Design and Simulation of a Three-way Microfluidic Mixer based on Pressure Disturbance

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Abstract – Bio-MEMS (Bio-Micro-electro-mechanical Systems) have been widely used for disease diagnosis and treatment. In bio-MEMS devices, the mixing of different micro-fluidics is frequently needed. However, such mixing has been very challenging due to the fact that micro-fluidic is generally laminar flow. As a result, MEMS mixers which can enhance the mixing of different micro-fluids are in pressing need. In this paper, the design and simulation of a 3-way pressure disturbance based micro-fluidic mixer for Bio-MEMS application is proposed. Three aqueous solutions with different concentrations represented by different colors (sea blue, sky blue and red) are introduced through six inlets. The mixing of micro-fluid in the proposed mixer is analyzed. The parameters of the mixer are decided through the theoretical analysis. Based on results of the experiment simulation, almost 100% mixing can be finished within a mixing distance x equal to 3.24mm of outlets for flow rates ranging in 1000μm/s, and when the micro-fluids (3 kinds of liquids) near the outlets, the mixing degree is better. More or less than this velocity, the micro-fluids cannot get a good mixing. ANSYS simulation is used to verify the effectiveness of the MEMS mixer device. Compared with passive mixer, the pressure disturbance design with the straight channel diffusion model mixer is easier to fabricate and it makes device smaller and cheaper. The fabrication flow of the MEMS mixer is also suggested in this paper. The proposed MEMS mixer can be used for lab-on-a-chip, digital micro-fluidics, PCR amplification, DNA analysis, cell manipulation, cell separation and other applications.

Keywords: BioMEMS (BioMicroElectroMechanical Systems), Microfluidics, Microfluidic mixer, Pressure distance.

INTRODUCTION

Micro-fluidics has facilitated major biochemical application advancements in point-of-care diagnostics, bioterrorism detection, and drug discovery. There are numerous potential applications in biotechnology, pharmaceuticals, the life sciences, defense, public health, and agriculture. Micro-fluidic lab-on-a-chip (LOC) technologies represent a revolution in laboratory experimentation, bringing the benefits of miniaturization, integration, and automation to many research-based industries.

Mixing is not only a ubiquitous natural phenomenon accompanying geophysical, ocean and atmospheric flows, but it is also an important step in many technological processes[1]. Effective mixing underlies the operation of chemical and fermentation reactors, combustion engines and other processes; it is required to make glasses, polymer blends and pharmaceutical formulations. The majority of these industrial processes are carried out on macroscopic scales, and it has only been in the recent years that mixing of small quantities of liquids has become technologically relevant in the context of micro-fluidics and micro total analysis systems [2].

Mixing on microscopic scales is, however, difficult. Although diffusion on the micro-scale is fast the Reynolds numbers are usually low (Re ~ 1), and the flows are laminar[3]. In the absence of turbulence, it is hard to increase the interfacial area of contact through which the molecules diffuse. Numerous and often ingenious micro-mixing devices have been developed that overcome the limitations imposed by the laminar of micro-flows. Before
discussing the architectures and principles of these micro-mixers in detail, a few words are in order to clarify certain nomenclatural nuances. Thus, both the process of mixing itself and the mixing devices are classified as either passive or active—these terms, however, have very different meanings in each of the contexts. Specifically, passive mixing refers to processes in which the interfaces between the substances being mixed follow the flow and have no back-effect on it, while active mixing refers to processes in which the interfaces interact with the flow and modify it\footnote{1}. Passive mixers, on the other hand, are those that have no moving parts and achieve mixing by virtue of their topology alone, while active mixers either do have moving parts or they use externally applied forcing functions such as pressure or electromagnetic fields\footnote{2}. In principle, one can have active mixing in a passive mixer or vice versa. To avoid any confusion, we will use the terms ‘passive’ and ‘active’ only as they are habitually used in the context of mixing devices.

**WORKING PRINCIPLE**

The basic principle of Micro-fluidics is the flow of a fluid through a micro-fluidic channel can be characterized by the Reynolds number, defined as:

$$Re = \frac{\rho v L}{\mu} = \frac{vL}{\nu}$$  \hspace{1cm} (1)

- $V$ is the mean velocity of the object relative to the fluid (SI units: m/s)
- $L$ is a characteristic linear dimension, (travelled length of the fluid; hydraulic diameter when dealing with river systems) (m)
- $\mu$ is the dynamic viscosity of the fluid (Pa·s or N·s/m² or kg/(m·s))
- $\nu$ is the kinematic viscosity ($\nu = \mu / \rho$) (m²/s)
- $\rho$ is the density of the fluid (kg/m³)

Due to the small dimensions of micro-channels, the Re is usually much less than 100, often less than 1.0. In this Reynolds number regime, flow is completely laminar and no turbulence occurs. The transition to turbulent flow generally occurs in the range of Reynolds number 2000. Laminar flow provides a means by which molecules can be transported in a relatively predictable manner through micro-channels. Note, however, that even at Reynolds numbers below 100, it is possible to have momentum-based phenomena such as flow separation.

A characteristic length scale $L$ is defined as:

$$L = 2 \frac{A}{W+H}$$ \hspace{1cm} (2)

Where $A = W \times H$, is wetted area, $W$ is the width of the main channel ($W=240\mu$m), and $H$ is the height of the channel ($H=100\mu$m).

