Numerical Study of Ferrofluid Mixing in A Double-Layer Magnetic Micromixer

Ran Zhou[1] (zhou970@pnw.edu), Athira N Surendran[1]

[1] Department of Mechanical and Civil Engineering, Purdue University Northwest
2200 169th Street. Hammond, IN, USA

Abstract

Microfluidics-based mixing has been widely used in various areas such as chemical engineering, biomedical engineering and materials science. The micromixer can be designated into two categories as passive and active method depending on the mixing principle. Magnetic mixing integrated into microfluidic system has been proven to be an efficient active method. Ferrofluid has been widely used as carrier medium in biological micromixer due to its advances of compatibility with bio-samples. Both permanent and electromagnet have been applied to actuate the mixing of ferrofluid, but the bulky size brings the problem that the precise manipulation is hard to be achieved. In this work, a magnetic micromixer with embedded microscale magnet was developed and the simulation of mixing performance and working mechanism were done by COMSOL Multiphysics. This investigation is of great significance to improve the magnetic efficiency on microscale.

Introduction

Microfluidics technique has recently been a significant tool in a wide range of areas such as chemical engineering, biological science and food industry [1]. The microfluidic system possesses the advantages that it is able to integrate various components into a single microdevice, making it portable and saving the consumption of reagents. The rapid mixing based on microfluids is playing an important role in different applications being chemical reactors, biomedical diagnostics, DNA analysis, and polymer synthesis.

Fluids behave differently on a micro scale compared to the macro scale. The characteristic of a fluid can be known by determining the Reynolds number of the fluid. Reynolds number determines if a flow is laminar or turbulent given a number of parameters, which are fluid viscosity, velocity and characteristic length of a channel. Turbulent flow does not exist naturally in the microfluidic channel because of the small channel diameter. In order for a flow to be turbulent, it has to meet three criteria, which are low fluid viscosity, high fluid velocity and a large characteristic length. Since the channel width is always small for all microfluidic channels, the flow inside the channel is laminar ($Re < 1$). To achieve the complete mixing between two fluids, turbulent flow is more desirable compared to laminar flow because it expedites the mixing time and shortens the length of channel needed for complete mixing. Since laminar flow is imminent in microfluidic channels, the main way for reagents and fluids to mix is through molecular diffusion, which is time consuming, requires a large sample size and a long channel.

According to the mechanism of physics, the micromixer can be classified into two categories which are passive and active micromixer. Passive micromixer mainly relies on the advection effect and does not require any external energy, while active micromixer depends highly on the external field for mixing generation. The design and fabrication of passive mixing is simple, but the mixing efficiency of active method is usually higher compared to passive mixing and more flexible to be manipulated. The external energy from acoustic field, electrokinetic field and magnetic field has been applied into active mixer, and among which, magnetic mixing has been proved to be more friendly to biological studies and cell viability [2-4]. Ferrofluid can be used in combination with external magnetic field to bond the cells with nano Fe_3O_4 particles for the isolation and enrichment of target bio-samples for the subsequent analysis in next stage [5-6]. Currently, most methods used for magnetic micromixers are based on electromagnets and permanent magnets [7-9], which are bulky, generate heat, leave a big footprint and not suitable for many biomedical applications. The cost of manufacture for a lot of micromixer designs are expensive, and the complex design of some micromixers makes it impractical for industrial use.

Hence, in the present study, a simple, low-cost and highly efficient micromixer using a microscale magnetic array is proposed for rapid and homogeneous mixing of ferrofluid and buffer flow. The microchannel and microscale magnet are located on different planes to induce magnetic mixing in three-dimension. Soft lithography method was chosen as the mode of manufacture because of the low cost and high resolution. A microscale magnet was created using a mixture of neodymium (NdFeB) and polydimethylsiloxane (PDMS) to generate a nonuniform magnetic field. Pressure driven flow is created using ferrofluid and distilled water, where ferrofluid is the magnetic fluid and distilled water is the nonmagnetic fluid. Ferrofluid is chosen as the working fluid because of its biocompatibility, which makes it suitable for biomedical and biochemical applications. The mixing performance between ferrofluid and distilled water was simulated by COMSOL at various magnetic field intensity.

