Numerical and Experimental Mixing Studies in a Split and Recombine Micromixer with Ellipse-Like Micropillars

Nhut Tran-Minh[1,2], Erik Andrew Johannessen[1], and Frank Karlsen[1]

[1] Buskerud and Vestfold University College, Raveien 215, 3184 Borre, Norway
[2] Norchip AS, Industriveien 8, N-3490 Klokkarstua, Norway

Abstract— **A passive planar micromixer with rapid mixing has been successfully demonstrated by simulations and experiments. The structure of this micromixer contains ellipse-like micropillars in the main channel. Adding micropillars to micromixer will reduce the diffusion distance of the fluids. So, this type of design can improve mixing efficiency.**

Keywords— **Passive mixing, splitting and recombination, computational fluid dynamics, absorbance test.**

I. INTRODUCTION

Miniaturized systems, such as lab-on-a-chips system (LOCs) and micro-total analysis systems (μ-TAS) have played an increasing role in the research and commercialization because of their low sample consumption, low cost, and rapidity of the analysis. Due to mixing fluids uniform for analysis, micromixer becomes one important component in miniaturized systems. Passive micromixers require no external energy for mixing, whereas active micromixers require external energy. These external energies can be pressure, temperature, electrohydrodynamics, dielectrophoretics, electrokinetics, etc. [1]

In this study, a simple and low cost splitting and recombination micromixer with ellipse-like micropillars was investigated. The efficiency of the proposed micromixer is shown in numerical results and is verified by measurement results.

II. MICROMIXER DESIGNS

Fig.1 shows the design of the mixing unit with ellipse-like micropillars in splitting and recombination (SAR) micromixer. The term ellipse-like micropillar is an element having the shape of an ellipse [2]. When the main stream reaches the ellipse-like micropillar, the stream is then split into two separated streams on the smaller channels. Afterward, two streams within smaller channels are merged as one stream. The contact interface of fluids is increased throughout each ellipse-like micropillar so that the mixing effect is enhanced.

SAR micromixer includes 3 inlet channels (I_1, I_2, I_3), one outlet channel (O_1), and some mixing units. The geometry of SAR micromixer with ellipse-like micropillars is shown in Fig.2a.

In order to evaluate the mixing phenomena, the outlet channel of SAR micromixer is split into four sub-channels. Hence, the second design of micromixer in this study includes 3 inlet channels (I_1, I_2, I_3), four outlet channels (O_1, O_2, O_3, O_4), see Fig.2b. Absorbance test is conducted at the outlets of these sub-channels.

III. NUMERICAL SIMULATIONS

Computational fluid dynamics software (COMSOL Multiphysics) was used to solve the governing equations. The governing equations, such as the Navier-Stokes equation, the continuity equation, the diffusion-convection equation can be described in the following:

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = -\frac{1}{\rho}\nabla p + \nu\nabla^2 u \quad (1)$$

$$\nabla \cdot u = 0 \quad (2)$$

$$\frac{\partial c}{\partial t} + (u \cdot \nabla)c = D\nabla^2 c \quad (3)$$

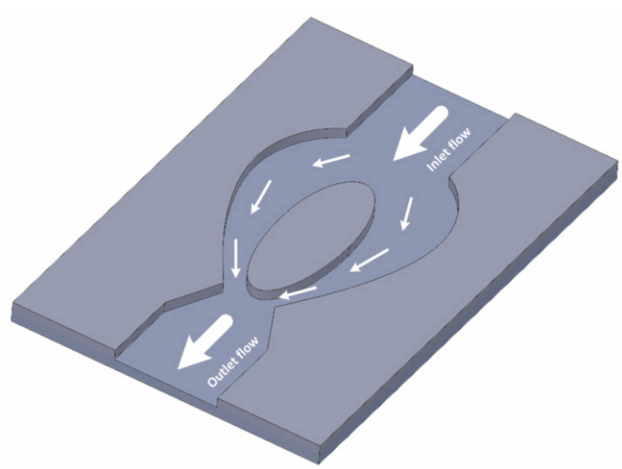

Fig. 1 Mixing unit of SAR micromixer

V. Van Toi and T.H. Lien Phuong (eds.), *5th International Conference on Biomedical Engineering in Vietnam,*
IFMBE Proceedings 46, DOI: 10.1007/978-3-319-11776-8_3