For periodical flow, the Strouhal number is usually used to characterize different time scales, which is a dimensionless number describing oscillating flow mechanisms. The parameter is named after Vincenc Strouhal, a Czech physicist who experimented in 1878 with wires experiencing vortex shedding and singing in the wind\footnote{3}. The Strouhal number is defined as the ratio of the characteristic time of the flow to the disturbance period:

$$St = \frac{fL}{V}$$ \hspace{1cm} (3)

Where $St$ is the dimensionless Strouhal number, $f$ is the frequency of vortex shedding, $L$ is the characteristic length (for example hydraulic diameter) and $V$ is the velocity of the fluid.
The inflow velocities are specified as \( V_i = V_0 + V_d \sin(2.0\pi ft + \phi_i) \) where \( V_0 \) stands for mean flow velocity, \( V_d \) is velocity disturbance from pressure perturbation, \( f \) is disturbance frequency, \( \phi_i \) is phase angle, and \( i = 1, 2, 3, 4, 5, 6 \) for six different inlets. For all different design of micro mixer, the typical method to enhance mixing is to increase interface area between two different solutions, but the final process of mixing is still through molecular diffusion.

**DEVICE DESIGN**

A micro-fluid mixer combines small amounts of two or more fluid species into a single stream where the intake components are evenly distributed. In this paper, we use an active two-dimensional micro mixer design based on pressure disturbances.

![Figure1. Coordinates and dimensions of the micro mixer model.](image)

Computational fluid dynamics (CFD) simulations were applied to guide the design of the cross-form micro mixer using ANSYS. The coordinates and dimensions of the cross-form mixer model are shown in Figure6. Three aqueous solutions with different concentrations represented by different colors (sea blue, sky blue and red) are introduced through six inlets, i.e., two inlets for each solution. The Density is 1.0g/cm³ for sea blue, 1.2g/cm³ for sky blue and 1.8g/cm³ for red solution. The two solutions are split and recombined to mix at the main mixing channel (horizontal). Compared with the T-form mixer\(^7\)[8], there are two more inlets to obtain better control of disturbances and to achieve more efficient mixing. Two dimensional simulations are used with structured grids.

**DEVICE DESIGN OPTIMIZATION**

Based upon the above analysis, an optimized design of MEMS mixer is achieved. The design parameters are shown in Table 1.

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of species 1</td>
<td>1.0g/cm³</td>
</tr>
<tr>
<td>Density of species 2</td>
<td>1.2g/cm³</td>
</tr>
<tr>
<td>Density of species 3</td>
<td>1.8g/cm³</td>
</tr>
<tr>
<td>Length of mixing channel</td>
<td>3000μm</td>
</tr>
<tr>
<td>Width of mixing channel</td>
<td>240μm</td>
</tr>
<tr>
<td>Length of inlet channel</td>
<td>500μm</td>
</tr>
</tbody>
</table>
Width of inlet channel  |  80μm  
|------------------------|--------|
| Velocities of species  | 1000μm/s  

**SIMULATION RESULTS**

The mixing performance was investigated using CFD (ANSYS) for computational fluid dynamic (CFD) analysis and using experiments for flow visualization.

The flow velocity vector plot of the micro-fluid along MEMS mixer is shown in Figure 2. From Figure 2, we can clearly see that turbulence by pressure disturbance is successfully mixed, which is very helpful for the mixing of laminar flow.

![Figure 2. ANSYS fluid velocity vector plot](image)

The contour plot of the flow density is shown in Figure 3. From Figure 3, it is shown how both micro-fluid flows are mixed rapidly along the channels. Three kinds of colors represent micro-fluid species1, species2 and species3 respectively.

![Figure 3. Contour plot of density distribution in ANSYS](image)

When the velocities of all species1, species2 and species3 at inlets are set to be the optimized v equals 1000μm/s by our analysis. The ANSYS simulated the density path plot along the cross section of x equal to 0.24mm, x equal to 1.24mm, x equals 2.24mm and x equal to 3.24mm (outlets) in Figure 4.
Figure 4. Density distribution at v=1000μm/s

**FABRICATION PROCESS**

The DRIE fabrication technology, Photolithography and Thermal oxidation used in this Micro-fluid-mixer research. The Figure 5 illustrates the fabrication flow.

1. (1) Preparing for the silicon wafer
2. (2) Si thermal oxidation to grow 0.2μm SiO$_2$
3. (3) Photolithography, etching SiO$_2$ to open windows
4. (4) Use SiO$_2$ as etching mask, KOH anisotropic etching to etch down microchannels
5. (5) Remove all SiO$_2$ with buffered HF solution
6. (6) Bond Si wafer with glass, the microchannels are sealed with glass top cover.

Figure 5. Fabrication Process
CONCLUSIONS AND FUTURE WORK

In this paper, the design and analysis of a 3-way pressure disturbance based micro-fluid mixer is proposed. The MEMS mixer utilizes pressure disturbance to improve the mixing efficiency of laminar micro-fluid flows. The mixing of micro-fluid in the proposed mixer is analyzed. Based on results of the experiment simulation in ANSYS, we can see that these three kinds of species micro-fluids totally mixed at x=3.24mm of outlets for flow rates ranging in 1000μm /s, and when the micro-fluids (3 kinds of liquids) near the outlets, the mixing degree is better. More or less than this velocity, the liquids cannot get a good mixing. Compared with passive mixer, this design is easier to fabricate the straight channel diffusion mixer and it makes device smaller and cheaper.

In the future, we will further analyze how other micro-fluid properties (such as the frequency of the pressure disturbance and the concentration of micro-fluids) affect the mixing result of the mixer. We may also use other low-cost fabrication process such as PDMS soft lithography for the device fabrication.

REFERENCES