COMPARATIVE STUDY OF MICROMIXERS FOR LAMINAR BLOOD MIXING

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ABSTRACT

Miniaturization is the trend in analytical chemistry and life science. It has been emerging into the research field of microfluidics in the application of LOC. The application is used for biochemistry analysis and require a rapid mixing in small area. Due to laminar flow (Reynold Number < 1) passive micromixer is the best method in fluids mixing. Passive micromixer also depend on the channel geometry for mixing effectiveness. In this study, four different micromixers were evaluated based on the baseline control Y-micromixer. The micromixers are internal rib micromixer, patterned grooves micromixer, obstruction micromixer and slanted rib micromixer. These micromixer has 1000µm channel length, 150µm inlet length, 90^{o} between inlets ports, width and depth are 40µm each. The fluids used for mixing were blood which has 1.0×10^{-6} kg/µms of viscosity and toluene which has low viscosity than blood (0.664×10^{-9} 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 slanted rib micromixer is the best micromixer design with the highest mixing efficiency of 99.85% at the outlet of the channel.

ABSTRAK

Pengecilan adalah kaedah masa kini dalam kimia analisis dan sains hayat. Ianya telah wujud dalam bidang penyelidikan *microfluidics* dalam penggunaan Lab-on-a-Chip (LOC). LOC ini digunakan untuk analisis biokimia dan memerlukan kaedah pencampuran yang cepat dan dalam jarak yang pendek. Kaedah pencampuran secara pasif adalah kaedah terbaik bagi aliran lamina (Nombor Reynold <1). Kaedah pencampuran secara pasif juga bergantung kepada geometri saluran bagi keberkesanan pencampuran antara dua cecair. Dalam kajian ini, terdapat empat kaedah pencampuran yang berbeza yang akan dinilai berdasarkan kaedah pencampuran kawalan Y. Kaedah-kaedah tersebut adalah kaedah dalaman rusuk, kaedah corak alur, kaedah halangan, dan kaedah rusuk condong. Kesemua kaedah ini mempunyai panjang saluran 1000µm, panjang masuk 150µm, 90^o antara masukan cecair, dan lebar dan kedalaman adalah 40µm setiap satu. Cecair yang digunakan adalah dengan pencampuran darah yang mempunyai kelikatan $1.0 \times 10E^{-6}$ kg / µms dan toluene yang mempunyai kelikatan $0,664 \times 10E^{-9}$ 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, kaedah pencampuran secara rusuk condong adalah reka bentuk kaedah pencampuran yang terbaik dengan kecekapan pencampuran tertinggi 99.85% pada keluaran salurannya

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Symbols / Abbreviation	
μ-TAS	Micro-total-analysis-systems
MEMS	Micro-Electro-Mechanical-Systems
LOC	Lab-on-a-Chip
MST	Microsystem Technology
BioMEMs	Biological microelectromechanical systems
PCR	Polymerase Chain Reactor
DNA	Deoxyribonucleic acid
SGM	Staggered Groove Micromixer
CFD	Computational fluid dynamic
FEM	Finite element method
FVM	Finite volume method
FDM	Finite difference method
Re	Reynold Number
ρ	density
U	Velocity
L	Length
μ	Absolute viscosity (Ns/m^2 or Pa.s)
v	Kinematic viscosity (m^2/s)
D_{hyd}	hydraulic diameter
A	Cross sectional area
Q	Flow rate (m^3/s)

γ	Specific weight
g	Gravitational constant = 9.8m/s^2
h	Height
σ	Standard deviation
MI	Mixing index
η	efficiency

CHAPTER 1

INTRODUCTION

1.1 Background

Micromixer is the one of the most important component in Micro-total-analysis-system (μ-TAS). The concept of μ-TAS is to integrate some instruments needed in traditional biochemical analysis. These instruments such as micro-pump, micro-actuator, micro-valve, micro-sensor and micro-mixer were fabricated using Micro-Electro-Mechanical-Systems (MEMS) techniques where the pretreatment transmission, mixing, reaction, separation and detection of the sample that can be proceeded on a single chip known as Lab-on-a-chip (LOC).

1.1.1 MEMs

MEMs is called by the American while European called MST (Microsystem Technology). Either it is MEMs or MST, according to Nadim Maluf & Kirt Williams (Nadim,2004), MEMS is simultaneously a toolbox, a physical product, and a methodology; a portfolio of techniques and processes to design and create miniature systems. They are miniature embedded systems involving one or many micromachined components or structures. M. E. Zaghloul said that they are miniaturized systems that combine sensors and actuators with high-performance embedded processors on a single integrated chip (Zaghloul,2006).