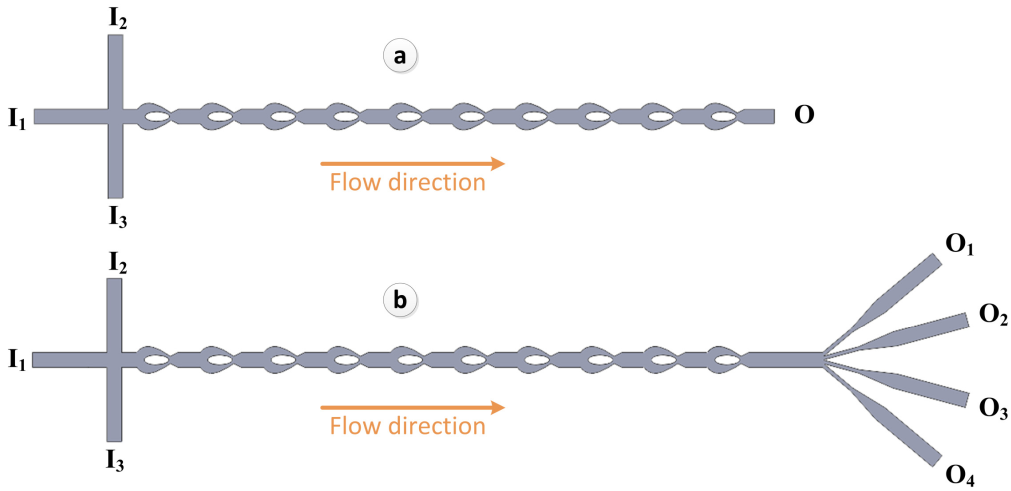

Fig. 2 SAR micromixer

In which appear velocity u, density ρ, pressure p, kinematic viscosity ν of the fluid, c and D are concentration and diffusion constant of the species, respectively. In this paper, the value of ρ and ν are 1000 kg.m^{-3} and 0.001 kg.s.m^{-1}, respectively. The diffusion coefficient of the water-ink mixture is 3.23×10^{-10} m^2.s^{-1} [3]. During simulation, the incompressible steady flow condition was assumed. No-slip condition is applied to the boundary on the wall. The fixed flow rate was set to the inlet of the micromixer. The fixed pressure (p = 0) was set to the outlet of the micromixer. The normalized molar concentration of the species was set 1 for inlet I_1, 0 for inlet I_2 and I_3. To investigate the mixing process, simulations were performed at nine flow rates as listed in Table 1. Flow rate at inlet I_2 and I_3 were kept at 0.02ml/min.

Table 1 Flow rate and *Re* value of numerical simulation

Case	Flow rate at I_1 (ml/min)	Reynolds number
i	0.020	0.952380952
ii	0.025	1.190476190
iii	0.030	1.428571429
iv	0.035	1.666666667
v	0.040	1.904761905
vi	0.045	2.142857143
vii	0.050	2.380952381
viii	0.055	2.619047619
ix	0.060	2.857142857

Assume that the flow rates of the fluids at the entrance I_1, I_2, I_3 of SAR micromixer are Fl_1, Fl_2, Fl_3, respectively. The concentration of the fluids are C_1, C_2, C_3. So, the concentration of the fluid at the outlet channel C_T can be derived in the following:

$$C_1 \times Fl_1 + C_2 \times Fl_2 + C_3 \times Fl_3 = C_T \times Fl_T \quad (4)$$

$$C_T = \frac{C_1 \times Fl_1 + C_2 \times Fl_2 + C_3 \times Fl_3}{Fl_T} \quad (5)$$

$$C_T = \frac{C_1 \times Fl_1 + C_2 \times Fl_2 + C_3 \times Fl_3}{Fl_1 + Fl_2 + Fl_3} \quad (6)$$

where Fl_T is the flow rate of the fluid at the outlet of SAR micromixer .

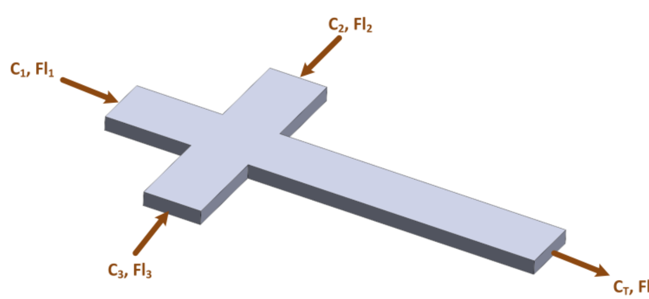

Fig. 3 Concentration and flow rates at the inlet/outlet channels

When C_1 is one, C_2 and C_3 are zero, the equation (6) can be rewritten:

$$C_T = \frac{Fl_1}{Fl_1 + Fl_2 + Fl_3} \quad (7)$$

The equation (7) will be used to verify the results from numerical simulations.

