced convective mixing and is related to the geometry parameters and Reynolds number. For micromixer with obstacles in the microchannel, even if Reynolds number for good mixing can be reduced down to $Re < 1$, a very long microchannel is also required. It is very important to obtain effective mixing in a shorter channel length or less mixing units of planar micromixers.

Typical channel depths are between 5 to 300 μm, channel widths between 10 to 1000 μm. The optimal size domain for microfluidic channel cross sections is somewhere between 10 μm and 100 μm. At smaller dimensions detection is too difficult and at greater dimensions with unaided mixing is too slow.

2.4.1 T and Y type micromixer

Z shape micromixer is a common type passive mixer. Studies done by Hamid et al (2012) compare three different geometry design which are z shape, y shape and rhombic type micromixer. From this comparison as shown in figure below, it is clearly shows that Zshaped micromixer is the best type of micromixer to produce the fastest mixing. When the two fluids in the channel was stretched and folded, the interfacial area within the fluids in the mixing channel is increased. Thus, the two fluids will be easier to mix and will results in reducing of time and the length of the micromixer requiredfor the channel to complete the mixing process.

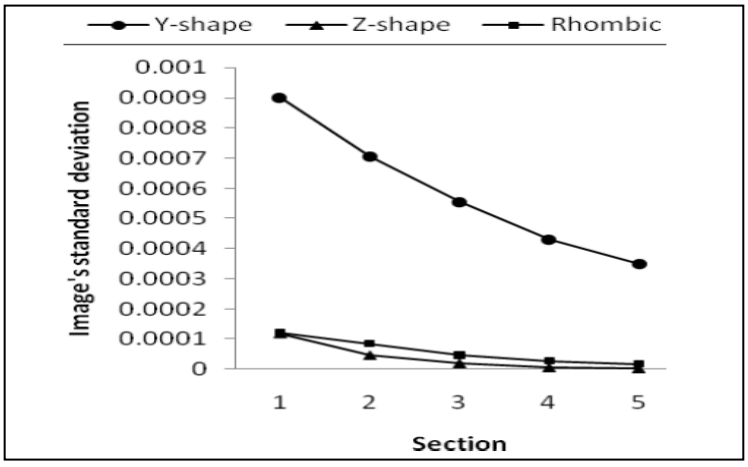

Figure 2.7: Graph of image's standard deviation for laminar mixing of blood and toluene for three types of micromixer.

T-type passive micromixeras is shown in Figure 2.8. Increase in mixing length consequently affects the mixing concentration. Figure 2.9 shows that due to high surface contacts between mixing fluid streams and width of interdiffusion zone is high, more chances to fluid molecules for diffuse across each other and improve the mixing of fluids.

