A Study of Two Fluids Mixing in a Helical-Type Micromixer

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Abstract. The mixing behavior of two fluids in a passive micromixer with Y-type inlet and helical fluid channel, along with herringbone grooves etched on the base of the fluid channel, was studied with computer simulation technique and experiments. The mixing of pure water and acetone solution under different Reynolds numbers and acetone concentrations were investigated. An image inspection method using the variance in contrast of the image gray level as the measurement parameter was adopted to calculate the mixing efficiency distribution. Inspection results show that the mixing efficiency is decreased with the increase of the concentration of the acetone solution, but the mean mixing efficiency around the outlet can reach to a value of 90% even the Reynolds numbers of the fluids were as low as Re = 1, and the best efficiency for the case of Re = 10 is over 98%. The results show that the proposed micromixer is possible applied to the field of biomedical diagnosis.

1. Introduction
Micromixers play a core role in many biochemistry and biomedical applications, such as analysis and synthesis of RNA/DNA, PCR amplification and so on [1-2]. Two key issues, a simple system design for high mixing efficiency and effective examining techniques of mixing efficiency, are usually concerned in micromixer development [3-4]. It is known that the flows inside microchannels are predominantly laminar and the Reynolds numbers are usually lower than 10. Therefore, the mixing of fluids in microchannels is not easily implemented with mechanical stirring methods because of size limitations and fabrication difficulties [5-6]. In general, most of traditional micromixers were constructed of straight fluid channel and companied with the design of fillisters and/or fold paths to enhance the mixing effect [7]. However, the design of straight channel needs longer length to achieve the goal of uniform mixing. Therefore, it is always persecuted with the problems of mixer size and full-field inspection.

In this paper, a novel passive micromixer with Y-type inlet and helical fluid channel is presented. The design of helical route increases the contact area of the mixing fluids that the uniform mixing can be achieved within a shorter mixing path and also the tortuous design much reduce the mixer size. The mixer was fabricated with a self-developed micromachining system, which eliminates the needs of high fabrication cost via the MENS process. The mixing of pure water and acetone solution in this
mixer under the streams with Reynolds numbers of 1~10 and acetone concentrations of 0~50% were investigated. An image inspection method using the variance of the image gray level contrast as the measurement parameter to determine the mixing efficiency distribution in the mixer. The steady and laminar flow fields inside the micromixer were simulated numerically with a finite volume discretization. Through the numerical integration over the chamber depth, the numerical prediction could be directly used to compare with the experimental measurements. In results, the numerical prediction of overall mixing efficiency agreed quantitatively with those obtained from the experiments, which show that high mixing efficiency can be obtained in the developed micromixer even the Reynolds numbers of the fluids were very low. It provides a valuable reference to the research work of micromixer design.

2. Design and Fabrication

The helical channel micromixer is conjoined with two PMMA plates which are a transparent cover plate and a base substrate as a device support, as shown in Figure 1(a). The mixing layer includes inlets, outlet and microchannel which are carved on the base layer. Figure 1(b) and Figure 1(c) show the schematic geometry and the image of the mixing layer, respectively. As it is shown, a 90° Y-type inlet was adopted for the input of mixing fluids and the traditional straight fluid channel was modified to a helical shape. The width and depth of the helical channel are 0.2mm and 0.1mm, respectively. Ten herringbone segments were grooved on the bottom of the mixing plate; the width and depth are 80μm and 25μm, respectively. The length of the shorter leg of the herringbone is 70μm, and the longer leg is 130μm. Four locations in the mixer were chosen for the inspection of the mixing effect, including three cross sections in the fluid channel and the outlet of the mixer chamber. Section1 apart from the junction of two fluids is \( l_1 = 0.65 \text{mm} \), section 2 is \( l_2 = 1.75 \text{mm} \), and section 3 is \( l_3 = 2.55 \text{mm} \). The outlet is a circle with a diameter of 0.2mm, the distance to the junction is \( l_4 = 2.95 \text{mm} \).

The fluid channel was fabricated via a micromachining system, shown in Figure 2, capable of performing high-speed drilling, milling and cutting operation with real-time monitoring capability. The micromachining system consists of a high precision X-Y-Z table equipped with a three-axis controller, a high-speed spindle (NSK-400) managed by a motor controller, and two CCD cameras. The high-speed spindle was operated at about 25,000 rpm in the cutting process, while a low speed of 2,000 to 40,000 rpm was used in the drilling/milling applications. One CCD camera of the micromachining system was employed to serve a real-time monitoring purpose, while the other one was used to ensure the correct tool orientation and perform position calibration.