IV. EXPERIMENTAL PROCEDURES

A. Microfabrication

The negative photoresist SU-8 50 (MicroChem Corp., MA, USA) was coated on a bare silicon wafer with a thickness of 100µm. The resist must be firstly baked at 65°C for 2 minutes. Afterward, the temperature of the resist layer should be increased to 95°C and maintained at this temperature for 30 minutes.

The SU-8 thin film with thickness of 100µm was contacted with a photomask and exposed to UV light with a dose of 600 mJ/cm^2. The unexposed SU-8 was removed in SU-8 developer (MicroChem Corp., MA, USA) (see Fig.4a).

The rigid SU-8 mold was coated with Polydimethylsiloxane (PDMS, Sylgard 184, Dow Corning, USA) (see Fig.4b). The PDMS was degassed to remove air bubbles, then it was cured in a leveled oven at 65°C for 3 hours. The PDMS was cut and peeled off from the SU-8 mold with tweezers. Both PDMS and glass substrate were treated with O_2 plasma (see Fig.4c), and placed on a hotplate at 65°C for 30 minutes to complete the bonding process (see Fig.4d).

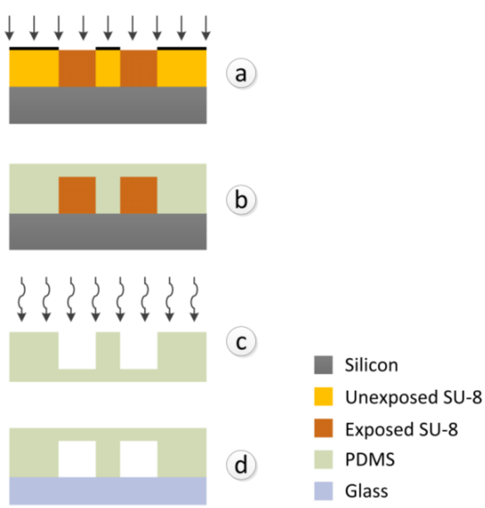

Fig. 4 Process flow of microfabrication

B. Inspection of Fluidic Mixing

The fluid flow system consists of three syringe pumps to supply two kinds of fluids into SAR micromixer. One fluid is pure water and the other is a mixture of 92 wt% pure water and 8 wt% red food dye (Idun Industri AS, Norway).

The samples at the outlet of SAR micromixer in both designs (see Fig.2), were transferred to 96-well microplate for conducting an absorbance experiment. A multidetection BioTek (Synergy 2, USA) was used to determine the absorbance spectrum of a sample solution.

V. RESULTS AND DISCUSSION

The microscopic images of the fabricated micromixers are illustrated in Fig.6. The main channels of micromixer have a width of 201µm and a depth of 92µm. The width of each sub-channel is 52µm.

According to our results (see Fig. 7), the model which was used in numerical simulations gives a good prediction of mixing performance of SAR micromixer. When the flow rate of the fluid at the inlet 1 was increased, the amount of red food dye was mixed with pure water was also increased. Hence, the concentration of the fluid at the outlet channel was also increased.

