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Effects of Magnetic Particles Entrance Arrangements on Mixing Efficiency of a Magnetic Bead Micromixer

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Abstract: In this study, a computer code is developed to numerically investigate a magnetic bead micromixer under different conditions. The micromixer consists of a microchannel and numerous micro magnetic particles which enter the micromixer by fluid flows and are actuated by an alternating magnetic field normal to the main flow. An important feature of micromixer which is not considered before by researchers is the particle entrance arrangement into the micromixer. This parameter could effectively affect the micromixer efficiency. There are two general micro magnetic particle entrance arrangements in magnetic bead micromixers: determined position entrance and random position entrance. In the case of determined position entrances, micro magnetic particles enter the micromixer at specific positions of entrance cross section. However, in a random position entrance, particles enter the microchannel with no order. In this study mixing efficiencies of identical magnetic bead micromixers which only differ in particle entrance arrangement are numerically investigated and compared. The results reported in this paper illustrate that the prepared computer code can be one of the most powerful and beneficial tools for the magnetic bead micromixer performance analysis. In addition, the results show that some features of the magnetic bead micromixer are strongly affected by the entrance arrangement of the particles.

Keywords: Magnetic bead micromixer; Mixing efficiency; Particle entrance arrangement

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Introduction

Microelectromechanical systems (MEMS) industry has a great rate of development which has affected all fields of engineering and science. By means of this technology, it is possible to develop microstructure devices for intensifying mixing, heat and mass transfer, and also reactions in chemical processes [1]. Microfluidic mixer is the most important component in microfluidic devices [3]. Rapid mixing of two or more analytes is essential for many microfluidic systems used in biochemical analysis, immunoassays, and DNA analysis. Mixing in a short time is the main challenge in micromixers design. In micro scale devices where the Reynolds number is often less than 1, mixing is not a trivial task due to the absence of turbulence. In such circumstances, mixing relies merely on molecular diffusion which is a very slow phenomenon [4]. To resolve this problem many researchers have proposed several different kinds of micromixers with various techniques for improving mixing. There are two general groups of micromixers: passive and active. Passive mixers have no moving parts and don’t consume energy. In this kind of micromixers, mixing is achieved by virtue of their structure or topology alone [5]. Most passive mixers reported only show relatively high mixing efficiency at low flow rate

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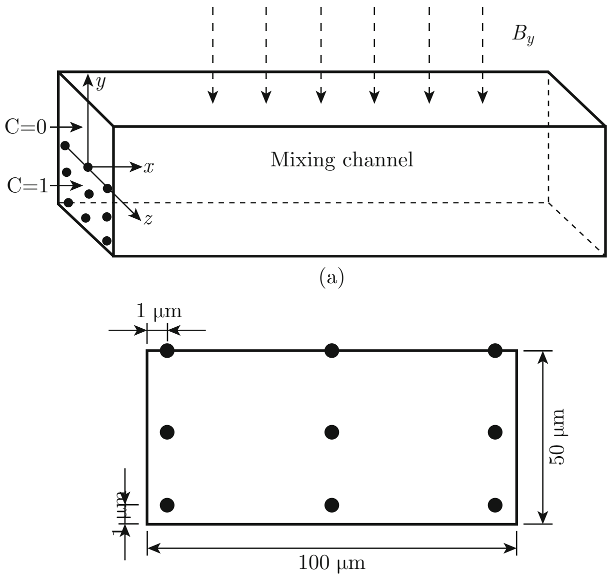
[5]. T-type micromixer, cross-shaped micromixer, 3D serpentine microchannel and microchannel with obstacles or patterned grooves are some examples of passive micromixers [2]. Active micromixers use external energy sources and can produce excellent mixing in the flow [5]. Ultrasound, acoustically induced vibrations, electrokinetic instabilities, small impellers, magnetohydrodynamic action and magnetic field are some examples for external energy sources which are used in active micromixers [5,6]. Magnetic field has many advantages which make it as a promising energy source to use in active micromixers. For example, objects inside a microfluidic channel can be manipulated by an external magnet that is not in direct contact with the fluid and In contrast to electric manipulation, magnetic interactions are generally not affected by surface charges, pH, ionic concentrations or temperature. There are generally two kinds of magnetic bead micromixers. One group of magnetic bead micromixer is designed to mix magnetic micro beads with a bio-fluidic solution to collect target cells or biomolecules (e.g. DNA, RNA and protein) by means of the special cover of the beads [4,8,11,12]. This active micromixer has some advantages over passive micromixer in magnetic bio-particle separation. For example by using lamination for mixing of particle laden fluids in a passive micromixer, clogging the narrow channels is quite probable [4].