![Figure 1. (a) Schematic of the helical channel micromixer. (b) Designed geometry of the mixing layer. (c) Image of the helical channel.](image-url)
3. Mixing Efficiency Evaluation Algorithm

Here an image inspection method using the variance in contrast of the image gray level as the measurement parameter is proposed. The boundary of the circular chamber can be obtained in advance by using an image processing technique, and the instant normalized relative gray level $E_{ij}$ at pixel $(i,j)$ is defined as [8]

$$E_{ij} = M_{ij} \cdot \frac{\sum_{q=1}^{m} \sum_{p=1}^{n} M_{pq} |a_{ij} - a_{pq}|}{\sum_{q=1}^{m} \sum_{p=1}^{n} M_{pq} (A_{\text{Max}} - A_{\text{Min}})} \cdot \frac{|a_{ij} - a_{\text{cal}}|}{B_{\text{Max}} - B_{\text{Min}}}$$  \hspace{1cm} (1)

where $a_{ij}$ and $a_{pq}$ are the image gray level at pixels $(i,j)$ and $(p,q)$, respectively, $M$ is 1 for pixels located inside the circular chamber, and 0 external to it, $M_{ij}$ and $M_{pq}$ are the $M$ values at pixels $(i,j)$ and $(p,q)$, respectively, $A_{\text{Max}}$ and $A_{\text{Min}}$ are the maximum and minimum of $|a_{ij} - a_{\text{cal}}|$ in this image, respectively, $a_{\text{cal}}$ is a gray level used for concentration calibration, $B_{\text{Max}}$ and $B_{\text{Min}}$ are the maximum and minimum of $|a_{ij} - a_{\text{cal}}|$ in this image, respectively, and $m \times n$ is the image size. In general, $a_{\text{cal}}$ is taken with the image gray level that the concentrations of the two mixed fluids are given and usually determined in advance, the normalized relative gray level $E_{ij}$ at pixel $(i,j)$ is one (bright image) in the unmixed region, and zero (dark image) at a pixel with a gray level of $a_{\text{cal}}$.

As shown, the cross sections at section 1, 2 and 3 are rectangles, the overall mixing efficiency $E_i$ at both sections can be seen as

$$E_i = \frac{1}{a \times b} \sum_{a=0}^{\text{b}} \sum_{b=0}^{\text{a}} (E_{ab})$$  \hspace{1cm} (2)

where $a \times b$ is the size of the section in the image and $E_{ab}$ is the normalized relative gray level at pixel $(a,b)$ obtained based on Eq.(1).

As for the inspection of the outlet, a polar coordinate system can be adopted. The overall mixing efficiency $E_r$ on a circle of radius $r$ can be defined as

$$E_r = \frac{1}{R} \sum_{r=0}^{R} \int_{0}^{\theta} \frac{E_{r \theta} d\theta}{2\pi}$$  \hspace{1cm} 0 < r \leq R$$  \hspace{1cm} (3)

where $\int_{0}^{2\pi} E_{r \theta} d\theta / 2\pi$ is the mean mixing efficiency around the circumference of a circle with radius $r$, $E_{r \theta}$ is the normalized relative gray level at a pixel with image coordinate $(r, \theta)$, $R$ is the radius of the outlet.
4. Numerical method
In our experiments, two fluids, pure water and acetone solution, were adopted for the mixing. The governing equations described the mixing process inside the mixer by solving the continuity, momentum, and concentration with a finite volume discretization were given as follows:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla \cdot \mathbf{p} + \nabla \cdot \left( \mu \left( \nabla \mathbf{u} + \nabla \mathbf{u}^T \right) \right)
\]

\[
\frac{\partial (\rho c)}{\partial t} + \nabla \cdot (\rho c \mathbf{u}) = \nabla \cdot (\rho \text{Diff} \nabla c)
\]

where \( u_i \) denoted the velocity components in the coordinate direction \( x_i \), \( \rho \) was the fluid density, \( \mu \) was the fluid viscosity, \( t \) expressed the time, \( p \) stood for the pressure, and Diff denoted the mass diffusivity and \( c \) denoted the volume fraction of fluid. Where \( c = 1 \) stood for cells filled by the first liquid, \( c = 0 \) for cells filled by the second liquid, \( 0 < c < 1 \) for cells filled by both fluids. The computer simulation of the mixing behavior was performed with a commercial package, named Ansys CFD. A multi-block structured grid with 75,000 ~ 142,000 cells was used to discretize the computational domain inside the micromixer.