Experimental Set-Up

From Figure 1 (a) and (b), the micromixer includes two layers: fluidic channel layer at top and micromagnet layer at bottom. The in-house fabrication method can be referred to Zhou's paper [10]. It can be seen from Figure 1 (c) that the micromagnet was fabricated vertically with respect to flow direction. The distilled water and ferrofluid EMG 408 (Ferrotec, USA) were injected from top and bottom inlets of microfluidic channel. In our work, a sharp interface existed at inlet which disappeared at the outlet meaning that ferrofluid mixed with distilled water after flowing past the micromagnet. The dimension of microfluidic channel and micromagnet is listed in Table. 1. As indicated in Figure 1 (d), two syringe pumps (Cole Parmer 74900) were used to control the flow of each stream separately and a high-speed camera (Photron, Japan) was applied to record the flow phenomenon inside microfluidic channel.

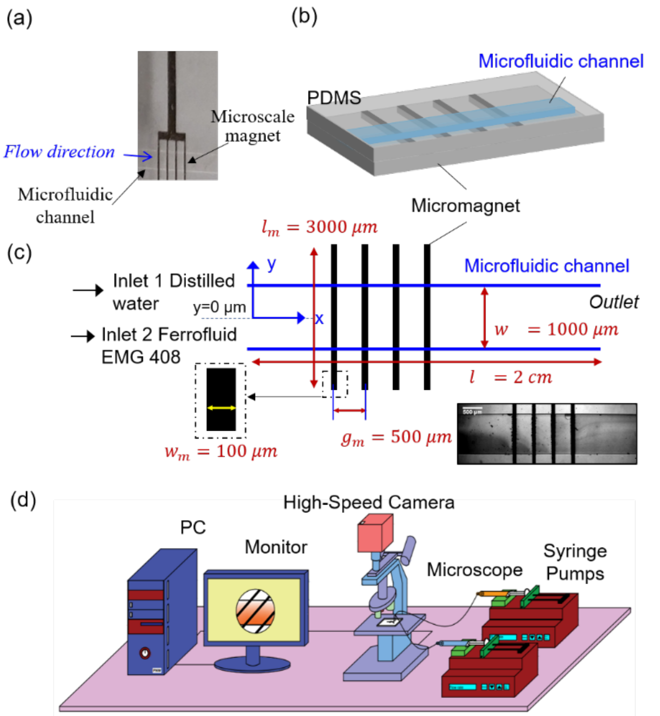

Figure 1. (a) and (b) are the photograph and schematic of the microdevice, respectively. (c) Dimension of microfluid channel and micromagnet. (d) Experimental system setup.

Simulation Methods

The simulation of microscale mixing was realized by two steps. The magnetic field was calculated by AC/DC module and then coupled the mixing phenomenon processed by laminar flow and species transport package. The flow in microfluidic channel can be considered as incompressible and described by the Navier-Stokes equation and continuity equation:

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

$$\nabla\cdot\boldsymbol{u} = 0 \quad (2)$$

where ρ denotes density of fluid, $\boldsymbol{u}$ denotes the fluid velocity, p is the pressure, η is the dynamic viscosity, and $\boldsymbol{f_m}$ denotes the magnetic force per unit volume acting on ferrofluid [11]

$$\boldsymbol{f_m} = \mu_0(\boldsymbol{M}\cdot\nabla)\boldsymbol{H} \quad (3)$$

where $\mu_0 = 4\pi \times 10^{-7}\ H/m$ is magnetic permeability of free space; $\boldsymbol{M}$ is the field-dependent magnetization; $\boldsymbol{H}$ is the applied magnetic field intensity.