MEMs have varieties of devices which are passive devices that are non-moving structures, devices that involve sensors and devices that involve actuators. Another class includes systems that integrate both sensors and actuators (Zaghloul,2006). Sensors are transducers that convert mechanical, thermal, or other forms of energy into electrical energy; actuators do the exact opposite. Passive devices are a device where no transducing occurs, including both mechanical and optical components.

1.1.2 BioMEMs

BioMEMs is the abbreviation of *biological microelectromechanical systems* and it is simply a biomedical application for the MEMs devices. BioMEMs devices are the platform upon which *nanomedicine* will be delivered for the improvement of the human condition. It is also the typical science for *genomics*, the study of sets of genes, gene products, and their interactions; and *proteomics*, the study of proteins, the expression of genes in health and disease.

BioMEMs represent the expansion of new host that covered 1) microfabrication of silicon, glass and polymer devices, 2) microfluidics and electrokinetics, 3) sensors, actuators and drug-delivery systems, 4) micro-total-analysis system (μ-TAS) and lab-on-a-chip devices (LOC) 5) clinical laboratory medicine, 6) detection and measuring systems, 7) Genomics, proteomics, DNA and protein microarrays, 8) emerging applications in medicine, research and homeland security, 9) packaging, power systems, data communication and RF safety and 10) biocompatibility, FDA and ISO 109993 biological evaluations (Saliterman, 2006). BioMEMs devices can typically be considered as having at least one feature's dimension in the submicron range (~100nm - 200µm). Among the advantanges of biochip miniaturization are lower manufacturing cost, reproducility, small sample size and reagent use.

1.1.3 Lab on a Chip

LOC is the one of BioMEMs application of non-moving structure on microfluidic (Zaghloul, 2006). LOC device can be described as to put one laboratory into one single chip as shown in **Figure 1.1.**

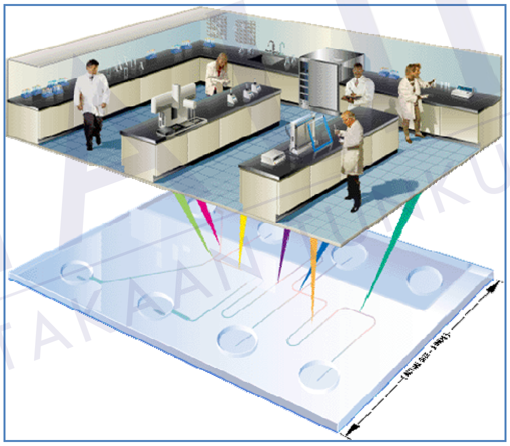


Figure 1.1 One laboratory in a single chip (Newman, 2012)

LOC devices have been designed for the past decades for many applications and one of them is for mixing fluids. But, in designing the LOC devices, there must be in microscale level and to realize it, only passive micromixer can be easily integrated into LOC devices. LOC technology has several advantages compared with conventional techniques, such as minimal sample requirement, rapid analysis times, ease-of-use, minimized exposure to hazardous materials and reduced waste generation (Agilent, 2001). According to (Dario,2009), the greatly reduced amount of sample needed will bring to lower cost as well as lower overall power consumption. Its shorter distances and higher surface-to-volume ratio in the droplets will make the analysis and response time faster. An example of LOC can be seen on **Figure 1.2**.

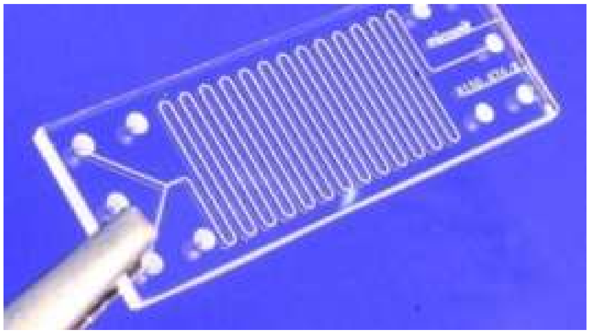


Figure 1.2 A glass lab-on-a-chip (Dario, 2009)

1.1.4 Microfludic

Fluid flow is generally categorized into two flow regimes which are laminar and turbulent, but in macroscale level, mixing is achieved by a turbulent flow, which makes the fluid segregation in small domains leading to effective mixing. The mixing in microfludic devices is generally achieved by taking advantages of the relevant small length, which dramatically increases the effect of diffusion and advection. The key to an effective mixing lies in producing stretching and folding, so that interface between fluids can be increased massively. This has to depend on the design of the microchannel geometries.