The other group is designed for mixing two or more fluids [5,7,9,10,13]. The main idea in this kind of micromixer is to use momentum transfer between magnetic beads and fluid flow to induce some disturbances in the flow field and as a result mixing occurs. Suzuki *et al.* [8,12] presented a magnetic bead micromixer as a bio-particle separator and performed some numerical investigation based on one-way coupling assumption between particles and fluid by using the superposition numerical method. Zolgharni *et al.* [4] proposed a magnetic bead micromixer which was similar to Suzuki's micromixer basically. They performed a 2D study on that by using the superposition numerical method based on one-way coupling assumption between particles and fluid flow and find the optimum range of micromixer function according to some important micromixer's properties.

Rong *et al.* [9] presented a magnetic bead micromixer with the aim of fluid mixing which was composed of some magnetic microtips. Mixing in this micromixer is achieved by a rotational/vibrating force exerted on magnetic beads as the magnetic microtips are sequentially excited to produce a rotating magnetic field. Rida *et al.* [10] performed an experiment on a magnetic bead micromixer by using a microchannel and achieved 95% of mixing within 400 μm length of channel. Their design was based on the dynamic motion of a self-assembled structure of ferrimagnetic beads that are retained within a microfluidic flow using a local alternating magnetic field. Grumann *et al.* [13] introduced a novel magnetic bead micromixer in which magnetic beads are filled in a disk-based mixing chamber. The disk is exposed to a magnetic field created by a set of permanent magnets resting in the lab-frame. Wang *et al.* [5] presented a numerical work of a magnetic bead micromixer which was designed to mix fluid flows. This micromixer was composed of a microchannel and two electromagnets. Micro magnetic beads enter the microchannel by the fluid flows. By making an alternative magnetic field, magnetic micro beads do periodic motions and exert variant forces on fluid flow and agitate it; consequently mixing efficiency improves. They have done many numerical simulations and found an optimum Strouhal number for efficient mixing. The important point is they have assumed a specific determined particle entrance in all of their cases which is clearly a very restricting condition and it is not obvious that their results can be generalized to other determined position entrance or random arrangements. Le *et al.* [7] numerically investigated the characteristics of the flow and mixing in a magnetic bead micromixer which was the same as Wang's [5] micromixer. They studied about some important parameters of the micromixer such as Peclet number, switching frequency, number of magnetic particles, magnitude of magnetic force and initial condition of fluid flow. In this paper a magnetic bead micromixer is studied and the effect of particles entrance arrangement on the mixing efficiency is investigated, which was not mentioned in previous works. It seems that this parameter affect the mixing efficiency extensively.

Characteristics of the magnetic bead micromixer

The magnetic bead micromixer which is investigated in this study is similar to the Wang's [5] micromixer. In this kind of micromixer magnetic micro beads enter the microchannel by the water flow and are actuated by means of an alternating magnetic field which is strong enough to overcome drag force exerted from fluid to the particles. This magnetic force accelerates the particles perpendicular to the main flow stream and makes a secondary disturbing flow which improves the mixing efficiency. The microchannel in this study is 500 μm in length, 100 μm in width and 100 μm in height. It is assumed that all particles are spherical that each particle is 8.27×10^{-16} kg in mass and 1×10^{-6} m in diameter. Wang *et al.* [5] discussed about a magnetic field with an electromagnet source and stated that in a microchannel which is 100 μm in width, it is possible to exert up to 100 pN force on the particles in the microchannel. This important result is used in this study and no new investigation into the magnetic force is needed. A stream of fluid with a sample concentration equals to 1 enters from the bottom half of microchannel entrance and a stream of fluid with 0 sample concentration enters from the upper half of the microchannel entrance. Magnetic micro beads enter from the bottom half with a specific arrangement according to the situation. Schematic diagrams of the micromixer and Points of particles entrance In the case of determined position entrances are shown in Fig. 1 As shown in the Fig. 1(b), In the case of determined position entrances, magnetic particles enter the micromixer from the nine locations of the bottom half of the channel [5].