During the mixing process, the properties of ferrofluid-water mixture kept changing, so the density and viscosity in Eq. (1) can be described as $\rho = c\rho_f + (1-c)\rho_w$ and $\eta = \eta_f e^{R(1-c)}$, where R is a viscosity parameter and $R = ln\left(\frac{\eta_w}{\eta_f}\right)$ $\rho_f, \rho_w, \eta_f, \eta_w$ denote the density and viscosity of pure ferrofluid and distilled water, respectively [12].

The mass flux in microfluidic channel can be expressed by equation of diffusion and convection, where the mass balance is

$$\nabla\cdot(-D\nabla c + c\boldsymbol{u}) = 0 \quad (4)$$

where D refers to the diffusion coefficient and c is the species concentration.

The simulation assumed the flow was fully developed at the inlet of microfluidic channel and the average velocities were set according to various total flow rates and consistent with the experimental conditions. The pressure was set to be zero at the outlet and the other boundaries were no-slip boundary conditions (B.C.). The magnetic force $\boldsymbol{f_m}$ was added as the volume force in laminar flow.

The concentration was calculated by Diluted Species Transport module. In our work, the concentration of ferrofluid at lower half was set as 1, and the upper half filled with pure water has the concentration as 0, so the B.C. was defined as

$$c_{inlet} = \begin{cases} 1, & y < 0 \\ 0, & y \geq 0 \end{cases} \quad (5)$$

The simulation geometry and the corresponding modules used in COMSOL, and the magnetic field line activated by micromagnet are indicated in Figure 2 (a) and (b), respectively. All the required parameters used in simulation are listed in Table. 1.

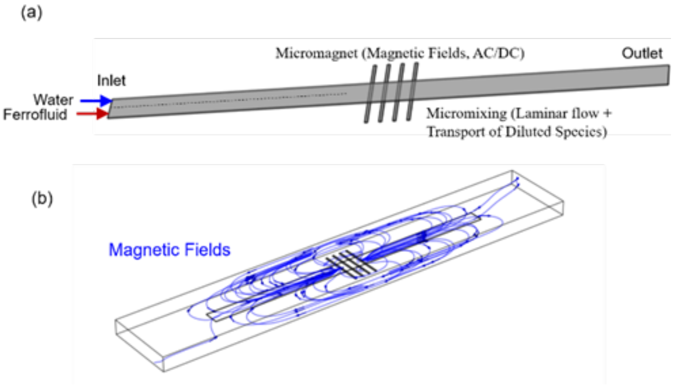

Figure 2. (a) Simulation geometry including microfluidic channel and micromagnet. (b) Magnetic field line generated by micromagnet.

Results and Discussion

Figures 3 (a1)-(a6) simulated the effect of magnetic field intensity H on the mixing performance. It is apparent that no mixing happened in Figure 3 (a1) when the magnetic field intensity is zero, so the magnetic force is zero to mix ferrofluid and distilled water. As the magnetic field intensity increased, the mixing performance became more homogeneous because of the stronger magnetic force. Mixing Efficiency (ME) is an important parameter to describe the mixing performance [13-14].

$$\mathrm{ME_{mixing}} = 1 - \sqrt{\frac{1}{N}\sum_1^N\left(\frac{\mathrm{c_i} - \bar{c}}{\bar{c}}\right)^2} \quad (6)$$

where $\mathrm{ME_{mixing}}$ is the mixing efficiency, $\mathrm{c_i}$ is the ferrofluid concentration within the cropped section at the outlet of microfluidic channel and $\bar{c}$ is the average ferrofluid concentration of cropped section. The mixing efficiency at the outlet of microfluidic channel in Figures 3 (a1)-(a6) was calculated under various magnetic field intensity and plotted in Figure 3 (b).