There were two types of micromixers which are passive and active micromixer. Passive micromixer takes an advantage of simple fabrication and a better pressure drop instead of active micromixer where the external energy input needed to make the fluid mixing. These external energy can be pressure field, dielectrophoretic, electrowetting (Capretto, 2011), ultrasonic, magneto hydrodynamic and electrokinetic micromixer (Vargas, 2006). Passive micromixer have the advantages in easier operation and one of the reported with fast mixing was by (Hamid, 2012) and (Lei, 2009). One of the passive micromixer reported by (Chung, 2006) developed a novel micromixer with baffles and side-wall injection into the main channel to simplify the fabrication complexity, reduce high pressure loss and improve mixing efficiency. Other passive micromixer are T- and Y- shaped micromixer, parallel lamination micromixer, sequential lamination micromixer, focusing enhanced mixer, chaotic advection micromixer and droplet micromixer (Capretto, 2011).

1.2 Objectives

The Following are the objectives of this project:

1. To design the selected micromixers:
    a) Y micromixer
    b) Y micromixer with internal rib
    c) Y micromixer with patterned grooves
    d) Y micromixer with obstructions
    e) Y micromixer with slanted rib

2. To analyze the fluids mixing performances via color changes, viscosity's standard deviation and mixing efficiency among the selected micromixers

3. To perform a comparative analysis and to select the optimum design among the selected micromixers

1.3 Scope of Study

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 (Capretto, 2011). To make the comparison between those designs, will take a lot of time also energy.

In this project, the comparison will make between four existed designs of different passive micromixers to see the viscosity's standard deviation of fluid mixing. These micromixers mentioned in section 1.2 were chosen because they were the best design in previous search (Lei, 2009) (Stroock, 2002) (Laser, 2004) while the first mixer is for baseline control. Using CoventorWave 2010 the simulation can be made between these four micromixers and analyze the viscosity's standard deviation. This project will be done using simulation without the practical comparison.

1.4 Problem Statement

LOC devices have been designed for the past decades for many applications and one of them is the mixing fluids. But, in designing the LOC devices, it must be in micron scale level and to realize it, only passive micromixer can be easily integrated into LOC devices.

Generally the active micromixers have higher mixing efficiency, but with an external field and the corresponding integrated components, the structures of active micromixers are often complicated and require complex fabrication processes. Active micromixer needs an external energy for operation of the micromixer, thus the operation will be more challenging and expensive (Wu, 2005).

Besides that, active micromixer has some limitation of some implementation especially in chemical and biological application. For example such mechanism as ultrasonic waves, will damage the biological fluids with its high temperature gradients.

The most basic passive micromixer are a T- or Y-micromixer, where two fluids mixed due to transverse diffusion. The different between T- and Y- micromixer are the degree between the inlets. T micromixer has a 180 degree between the inlets while Y micromixer had <180 degree between the inlets. However, a long mixing channel is needed to ensure the complete of fluids mixing and the flow is rather slow (Capretto, 2011). Thus, a variety of channel geometry is sometimes used in order to more effectively use in the microdevice by decreasing the total length of the device.

In this project, a slight modification has been made to the geometrical channel mixing by roughening the channel walls or by adding obstacles. The modification of the channel geometry can create the transverse flows and it can be done by inserting obstacles either into the walls or into the channel itself. Thus, four different kind of obstacles were installed in the channel wall create an internal rib micromixer, obstruction micromixer, patterned grooves micromixer and slanted rib micromixer to observed the mixing performance of laminar blood and reagent mixing at low Reynold Number. The results on performances are based on the simulation carry out by using ConventorWare2010 software.

1.5 Report Outline

Chapter 1 has presented a briefly introduction of the thesis project mainly about MEMs and its applications, 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 BioMEMs devices and applications. This chapter will also explain more about the fundamental of mixing fluid, the Reynold number and the mathematical background of flid flow. In addition, there will be some briefly explanation on the material using in BioMEMs applications.

Chapter 3 will present the methodology used to complete this project. Using only ConventorWave2010, 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 ect.

Chapter 4 is the result and discussion for all the analysis of the five 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

2.1 Introduction

Over the decades, the development of Micromechanical Systems (MEMs) has promised of increase performance while decreased the costing. The systems could perform sample handling, analysis and detection in a compact system. This allows integration of many applications in electrical, mechanical, chemical and biological including sensing, computing, actuation, control, communication, and power.