(a)

(b)

Fig. 1 Schematic diagrams of the (a) Micromixer; (b) Points of particles entrance in the case of determined position entrances at the bottom half of the micromixer entrance [5].

Theory and assumption

The numerical model that is used in this paper is called "point-volume" which is a branch of two-phase flow simulation models [15]. This model belongs to an approach that represents drag and lift forces instead of calculating them by using fine mesh around the object. For using this method there is a necessary condition: particle's dimensions should be smaller than the computational cell's dimensions. In this approach angular velocity could also be modeled. At limit, when the particle's volume fraction of dispersed phase is very small, particles are treated as "points". It is a very usual method that is used by many researchers such as [4,5,7]. In this situation particle's volume is assumed to be zero, therefore there is no angular velocity and the only equation that should be solved is the linear momentum equation. The fluid is assumed to be Newtonian incompressible isothermal liquid. The behavior of fluid is governed by incompressible continuity and Navier-Stokes equations [7,16],

$$\nabla \cdot V = 0 \tag{1}$$

$$\rho_f \left(\frac{\partial V}{\partial t} + (V.\nabla)\, V \right) = -\nabla P + \mu \nabla^2 V + f(r,t) \tag{2}$$

According to the point-volume model, f in Eq. 2 is the force that is exerted by a particle on the fluid element at point r and time t.

The mass transport equation which should be solved to obtain the sample concentration is described as [5],

$$\frac{\partial C}{\partial t} + V.\nabla C = D\nabla^2 C \tag{3}$$

In this equation C is the dimensionless concentration.

Mixing efficiency, e_{mixing}, at a cross-section of the microchannel is evaluated by the following parameter [5],

$$e_{mixing} = \left(1 - \frac{\iint_{Cross\ section} |C - C_{Ideal}|\, dA}{\iint_{Cross\ section} |C_0 - C_{Ideal}|\, dA} \right) \times 100 \tag{4}$$

where, A is the cross section area of the microchannel, C_{Ideal} is the ideal concentration which is 0.5 in this study and C_0 is the initial concentration which was only due to the molecular diffusion. A Dynamics equation of motion of magnetic micro beads which is used in magnetic bead micromixers is [17],

$$m_p \frac{dv}{dt} = F_d + F_m \tag{5}$$

$\boldsymbol{F}_d$ is the drag force and $\boldsymbol{F}_m$ is the magnetic force. Other forces can usually be neglected in magnetic bead micromixers studies [5,7].

$\boldsymbol{F}_d$ is calculated from the following equation [17],

$$F_d = \frac{1}{2} C_d \rho_f (V - v)\, |V - v|\, A_p \tag{6}$$

where C_d, the drag coefficient, depends on the Reynolds number. Since the Reynolds number in microfluidic application is usually below 1, it is not necessary to model turbulent flow. V is the velocity vector of fluid flow and v is the velocity vector of the particles. A_p and ρ_f are the cross-section area of the magnetic particles and the density of fluid respectively.

Boundary conditions and initial conditions

The micromixer inlet boundary condition is constant velocity and fluid flow enters the microchannel at 1 mm/s. The stream of fluid with dimensionless concentration equals to 1 enters from the bottom half of the channel and the stream with dimensionless concentration equals to 0, enters from the upper half of the channel. Magnetic beads enter the microchannel in two arrangements. In the first arrangement particle enter the microchannel from nine determined locations of the bottom half of the channel with a velocity equals to the local velocity of the fluid. In the second arrangement particles enter the microchannel at random locations of the bottom half of the microchannel entrance. The second arrangement is more similar to the actual conditions. The No-slip boundary condition is applied on all walls of the microchannel. At the outlet, constant pressure condition is used. Initial condition for simulating the magnetic bead micromixer, is an undisturbed fluid flow and concentration distribution which is achieved from the code in a steady condition. In the steady condition no magnetic particle enters the microchannel and no disturbance is induced to the fluid.

Numerical scheme and code abilities

A computer code for taking numerical tests is developed to calculate flow field, concentration distribution, particle's dynamic equations and fluid-particle interaction. Numerical method for calculating flow field and concentration distribution is three dimension unsteady simple method [16]. Particle's dynamics equation is integrated by using Cranck-Nicolson method [18]. Mass, momentum and particles dynamics equations are solved simultaneously to consider two-way coupling of fluid phase and solid phase. Interaction forces between fluid phase and solid phase are also improved at the same time. The numerical process continues until the solution of all parameters converges at one time step. Afterwards new time step iterations will start. The code is able to simulate a magnetic bead micromixer with a cubic geometry for an arbitrary magnetic force function with determined and random arrangements of particles entrance for any physically possible number density of particles. Flowchart of the numerical simulation at one time step is shown in Fig. 2.