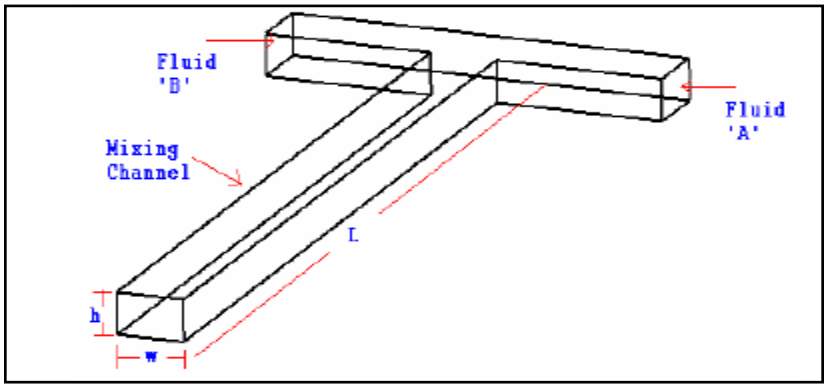

Figure 2.8: Schematic Diagram of T type micro mixer

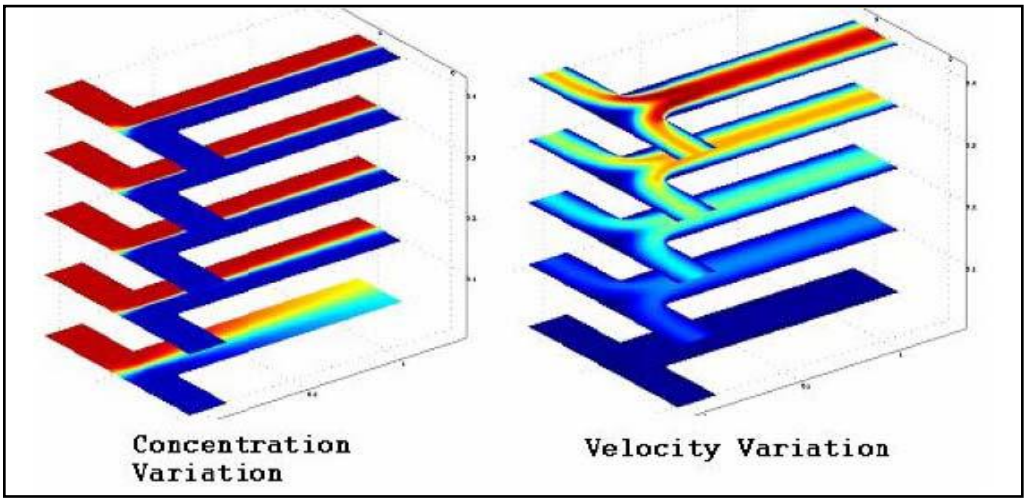

Figure 2.9: Mixing Concentration Variation

Another study by Siddarth et al (Bhopte, Sammakia, & Murray, 2010) suggested that T type mixer with variation geometry alignment improved mixing efficiency. As planar T type mixer may need a long channel to mix completely, the studied two ways split, split and merge (SAM), opposing SAM stream and SAM groove flow design. It is found that SAM groove improved mixing efficiently compared to the others.

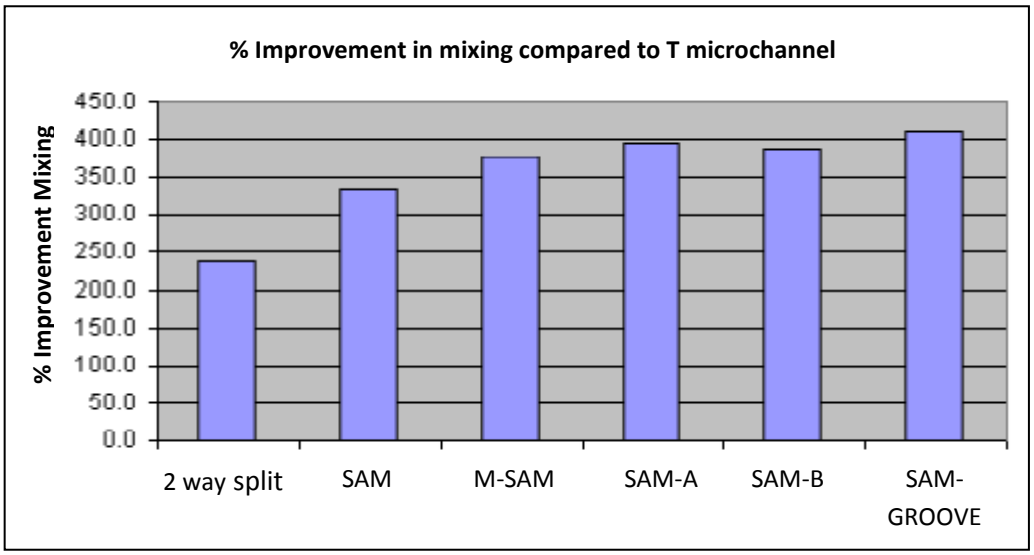

Figure 2.10: Percentage improvements in mixing over T microchannel by the use of split and merge micro-mixing technique.

2.4.2 Rhombic micromixer

Numerical simulation and mixing experiment demonstrated the design of rhombic micromixer with simple structure design. Fluid mixing of the rhombic micromixer is closely related to the rhombic geometries and Reynolds number (Hamid, Kamaruzzaman, & Jamil, 2011). The mixing is better if the reagent is smaller in viscosity compared to blood. The recirculation phenomenon in rhombic micromixer

enhances the fluid mixing. The better fluid mixing is obtained at the higher rhombus number.