Microfludics is one of the MEMs applications and has been developed as one of the MEMs technology. According to the dictionary, microfluidics is the science and engineering of systems in which fluid behavior differs from conventional flow theory primarily due to the small length scale of the system.

The recent development of MEMs is the applications in the biology, chemistry and medicine called BioMEMs. It is to seek the improvement in preserving human health and quality of life.

2.2 Microfluidic BioMEMs Devices

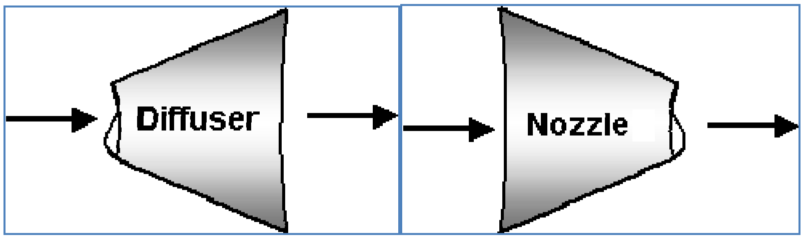
BioMEMs include the technologies that enable scientific discovery, detection, diagnostics, and therapy and span the fields of biology, chemistry and medicine. Rapid progress by researchers worldwide had led to the development of many BioMEMs devices including microfluidics devices with pumps and valves, micronozzles and biosensors.

2.2.1 Microchannels

Microchannel in microfluidics devices is dealing with a channel that used in fluid control and heat transfer with a hydraulic diameter of tens to hundreds of micrometers. This channel is not only fabricating in cylinder but also in many different kind of shape mentioned in previous research.

2.2.2 Diffusers and Nozzles

Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses. A nozzle is a device that increases the velocity of a fluid at the expense of pressure while a diffuser is a device that increases the pressure of a fluid by slowing it down. That is, nozzles and diffusers perform opposite tasks. The cross-sectional area of a nozzle decreases in the flow direction for subsonic flows and increases for supersonic flows. The reverse is true for diffusers. **Figure 2.1** illustrates the diffusers and nozzles in figure form.



(a) (b)

Figure 2.1 Diffusers and Nozzles (Thermo, 2003)

The diffuser is a flow channel that has gradually expanding cross-section while a nozzle is the opposite. Nozzles and diffusers form part of the non-moving part micropump, acting as passive valves. Passive valves aim to have the fluid flow in one direction only. It should ideally have zero resistance in one direction and infinite resistance in the other direction

Diffusers were designed to increase pressure and reduce kinetic energy. As fluids entered the diffuser, its flow velocity decreases and the static pressure increases. Researchers nowadays were concentrate on fabricate the micronozzles and microdiffusers in low cost but efficiently fluid flow. The flow proficiency of these channels strongly depends on proper design and fabrication of its diffusers and nozzles. This can be found in (Bahadorimehr, 2010).

2.2.3 Microvalves

The development of microvalves started in 1990s to reveal the advantages and various MEMs based microvalves concepts. Then in 2000, the study of traditional technologies had been done. The technology of microvalves has been progressing rapidly due to its performance and features (leakage flow, resistible pressure, power consumption, dead volume, response time, biochemical compatibility and disposability). **Figure 2.2** showed one of the examples of microvalves.

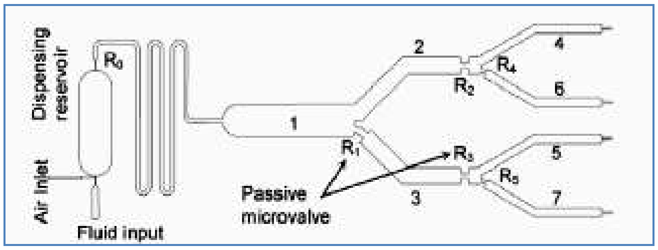


Figure 2.2 Series of microchannels with passive valves located at programmed positions by Ahn's group (Oh, 2006)

However, the performance needs to be improved further more along with making them cost effective for commercialization. Furthermore, the microvalves will be embedded in various microfluidic systems, including space exploration, fuel cell etc (Oh, 2006).