Code validation

Two validation tests are done to ensure the code abilities and accuracy. One of them relates to motion of a single magnetic bead in a periodic magnetic field in a stationary fluid surrounding. A magnetic micro bead with properties which was mentioned in section 2 is actuated with a sine-like magnetic force in a stationary fluid surrounding. By using a mathematical method similar to [14], one dimensional particle's equation of motion in a periodic Sine-like function by assuming one-way coupling, is described as:

$$\frac{dv}{dt}+\frac{v}{\tau_v}=F\sin(\omega t) \tag{7}$$

$$v=\frac{-\omega F\cos(\omega t)+F/\tau_v\sin(\omega t)}{\omega^2+1/\tau_v^2}+\frac{\dfrac{\omega F e^{\left(-\frac{t}{\tau_v}\right)}}{\left(\omega^2+1/\tau_v^2\right)\tau_v^2}+\dfrac{\omega^3 F e^{\left(-\frac{t}{\tau_v}\right)}}{\left(\omega^2+1/\tau_v^2\right)}}{\omega^2+1/\tau_v^2} \tag{8}$$

where τ_ν is the relaxation time of the particle. Initial condition which is used to obtain Eq. 8 is $v(0)=0$.

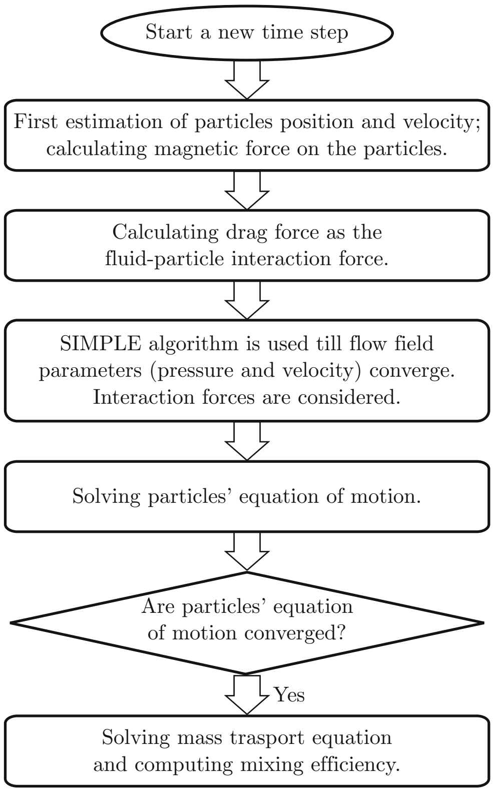


Fig. 2 Flowchart of the numerical simulation at one time step.

Velocity of a magnetic bead with properties which were mentioned in section 2 is studied numerically and analytically. The particle is actuated by a sine-like magnetic force. The equation of the force is $8.27\times10^{-3}\sin(10t)$ pN. This weak force does not agitate the fluid and Eq. 8 could be used as the analytical solution of the particle dynamics equation. In Fig. 3(a) numerical result from the code vs. the analytical solution is shown which are in good agreement.

Also one case of micromixer simulations from [5] is studied and compared with the reference's result. Properties of the micromixer are listed below:

Length= 0.001 m

Width = height = 0.0001 m

Magnetic bead's volume= 5.236×10^{-19} m

Magnetic force on particles= ±16.6 pN. in a step function manner with a frequency equals to 18.81/s

