Micromixer Based On Taylor Dispersion

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Abstract. This paper reports an analytical model, the fabrication and the characterization of a polymeric micromixer based on Taylor dispersion. Due to the distributed velocity field over the channel cross section, the effective dispersion in axial direction in a microchannel is much stronger than the pure molecular diffusion. In our work, sequential segmentation was used in the micromixer for improving mixing in a microchannel. The micromixer was designed and fabricated based on lamination of five 100-μm-thick polymer sheets. Rubber valve seats were embedded between the forth and the fifth layers. The polymer layers were machined using a CO₂ laser. The lamination of the five layers was carried out by a commercial hot laminator (Aurora LM-450HC). External solenoid actuators are used for closing the valves at the mixer inlets. The experimental results confirm the effect of Taylor dispersion. Mixing ratio can be adjusted by pulse width modulation of the control signal of the solenoids.

Keywords: micro mixer, microfluidics, Taylor dispersion, polymeric MEMS.

1. Introduction

Many applications for biochemical analysis require effective mixing in microscale. However, mixing in microchannels is a challenging task because of the laminar flow behavior and the resulting relatively slow mixing based on pure molecular diffusion [1]. The most common technique for improving mixing, as reported in the past, is reducing the mixing path between solvent and solute. Parallel lamination and sequential lamination are the two key strategies for reducing mixing path. Parallel lamination splits the solute and solvent into sub streams and joins them in the main mixing channel [2]. Both parallel and serial laminations keep solvent and solute in their particular streams. Molecular diffusion still remains as the main mixing mechanism. Molecular diffusion coefficient is a material constant and can not be improved.

Sequential segmentation reduces the mixing path in the axial flow direction. This technique divides the solvent and solute into segments, which usually occupy the whole channel width. Mixing occurs through dispersion in flow direction. Since dispersion is more effective than molecular diffusion, mixing can be improved significantly. Sequential segmentation can be implemented by alternate switching of the inlet flows using valves. The mixing ratio is adjusted by the switching ratio. Micromixers based on sequential segmentation were already reported in the past. Deshmukh et al. [3] used integrated micropump to create time-interleaved sequential segmentation. The concentration field inside the microchannel was investigated numerically and observed optically. Similar concepts
realized by external pumps were reported later by Fujii et al. [4] and Okamoto et al. [5]. All these previous papers are based on numerical simulation and experimental observation. The effect of Taylor dispersion was not identified and analyzed.

2. Theory

A one-dimensional model for sequential segmentation is presented here. We assume a pressure driven flow in a rectangular microchannels with low aspect ratio ($W << H$). Because of this low aspect ratio, we can further assume a flat velocity profile in the channel width direction ($z$-axis) and a parabolic velocity profile in the channel height ($y$-axis). The parabolic velocity profile causes the so-called Taylor-Aris dispersion, which can be described by an effective diffusion coefficient $D^*$. Using the Taylor-Aris approach [6] and the parabolic velocity profile, the effective diffusion coefficient can be estimated as [7]:

$$D^* = D + \frac{H^2 U^2}{210D}.$$  \hspace{1cm} (1)

where $D$ is the molecular diffusion coefficient of the solute in the solvent and $H$ is the channel height. With the effective diffusion coefficient $D^*$, the problem of sequential segmentation can then be reduced to a simple one-dimensional macro transport model. Only the concentration profile along the flow direction $x$ needs to be considered. The characteristic segment length is defined as $L = UT$, where $U$ and $T$ are the mean velocity and the switching period of the inlet valves, respectively. The governing transport equation has the form:

$$\frac{\partial c}{\partial t} + U \frac{\partial c}{\partial x} = D^* \frac{\partial^2 c}{\partial x^2}.$$  \hspace{1cm} (2)

where $c$ is the concentration of the solute. Figure 1 depicts this one-dimensional model with the boundary condition at the inlet:

$$c(t,0) = \begin{cases} c_0 & 0 \leq t \leq \alpha T/2 \\ 0 & \alpha T/2 < t \leq T - \alpha T/2 \\ c_0 & T - \alpha T/2/2 < t \leq T \end{cases}.$$  \hspace{1cm} (3)

where $c_0$, $T$, and $\alpha$ are the initial concentration of the solute, the period of the segmentation, and the mixing ratio, respectively. Introducing the dimensionless variables $c^* = c/c_0$, $x^* = x/L$ and $t^* = t/T$, equation (1) is transformed into the dimensionless form:

$$\frac{\partial c^*}{\partial t^*} = \frac{1}{Pe} \frac{\partial^2 c^*}{\partial x^2^*} - \frac{\partial c^*}{\partial x^*}.$$  \hspace{1cm} (5)

where the Peclet number is defined as $Pe = UL/D^*$. The dimensionless boundary condition of (5) is then:

$$c^*(t^*,0) = \begin{cases} 1 & 0 \leq t^* \leq \alpha/2 \\ 0 & \alpha/2 < t^* \leq 1/2 \end{cases}.$$  \hspace{1cm} (6)

Solving the (5) using separation of variables with (6) and $c^*(\infty) = \alpha$ results to the transient behavior of the concentration profile along the mixing channel:
where $j$ is the imaginary unit, $\Re$ indicates the real component of a complex number. The concentration distributions along the mixing channel at different Peclet numbers are depicted in Figure 3. Figure 3 shows clearly that only a short mixing channel is required if the Peclet number is small, that means either a small mean velocity $U$ or a short characteristic segment length $L$. A short segment length can be realized by or a short switching time $T$ or a high switching frequency $f=1/T$. Sequential segmentation can achieve different final concentrations simply by adjusting the switching ratio.