Microvalves have the ability to stop and start the fluid flow. Microvalves are used to rectify fluidic flows, used in pairs in directing fluid flow in and out of a micropump or individually in microchannel. Microvalves have been developed in the form of active or passive microvalves employing mechanical, non-mechanical and external systems. Static microvalves are mostly mechanical check valves consisting of a micromachined orifice and a deflectable sealing element. This sealing element can be plate, a ring mesa, a cantilever or a float. Dynamic microvalves have micronozzles and microdiffusers functioning as valves. These are known as dynamic valves.

2.2.4 Micropumps

Since the first micropumps were introduced in the early 1980s, progress in micropump development and analysis has been rapid. Reciprocating displacement micropumps, the most widely reported micropumps, have been produced with a wide variety of chamber configurations, valve types, drivers and constructions. Piezoelectrically driven reciprocating displacement micropumps have been the subject of particular attention and are now available commercially. Aperiodic displacement pumping based on localized phase change, electrowetting and other mechanisms are effective for transporting finite quantities of fluid in a generally unidirectional manner. Dynamic micropumps based on electromagnetic fields—electrohydrodynamic, electroosmotic and magnetohydrodynamic micropumps—are a subject of increasing interest. Electroosmotic micropumps are emerging as a viable option for a number of applications, including integrated circuit thermal management. As the reliability and ease of manufacture of micropumps improve, we can expect that micropumps will be increasingly used in a wide variety of systems in fields including life sciences, semiconductors and space exploration (Laser, 2004).

2.2.5 Micromixer

The development of micromixers has been progressing rapidly in recent years. From the early, devices made of silicon and glass, a number of polymeric micromixers have been fabricated and successfully tested (Branebjerg, 1996) (Asgar, 2008) (Tang, 2004). Due to their simple designs, passive micromixers found the most applications in analytical chemistry. While conventional parallel lamination mixer works well in low Reynolds Numbers and low Peclet numbers (Branebjerg, 1996). Micromixer based on chaotic advection can be designed to suit a wide range of Reynolds numbers and does not depend on Peclet numbers (Nimafar, 2012) (Stroock, 2002). With a trend for polymeric microfluidic systems, a simple but efficient passive micromixer is the choice for many applications in chemical and biological analysis. Further information on this will be discussed in section 2.3.

2.2.6 Microfluidic BioMEMs Applications

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. Mixing in mircroscale is relies mainly on diffusion due to laminar behavior at low reynold numbers while mixing in macroscale is achieved with turbulence.

In medical microdevices, there are some applications that benefit the world of medical society. There are include:

a) Enzyme assays
b) Immunoassays
c) Polymerase Chain Reactor (PCR)
d) DNA Separation
e) Lab-on-a-Chip (LOC)

However, this task will not cover all the applications mentioned above. Concentration on LOC is the main priority as it will be the mixing platform for complex chemical reaction. LOC technology is already being applied in labs for chemical control and analysis (gas detectors), medical testing (DNA testing or bacterial culturing), and occasional miscellaneous devices (implantable drug pumps). **Figure 2.3** is one of the examples of LOC. The picture showed the fluids being injected with stainless steel needles into the human hair size microchannel.

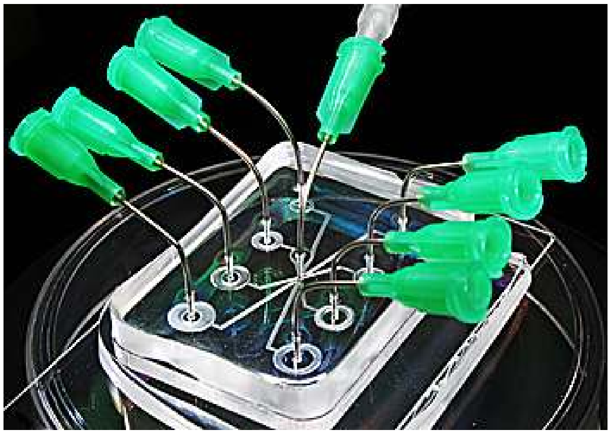


Figure 2.3 Example of lab on a chip (Newman, 2012)

2.3 Micromixer

Micromixers can be categorized as passive and active micromixers where passive micromixers do not require external disturbance to improve mixing while active micromixer do require one. Passive micromixers rely entirely on diffusion and chaotic advection. **Figure 2.4** showed an overview of different micromixer types.

Passive micromixer are based on four different types of way which are lamination that divided into two groups (serial and parallel), chaotic advection, injection and droplet. Some said that passive micromixer can be categorized into six types of way Capretto, 2011). Either way, the most important is the basic knowledge of the passive micromixer itself, which is micromixer that does not need an external force to fluids mixing. Due to its microscale, passive micromixer only needs a small amount of sample and reagent with its less time consumption, lower cost and high throughput. With nowadays biochemistry applications, often involve in reactions that require mixing of reactant.