Volume flow rate of magnetic beads = 5.7×10^{-15} m^3/s

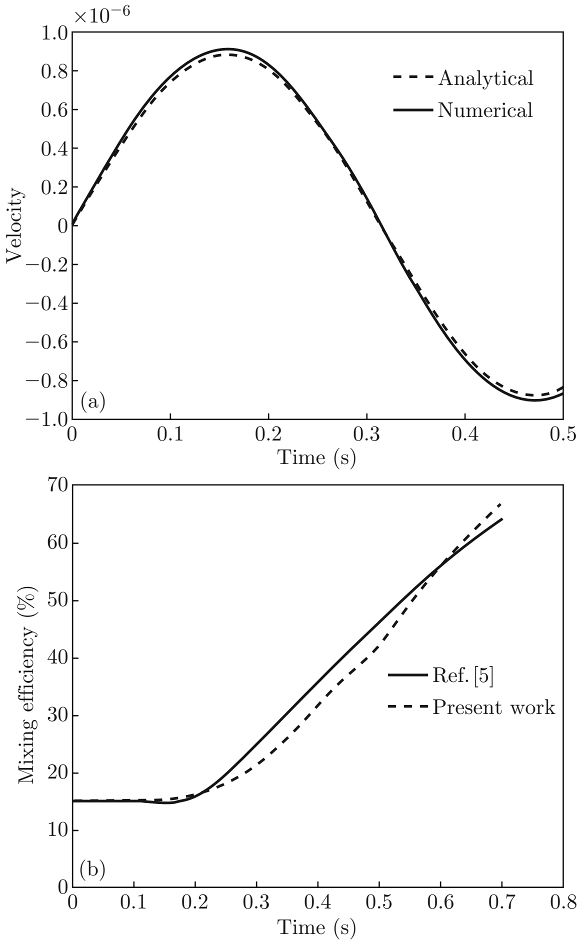


Fig. 3 (a) An analytical solution vs. a numerical solution for particle's velocity in a periodic magnetic field. (b) Mixing efficiency as a function of time at the micromixer outlet.

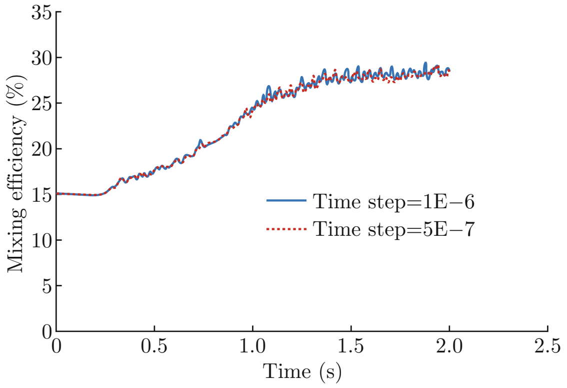


Fig. 4 Mixing efficiency as a function of time at the intermediate position of the micromixer.

The fluid in the micromixer is water. This test shows the correct functionality of the code and numerical methods of this study. Particles entrance arrangement is determined which is shown in Fig. 1(b). Fig. 3(b) shows the result of the simulation. A good agreement can be seen between two curves.

Magnetic bead micromixer simulation is an unsteady problem and it is necessary to choose a suitable time step for calculations. Several tests have shown that a 10^{-6} s time step is an appropriate selection; but for sureness a 5×10^{-7} s time step is also tested. Results of both conditions are plotted for a specific location of microchannel and are presented in Fig. 4. The excellent agreement of the results is a sure sign of correct time step selection.

Results and discussions

Some studies are done to illustrate the effect of particles entrance arrangement on mixing efficiency of a magnetic bead micromixer (e_{mixing}). There are two