3. Device Fabrication and Experimental Setup

Our micro mixer was fabricated using a simple polymeric technique. The device was formed by five polymer layers, which are micro machined by a CO$_2$ laser. Fig. 2(a) depicts the design concept of the mixer. The first polymer layer is the cover for optical access in later experiments. The mixing channel is defined by the second layer. The channel height is fixed by the layer thickness of 100 $\mu$m. The channel width is 1 mm. The third layer defines the inlet channels for the solvent and solute flows. The valve seats in form of two rubber disks are embedded between layer 4 and layer 5. External actuation from the two solenoid will close the inlet valves. This design allows the valves to be opened automatically by the inlet pressures. Layer 5 contains the fluidic access for the two inlets and the outlets. All layers are bonded together by hot lamination (Aurora LM-450HC). Fig. 2(b) shows the complete experimental setup with two external solenoid actuators.

In our experiments, the flow rates at all the inlets were kept constant at 1.5 ml/hr. Two identical syringes were filled with diluted dye as well as DI water and placed on a syringe pump (Cole-Parmer 74900-05, 0.2 $\mu$l/hr to 500 ml/hr, accuracy of 0.5%). The identical syringes make sure that all inlets have the same flow rate. In case of valve closure, the flow is diverted using T-pieces at the device inlets. For the mixing measurement, de-ionized (DI-) water was used as solvent. The solute is a aqueous solution of fluorescein disodium salt C20H10Na2O5 (Acid Yellow 73 or C.I. 45350) diluted in water. The diffusion coefficient of this dye $D=1.8\times10^{-9} \text{ m}^2/\text{s}$ was determined experimentally in our previous works [8].

The main part of the optical system was a Nikon inverted microscope (Model ECLIPSE TE2000-S) with a set of epi-fluorescence attachment. The measured area was illuminated with a Mercury lamp.

![Fig. 1. Transient one-dimensional model for a micromixer with sequential segmentation](image-url)
For the measurement an epi-fluorescent attachment of type Nikon B-2A was used (excitation filter for 450-490 nm, dichroic mirror for 505 nm and an emission filter for 520 nm). Concentration images were recorded by a DVD-based camcorder (Sony DCR-DVD803E). The moving images are recorded and subsequently transferred to a personal computer for further evaluation.

\[ a \]

Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
Rubber discs

(a) (b)

Mixer
Inlet 1
Inlet 2
Outlet
Solenoid actuators

Fig. 2. Transient one-dimensional model for a micromixer with sequential segmentation

4. Results

The experimental results showed that the valves were able to control the mixing ratio, \( a \) in Eq. (7), by adjusting the pulse width ratio of the drive voltages for the two solenoid actuators. Figure 3 shows the measurement results of the concentration field at the entrance, at the middle and at the end of the mixing channel. The results show that the concentration field near the end is more homogenous if the mixing ratio is around 0.5 (see cases in Fig. 3(b) and Fig. 3(c)). This effect can be explained by the short closing time, which may lead to leakage at the particular inlet.

The corresponding probability density functions (PDF) at the different switching ratios are depicted in Fig. 4. Two peaks in the PDF mean the liquids do not mix well.

5. Conclusions

This paper reports the theory, fabrication and characterization of a micromixer based on sequential segmentation. The micromixer was fabricated using four polymeric sheets, which are micromachined by a laser beam. Hot lamination bonds all four layers and forms the mixing channel as well as the valve chamber. The mixer used two active valves for its inlets. The valve was actuated by two external solenoid actuators, which are driven by a switching circuit. Experimental results show that a desired mixing ratio can be achieved by selecting the corresponding switching ratio. Higher switching frequency does not mean a better mixing quality, because the dynamic characteristics of the valves and the flow in the mixing channel.
Fig. 3. Concentration distribution at the entrance, at middle and at the end of the mixing channel with different mixing ratios; flow rate at $\alpha=1$ is 1.5 mL/hr; switching frequency is 2 Hz.
Fig. 4. Probability density functions at the end of the mixing channel with different mixing ratios; flow rate at $\alpha=1$ is 1.5 mL/hr; switching frequency is 2 Hz.

References

[1]. N. T. Nguyen, Z. Wu. ‘Micromixers – a review’. Journal of Micromechanics and Microengineering, 2005, 15, R1.
[2]. V. Hessel, S. Hardt, H. Lowe, F. Schonfeld, Laminar Mixing in Different Interdigital Micromixers: I. Experimental Characterization, AIChE Journal, 49 (2003) 566
[3]. L. D. Deshmukh, A. P. Pisano, Continuous micromixer with pulsatile micropumps, In Technical Digest of the IEEE Solid State Sensors and Actuator Workshop (2000) pp. 73-76
[4]. T. Fujii, Y. Sando, K. Higashino, Y. Fujii, A plug and play microfluidic device, Lab Chip, 3 (2003) pp. 193.
[5]. U. T. Okamoto, H. O. Kitoh, New methods for increasing productivity by using microreactors of planar pumping and alternating pumping types, Chemical Engineering Journal 101 (2004), pp. 57.
[6]. R. Aris, On the dispersion of solute in a fluid flowing through a tube, Proc. Roy. Soc., A235 (1956) pp. 67.
[7]. H. Brenner, D. A. Ewards, Macrotransport Processes (1st edition, Butterworth-Heinemann, Boston, MA, 1993)
[8]. Z. Wu, N. T. Nguyen, X. Huang. Non-linear diffusive mixing in microchannels: theory and experiments, Journal of Micromechanics and Microengineering, 14 (2004) pp. 604.