Table 1. Dimension of microdevice and fluid properties

Component and Fluid	Parameter	Symbol	Value
Micromagnet	Length	l_m	1000 μm
	Width	w_m	100 μm
	Depth	d_m	35 μm
Microfluidic Channel	Length	l	2 cm
	Width	w	1000 μm
	Thickness	d	35 μm
Original Ferrofluid [ref]	Density	ρ_f	1.07×10^3 kg/m^3
	Saturation Magnetization	M_s	6.6 mT
	Magnetic Susceptibility	χ_f	0.5
	Viscosity	η_f	$2\ N \cdot s/m^2$
Distilled Water	Density	ρ_w	1×10^3 kg/m^3
	Viscosity	η_w	$1\ N \cdot s/m^2$

It was found that when the magnetic field intensity increased, the mixing efficiency increased because the strong magnetic force accelerated the mixing between ferrofluid and distilled water. To explain the mixing process, Figures 3 (c1)-(c5) showing velocity magnitude correspond to Figures 3 (a2)-(a6) are discussed. It is found that when the flow approached the micromagnet, it was accelerated and thus the flow distribution width became narrow according to mass conservation; however, when the flow left the micromagnet, it was decelerated (Figure 3 (c2)), and thus the flow distribution became wider suggesting the ferrofluid was mixed with distilled water.

To further understand the mixing phenomenon, the pressure distribution along y direction at various magnetic field intensity H was calculated in Figures 4 (a1)-(a5). For all the magnetic field intensity in Figures 4 (a1)-(a5), the pressure decreased from y=-500 µm (lower channel wall filled with ferrofluid) to y=500 µm (upper channel wall filled with distilled water), explaining that the ferrofluid migrated to upper half of fluidic channel and mixed with distilled water.

Conclusions

The basic Multiphysics Module and AC/DC Module were applied in the modelling work using Navier-Stokes equation, convective diffusion equation and magnetic fields generated by the micromagnet. The simulation of microscale mixing can be achieved by two steps. The magnetic field was first calculated by AC/DC module and then coupled with the mixing phenomenon processed by laminar flow and species transport package. The intensity of magnetic field intensity was studied to characterize the effect on the mixing performance. The benchmark with four magnetic bars and total flow rate of 0.2 mL/h was developed and compared with experimental results indicating good agreement with each other.