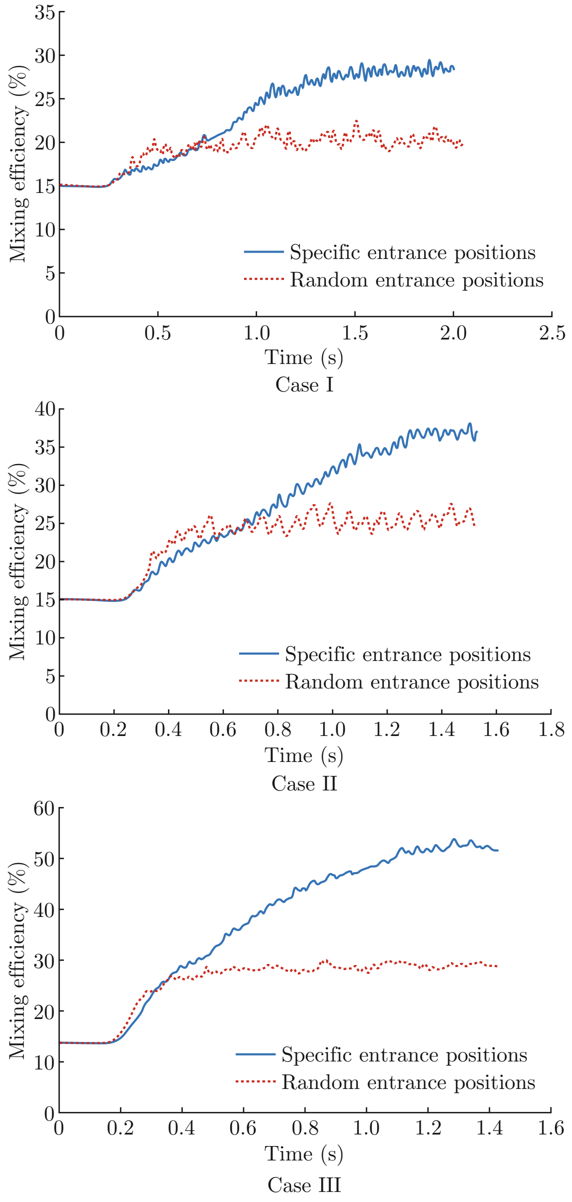


Fig. 5 Mixing efficiency as a function of time at the micromixer outlet.

general micro magnetic particle entrance arrangements in magnetic bead micromixers: determined position entrance and random position entrance. In the case of determined position entrances, micro magnetic particles enter the micromixer at specific positions of entrance cross section that is show in Fig. 1(b). However, in a random position entrance, particles enter the microchannel with no order. In all of the studies working fluid is water. Magnetic micro bead and microchannel dimensions have the same characteristics as mentioned in section 6. In this study three cases of particle flow entering the micromixer are considered (Case I: 500 particles/sec, Case II: 1000 particles/sec, Case III: 3000 particles/sec). In these three cases, magnetic force on the particles are 16.6sin(110t)pN, 16.5sin(100t)pN and 16.6sin(110t)pN, respectively.

Mixing efficiency as a function of time at the micromixer outlet is illustrated in Fig. 5 for case I, case II and case III. For two reasons mixing efficiency at the microchannel ending sections is more than the opening: diffusion has more time to mix the flow and particles can affects more the flow. After particles entrance, mixing efficiency is constant at every section of microchannel until particles perturbation affects reaches there. For example, mixing efficiency in case II is constant before 0.25 second and equals to 15%. According to Fig. 5, it is obvious that there is a large difference of mixing efficiency between determined position entrance and random position entrance arrangements in all three cases.

Figure 6 shows concentration contours before and after mixing in some sections and in the middle longitudinal plane of the microchannel, before and after the mixing process. As shown in this figure, before particles entrance to the micromixer, mass transfer and mixing is merely due to diffusion in the middle plane of the microchannel between two streams of fluids. Diffusion is a time consuming mechanism. Therefore, a longer microchannel results in more mixing. As well, Fig. 7 shows velocity contours in the applied magnetic force direction before and after the mixing process.

Conclusions

This investigation is done to numerically study the effect of magnetic particles entrance arrangement in mixing efficiency of a kind of magnetic bead micromixer. For this purpose a computer code is developed and validated by several tests. The studied cases are able to support the paper's idea properly. The results have proven that the particle entrance arrangement has an