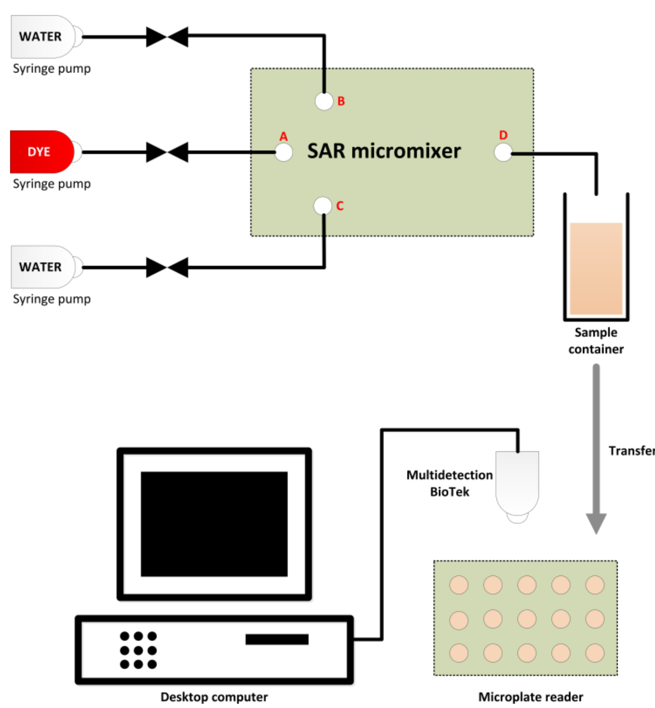

Fig. 5 Schematic of the experimental setup

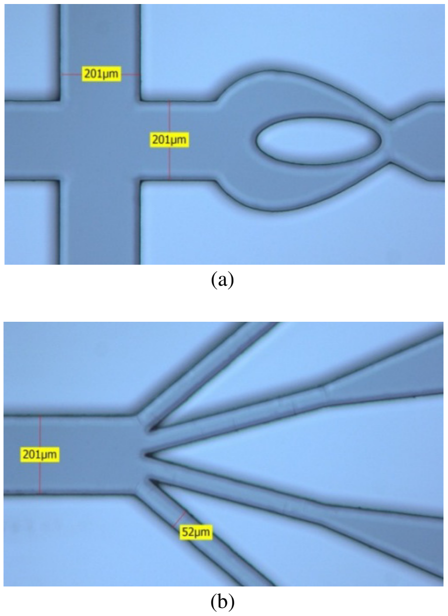

Fig. 6 Microscopic images of the SAR micromixer. (a) The junction of three inlet channels. (b) Four sub-channels.

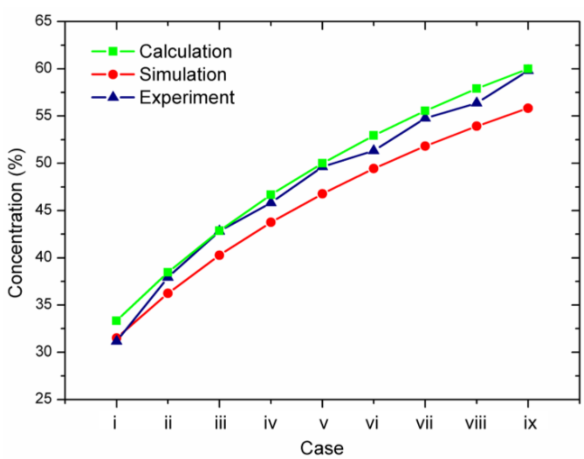

Fig. 7 Outlet concentration of SAR micromixer in different cases

In the second design (see Fig.2b), the fluids at the outlet O_1, O_2, O_3, O_4 were collected and tested separately. The results from absorbance test are listed in Table 2.

At the same flow rate of 0.004ml/min, the concentration of the outlets of four sub-channels are nearly the same. It means that the high mixing efficiency of the fluids can be achieved at this flow rate. When the Fl_1 was slightly increased, Fl_2 and Fl_3 were kept at 0.004ml/min, the concentration of outlets O_2, O_3 increases, the concentration of outlets O_1, O_4 decreases. So, the mixture of the outlet of SAR micromixer is not homogeneous. With these tests, the operation condition of SAR micromixer can be known.

Table 2 Concentration of the fluid at the outlet of each sub-channel

Fl_1 (ml/min)	O_1	O_2	O_3	O_4
0.004	18.16 %	20.65 %	19.35 %	17.57 %
0.006	11.13 %	54.26 %	49.05 %	6.56 %
0.008	3.62 %	55.15 %	49.09 %	6.67 %
0.010	6.78 %	58.72 %	54.63 %	7.75 %
0.012	4.67 %	55.41 %	51.80 %	2.81 %

VI. CONCLUSIONS

According to the numerical and experimental results, this splitting and recombination micromixer with ellipse-like micropillars shows high mixing efficiency can be achieved at low Reynold number. The homogeneity of SAR micromixer was studied by absorbance test. Due to the advantages of SAR micromixer, such as simple and low cost, proposed micromixer may be ideal for a rapid and optimal collection and mixing related sample preparation of biological fluids.

ACKNOWLEDGMENT

This research work is supported by the Research Council of Norway and Norchip AS (Norway). The Research Council of Norway is acknowledged for the support through the Norwegian Micro- and Nano-Fabrication Facility, NorFab (197411/V30).

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

1. Nguyen, N.T, Wu, Z.: Micromixers—a review. J. Micromech. Microeng. 15, R1-R16 (2005).
2. Tran-Minh, N., Dong, T., Su, Q., Yang, Z., Jakobsen, H., Karlsen, F.: Design and optimization of non-clogging counter-flow microconcentrator for enriching epidermoid cervical. Biomed. Microdevices 13, 179-190 (2011).
3. Lee, S., Lee, H-Y, Lee, I-F, Tseng, C-Y: Ink diffusion in water. Eur. J. Phys. 25, 331-336 (2004).

The address of the corresponding author:

Author: Nhut Tran-Minh
Institute: Buskerud and Vestfold University College
Street: Raveien 215
City: Borre
Country: Norway
Email: Nhut.Tran-Minh@hbv.no