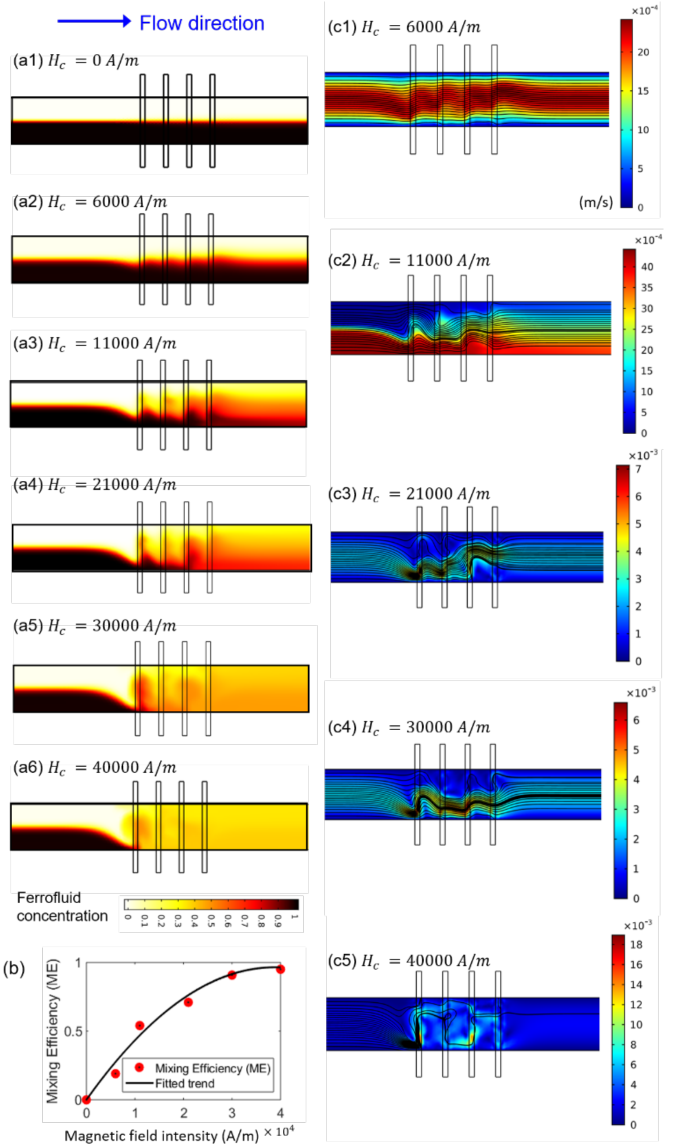

Figure 3. (a1)-(a6) are the progress of mixing at various magnetic field intensity. The total flow rate is Q=0.2ml/h for all the groups. (b) is the mixing efficiency corresponding to (a1)-(a6). (c1)-(c5) are the simulated distribution of velocity magnitude corresponding to (a2)-(a6).

The conclusion of this work includes 1) the new design provides an efficient method for high-throughput ferrofluid mixing, and 2) the increase of magnetic field intensity can accelerate the mixing performance of ferrofluid in microfluidic channel. This work enables the rapid magnetic mixing of ferrofluid on microscale and brings its potential to be applied in biomedical applications.

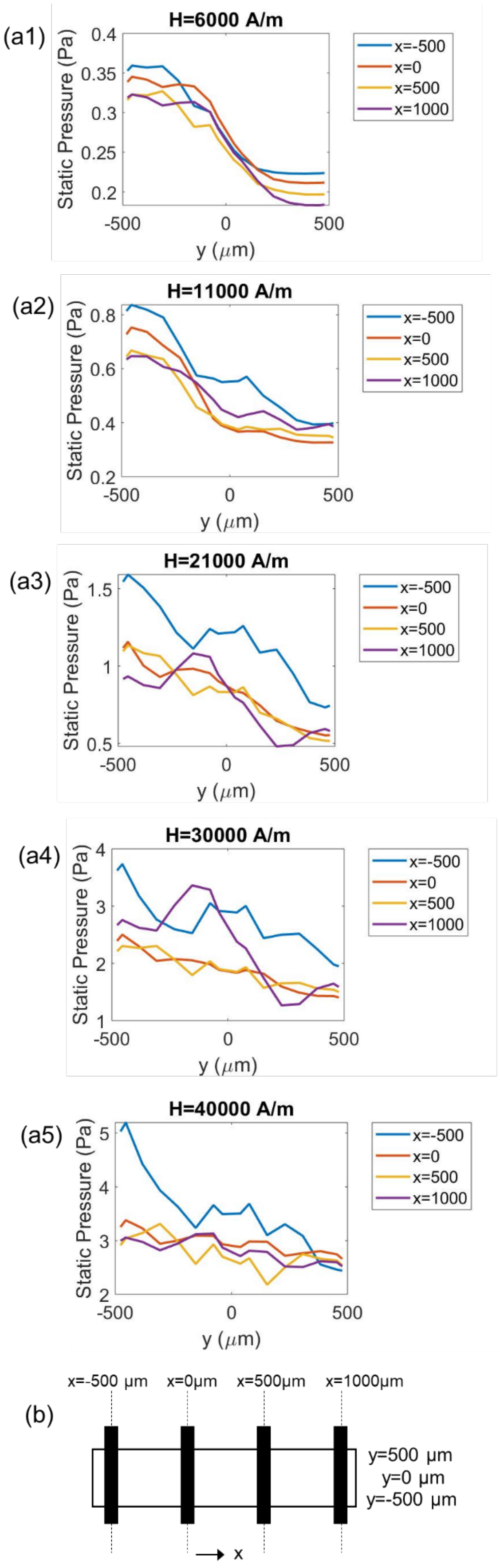

Figure 4. (a1)-(a5) are the pressure distribution corresponding to Figures 3 (a2)-(a6). The x, y coordinates can be referred to (b).

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