5. Experimental System
The measurement system included a supplied system and an inspection system, shown in Figure 3. Two fluids were separately injected into the channels through two inlets at a constant flow rate. The motor driving velocity of the power system was in the range of 0.625 μm/s ~ 31.25 μm/s. The cross area of the pump was 68 mm², so that the induced flow rate range was 0.0425 μl/s ~ 2.125 μl/s. In our experiments, flow rates including 0.1 μl/s ~ 1.0 μl/s were applied. The related Reynolds numbers of water are 1 ~ 10, respectively. Both channels were identical. The mixing processes were recorded using a high-resolution digital camera (IDT XS-3) with a resolution of 512×512 pixels in a 24-bit color level. The image acquisition speed was 665 frames per second (fps). The field of view was 1.3 mm × 1.1 mm, so that the image resolution was roughly 2 μm/pixel.

Here the mixing of pure water and acetone solution in the developed micromixer was investigated. For the purpose of better observation, the pure water was mixed with red dyne and the acetone solution was mixed with blue dye. The adopted acetone concentration is in the range of \( \phi = 0 \sim 0.5 \). The physical properties of these two fluids are shown in Table 1. A gray level for a uniform mixing state of these two mixing liquids was first acquired and used to obtain the mixing calibration factor \( a_{cal} \).
Table 1. The physical properties of fluids.

|                    | Colored dye | Density       | Viscosity          | Diffusion          |
|--------------------|-------------|---------------|--------------------|--------------------|
| Water              | Red         | $997 \text{kg/m}^3$ | $1.002 \times 10^{-3} \text{N} \cdot \text{s/m}^2$ | $2 \times 10^{-5} \text{kg/m}$ |
| Acetone solution   | Blue        | $780 \text{kg/m}^3$ | $0.324 \times 10^{-3} \text{N} \cdot \text{s/m}^2$ | $2.06 \times 10^{-5} \text{kg/m}$ |

Inspections were carried out with the cases of Reynolds numbers of mixing fluids under 10. Figure 4 shows the mixing results of the fluids with Reynolds numbers of 1 and 10, where the concentration of acetone solution is 0.5. Figure 4(a) and 4(b) are the full-field mixing images obtained from computer simulations and experiments, respectively. The calculated full-field mixing efficiency distribution in the micromixer is shown in Figure 5. As it is shown, the numerical prediction of overall mixing efficiency agreed with those obtained from the experimental measurements, and the mean mixing efficiency around the outlet can reach to values over 90%, even for the fluids with Reynolds numbers as low as $Re = 1$.

Figure 6 shows the overall mixing efficiency distributions in the inspected ranges of fluids Reynolds numbers and acetone concentration. The best mixing efficiency around outlet was roughly 98%, where the influence of acetone concentration is not obvious. Since the uniform mixing can be achieved within a very short mixing path, the mixer size can be effectively reduced.

6. Conclusion
A novel passive micromixer with Y-type inlet, helical channel, and carved herringbone grooved was developed. The mixer was fabricated with a self-developed micromachining system, that makes the mixer can be easily implemented with low cost. The mixing of pure water and acetone solution were performed to investigate the mixing efficiency of fluids under low Reynolds numbers. The mixing processes were numerically simulated via a commercial FEM package. Inspected results show that the design of helical fluid channel can much increase the contact area of the mixing fluids and enhances the mixing effect. The numerical prediction of mixing efficiency agreed with those obtained from the experimental measurements. Besides, the design of helical channel can reduce the size of the micromixer. This means that a more compact microfluid device compares to the traditional mixers with straight channel could be expected.
Figure 5. Full-field mixing efficiency distribution in the micromixer for the case of $\phi = 0.5$.

Figure 6. The overall mixing efficiency distributions under different fluids Reynolds numbers and acetone concentration.

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