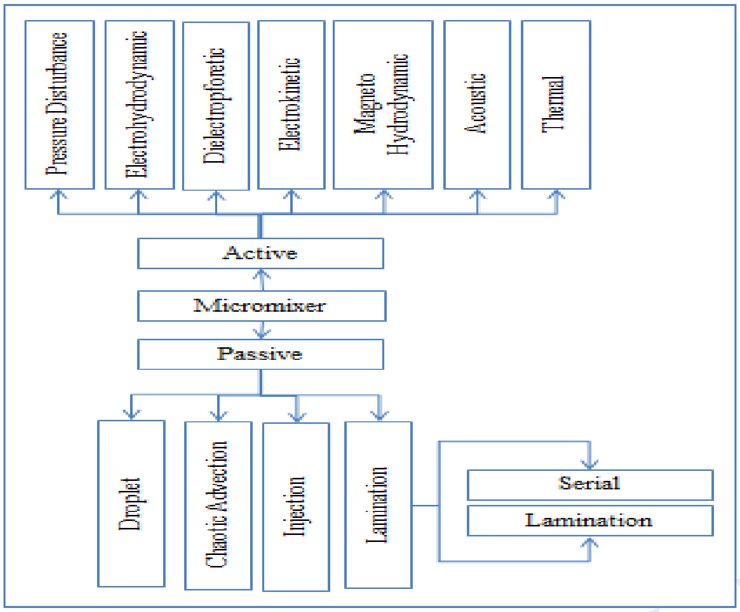


Figure 2.4 Overview of different micromixer types (Wu, 2005)

Passive micromixer as mentioned above is entirely depends on molecular diffusion and chaotic advection. The first microfluidic devices reported is T-mixer and Y-mixer, but they have a very long channel for mixing. These kinds of designs are needed for a high peclet number, if the channel width and the diffusion coefficient are fixed. (Wong et al., 2006) has reported that the mixer utilizes a very high Reynold Number up to 500 to generate fast vortices. He used the silicon substrate and Pyrex glass plate to observe the performance of the mixing. .

In order for the channel to be decreased, the basic T design can be improved by roughening the channel wall or throttling the channel entrance. The theory is need to increase the contact surface between the different fluids and decreasing the diffusion path between. This could improve the molecular diffusion.

Instead of the traditional straight channel, mixing channel with turns and geometrical obstacles can be implemented by roughening the channel wall or throttling the channel entrance. Another design of micromixer that will enhance the mixing fluids is through splitting and later joining the stream. This serial lamination micromixers has been reported successfully leads a few times of improvement in mixing times (Branebjerg, 1996)

Another design by passive micromixer is based on chaotic advection. This design based on equation (2.1) where an advection is another important form of mass transfer.

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} + w\frac{\partial c}{\partial z} = D\left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2}\right) \tag{2.1}$$

Chaotic advection can be induced by manipulating the laminar flow in microchannel. The basic design concept for generation of advection is the modification of the channel shape for splitting, stretching, folding, and breaking of the laminar flow (Nguyen, 2006). There are some different geometries have been proposed such as SAR mixer (Hardt, 2006) and H-shaped mixer (Nimafar, 2012) using SAR approach while staggered herringbone mixer (Stroock, 2002) and modified tesla mixer (Asgar, 2008).

2.4 Fundamental of Mixing Fluids

Mixing fluids can be achieved at macroscale and microscale level. In macroscale level, a turbulent flow needed for the mixing successful while in microscale level, the mixing is relies entirely by diffusion and advection within the relevant of small length.

Diffusion is the best method for efficient laminar mixing. Diffusion time is decreased in microscale system when mixing path is shorter with the large of surface area-to-volume ratios. Micromixers generally designed with channel geometries that decrease the mixing path and increase the contact surface area. For example, a Y-mixer consists a long straight channel. To increase the mixing fluids, the straight channel can be replaced with a winding serpentine channel or many other alternative solutions for efficient mixing have been explored

The reduction in mixing time generally can be achieved by splitting the fluid stream using serial and parallel lamination (Branebjerg, 1996), or enhancing chaotic advection using ribs and grooves on the channel floor (Stroock, 2002). The new strategy of mixing is through splitting and recombining fluids in the mixer channel have been explored (Nimafar, 2012).