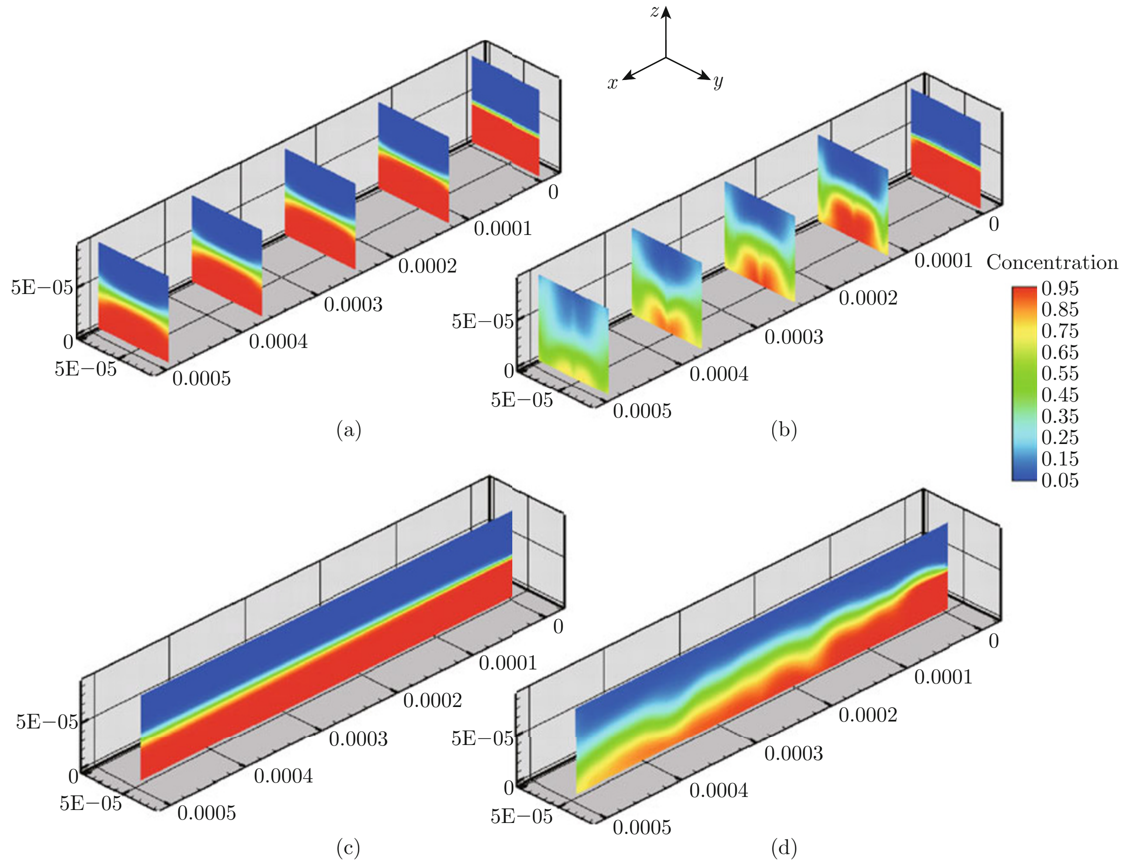


Fig. 6 Concentration contours (a) Before mixing process; (b) After mixing process; (c) In the middle longitudinal plane before the mixing process; (d) In the middle longitudinal plane after the mixing process.

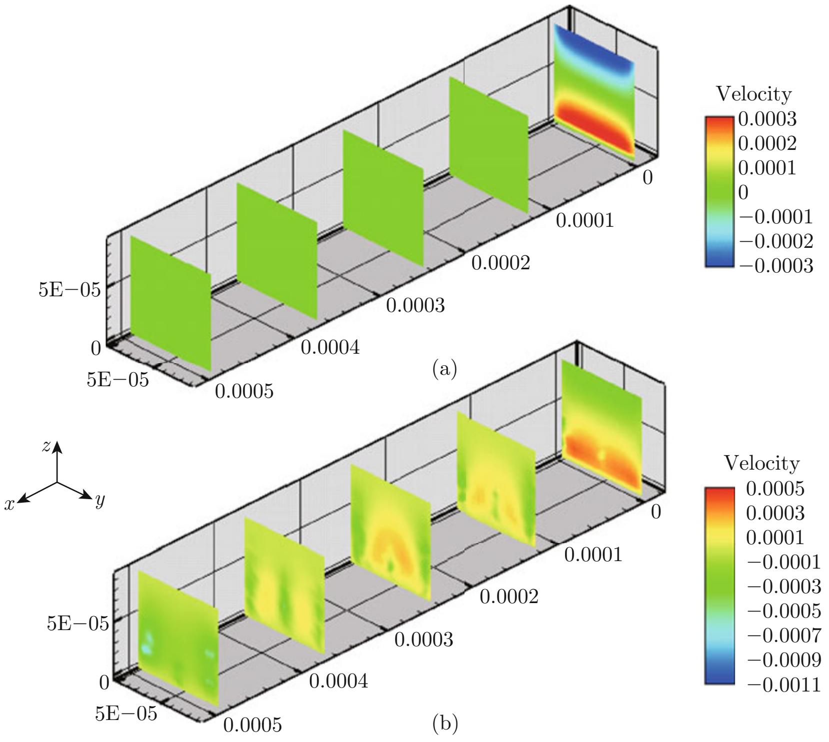


Fig. 7 Velocity contours in the applied magnetic force direction (a) Before mixing process; (b) After mixing process.

important role in mixing efficiency; for example in one case, the mixing efficiency increase in a random entrance arrangement is almost half of a determined case. This great difference shows the importance of the studied characteristic of the micromixer.

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