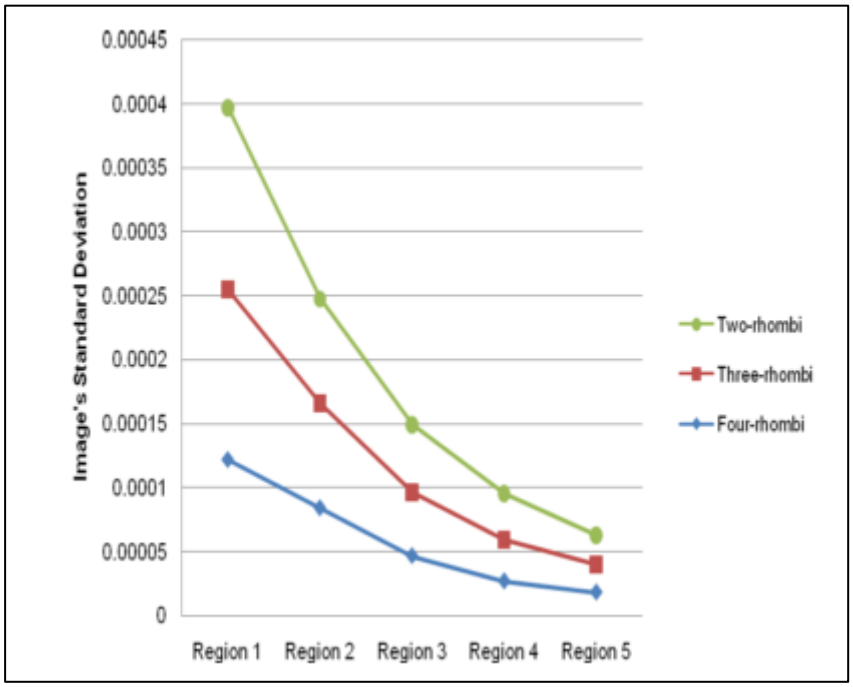

Figure 2.11: Graph of image's standard deviation for laminar mixing of blood and Toluene for micromixer which consists of two, three and four rhombi. (Hamid et al., 2011)

As for Chung et al (2009) who studied the truncated angle micromixer type is compared to cross shape micromixer, shown in Figure 2.11. They conclude that mixing by molecular diffusion is very poor in this cross-shape channel at higher Reynolds number. As Reynolds number increases to 100, interface are much distorted by the stronger centrifugal forces. The centrifugal forces push inside fluid toward outside as well as interface stretching. As the fluid flow passes the next turning, the centrifugal forces exert in the opposite direction. After one cycle of left and right turns, fluid mixing can be enhanced. Repeated interface distortion can be also observed in the third and

fourth rhombus for continuous mixing enhancement. The mixing efficiency is higher for rhombic micromixer compared to cross shape micromixer as shown in Figure 2.12.

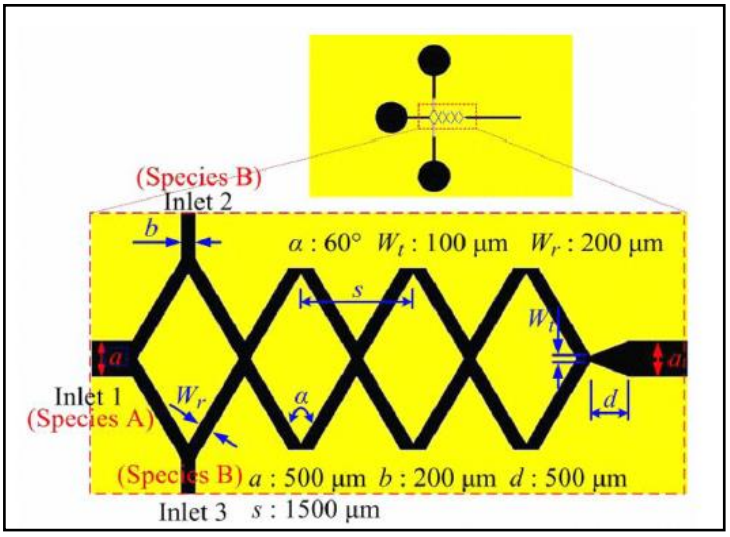

Figure 2.12: A schematic diagram of the rhombic micromixer with truncated angle.

Advanced rhombic micromixer with branch microchannels was studied to measure good mixing with low pressure drop(Chang, Shih, & Chung, 2011). The 3D numerical simulation was used for design of micromixer to evaluate the effect of geometric parameters on fluid mixing for three micromixers of the rhombic with branch-channels, pure rhombic one and crossshape microchannel. The results shown in Figure 2.13 proved that in vortices-enhanced mixing mechanism at *Re* 10~120, the mixing efficiency increases with Reynolds number. The advanced rhombic mixer with branch-channels has the highest efficiency among three mixers at the same *Re*. Over 90% mixing is achieved at *Re*>80 and about 98% mixing at *Re* 120.

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