2.4.1 Fluids Flow and Reynold Number

Fluids flow is generally can be categorized into two parts: laminar and turbulent. Laminar flow is characterized by smooth and constant fluid motion while turbulent flow is characterized by vortices and fluctuation. For the determination weather the fluid is laminar or turbulent is measured by Reynold Number (Re)

A dimensionless number was introduced to determine the relatives importance of inertial effects compared to viscous effects known as the Reynold Number, Re as shown in equation (2.2).

$$\mathrm{Re} = \frac{\rho UL}{\mu} = \frac{UL}{\nu} \tag{2.2}$$

Where U is the velocity and L is the characteristic length scale of the flow. Fluid flow with Re > 1 tend to be turbulent while below that fluid is laminar. In microfluidic, the scales are too small that the fluid flows nearly laminar.

Microfluidic channels assume a number of different geometries and their length. It is usually substituting the hydraulic diameter, D_{hyd} in the Re equation as follows (Ellis, 2011):

$$\mathrm{Re} = \frac{\rho U D_{hyd}}{\mu} = \frac{Q D_{hyd}}{\nu A} \tag{2.3}$$

Hydraulic diameter for cross sections of square channel is guided by **Figure 2.5**: At low Re, the fluids flow is laminar and the mass transfer occurs only in direction of fluid flow, therefore the mixing only be achievable by diffusion and advection (Hardt, 2006).

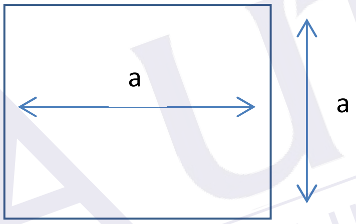


Figure 2.5 A D_{hyd} =a for square channel of microfluidic (Ellis, 2011):

The motion of a viscous fluid flow is governed by the Navier-Stokes equation, which use volumetric flow rate, Q (m^3/s) as shown in equation (2.4).

$$Q=VA \tag{2.4}$$

Where A is the cross sectional area of the flow.

2.4.2 Properties of the Fluids

The thermodynamic properties of fluids are including pressure, density and temperature, while for the mechanical behavior including viscosity, thermal conductivity and surface tension.

In microfluidic systems, static pressure is often a driving force used to move fluids in microchannels, while temperature, quantifies a fluid's internal energy. However, the density is a function of both temperature and pressure. In the fluids mechanical behavior, viscosity played the main role as it is the ability of the fluid to resist motion due to shear stress. The presence of a temperature gradient in microfluidic system induces heat transfer. This leads to thermal conductivity which is dependent to the temperature and pressure (Ellis, 2011).

2.4.2.1 Density

The density of the fluid is its mass per unit volume (kg/m^3) as in ρ. Liquids is incompressible therefore it forces to be constant although in the presence of pressure (Ellis, 2011).

Specific weight, γ, is related to density and is defined as the weight per unit volume of the fluid:

$$\gamma = \rho g \tag{2.5}$$

Where g is the gravitational constant ($g=9.8m/s^2$). The unit for specific weight is N/m^3. Assuming the density is constant and that a fluid is stationary, we can define hydrostatic pressure as follows:

$$P = \rho g h \tag{2.6}$$

Where h is the height measured in the direction of gravity (Ellis, 2011)

2.4.2.2 Viscocity

Viscosity is a measure of the fluid resistance because of either shear stress or tensile stress. The greater the viscosity, the greater its resistance to stress. This lead to viscous. In common usage, a liquid with a viscosity less than water is known as mobile liquid while, in opposite case, it is called viscous liquid. The physical behaviour associated with viscosity can be described as follows:

a) Molecule's layers move at different velocities in any flow
b) The fluid's viscosity arises from the shear stress between the layers that ultimately oppose any applied force.

We are concerned with the Kinematic Viscosity, v (m^2/s) which is related to absolute viscosity (dynamic viscosity) through density as equation (X). Where the absolute viscosity, μ (Ns/m^2 or Pa.s) is the ability of the fluid to resist motion (Ellis, 2011).

$$v = \frac{\mu}{\rho} \tag{2.7}$$

Newtonian fluids is said to be the viscosity independent of the velocity gradient. It should be noted that that viscosity is a function of temperature; fluid become less viscous as temperature increases. In this task, we assume the temperature is constant during the operation of microfluidic devices.

2.5 The Continuum Model

The continuum assumption is generally holds, for microfluidic system. The fluids can be considered continuum and is well defined everywhere in space, determining the density at a point is sufficient (Ellis, 2011).

2.5.1 Navier-Stokes Equation

The flow is considered as incompressible as the viscosity is not depending on temperature therefore the energy can be eliminated altogether. The governing equation applied is the Navier-Stokes equation for the incompressible, non-turbulent fluid:

$$\rho\left(\frac{\partial v}{\partial t} + v.\nabla v\right) = \rho g - \nabla p + \mu \nabla^2 v \tag{2.8}$$

2.5.1.1 Poiseuille Flow

Most microfluidic system relies on pressure-driven flow in which a pressure difference exists between the ends of the channel. The pressure as a driving forced can lead to the steady-state Poiseuille Flow. Hagen-Poisseuille flow or Poiseuille flow is a steady, incompressible, laminar flow through a circular tube of constant cross section. Slightly modification will be made to account for many channel geometries. From the equation 2.8 above, we can consider a simple case which Poisseuille flow is induced in an infinite parallel-plate channel (**Figure 2.6).**

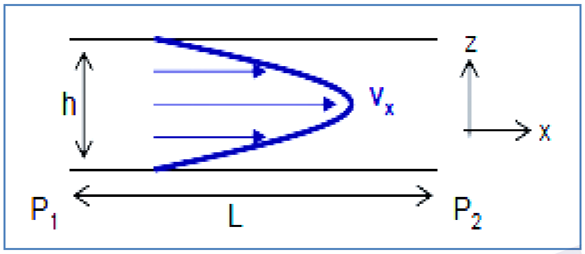


Figure 2.6 Poisseuille flow between two infinite parallel plates (Institute, 2010)

A pressure, P is applied across the channel of height h. To determine the velocity profile for this system, we assume that gravity can be neglected and thus obtained the following equation (Institute, 2010):

$$\mu \frac{\partial^2 u_x}{\partial y^2} = -\frac{\Delta P}{L} \tag{2.9}$$

For solving the constant pressure drop, flow rate, Q for the Poisseuille (laminar) flow for square cross sectional is (Ellis, 2011):

$$Q = \Delta P \frac{28.4\mu L}{h^3 w} \tag{2.10}$$

2.5.2 Surface Forces in Microfluidic

At a microscale level, the volume is in microliter range, so the behavior is reversed than the macroscale level. The surface tension and capillary forces cannot be neglected. As volume decreases, the surface-to-volume ratio increases.

Since the Reynold Number used is less than 1, turbulence is not achievable in microscale. Because of the mixing is relies fully on diffusion and chaotic advection, it is hard to get fully mixing between two fluids. The design had to be considered of mixing fluids in shorter path so, the manipulation of the mixing path were designed to increase the contact surface. Fast mixing time can be achieved by decreasing the mixing path and increasing the interfacial area (Nguyen, 2006).

2.5.2.1 Surface Tension

Surface tension is the result of cohesion between liquid molecules at the liquid/gas interface. The surface free energy of a liquid is a measure of how much tension its surface contains. Surface tension takes a unit in a form of N/m which suggesting that this behaviour is a force (Vowell, 2009)

2.5.2.2 Marangoni Effect

The effect of an inhomogeneous interface called a Marangoni effect. When there exists a gradient across an interface, the tangential force due to the surface tension pulls liquid along the surface from regions of low tension to regions of high tension. Since the Marangoni effect stems from surface tension, and surface tension is the dominant force on the microfluidic scale, making use of the Marangoni effect is among the most effective means of actively controlling microfluidic systems.

The overall motion depends strongly on not only the surface tension gradient, but also the properties of the liquid (e.g. viscosity), the interfaces of the liquids, the viscosity and density of the surrounding environment etc (Vowell, 2009).

2.6 MEMs Manufacturing

The current techniques used for fabricating microfluidic devices include micromachining, soft lithography, embossing, in situ construction, injection molding and laser ablation. The most suitable method of device fabrication often depends on the specific application of the device.

For this task, soft lithography was used in modeling the micromixer. This method gives advantages of a faster, less expensive and less specialized method for device fabrication (Beebe, 2002).

2.6.1 Materials

In order for the fluids flow smoothly without any other obstacles, the material used for the micromixer also takes very important figures for fabrications. The flows might have been disturbed in some way with different kind of material used.

Long time ago, glass has been the most priority material for microfluidic researcher and it is upgraded to use a silicon technology in electrical and mechanical material in MEMS and microfluidics. But nowadays, polymers became famous among

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