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Active Mixing in a Microchannel

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We investigate a minute magneto hydro-dynamic mixer with relatively rapid mixing enhancement experimentally and analytically. The mixer is fabricated with brass and polymethyl methacrylate (PMMA) layers. A secondary flow is generated by using the Lorentz force in the fluids. The efficiency of mixing is greatly improved due to the large increase of the contact area between two mixing fluids. The micro particle image velocimetry technique is employed to measure the fluid flow characteristics in the micro-channel. Numerical simulation is performed based on the theoretical model of the computational fluid dynamics and the electromagnetic field theory. The experimental results are in good agreement with the numerical results, which indicates that the mixing area is enlarged by the driving of Lorentz force and the mixing can be enhanced.

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Recently, a wide range of applications for the micro-fluidic systems have been found with the use of miniaturized analytical systems in the field of chemistry and biology, such as genomic and proteomic analysis, chemical reaction and micro flow transmission etc.[1] Two or more kinds of fluids are mixed in these applications. The flow is laminar due to the low Reynolds number in the micro-channel when the fluid is driven by pressure, therefore mixing in the micro-channel greatly depends on the diffusion. However, the diffusion coefficient of the liquid molecules is about $10^{-10}\,\mathrm{m^2/s}$, which results in a low mixing efficiency. In recent years, researchers have conducted a lot of researches both theoretically and experimentally on different micro-mixers to improve their efficiency.

The micro-mixers can be divided into active mixers and passive mixers. The principle of passive micro-mixers is to use special geometric shapes to make fluid flow transverse and disordered. The principle of active mixers is to use some active control to produce better mixing efficiency, including touching parts, pressure control, heat, the electro osmosis driver, ultrasonic, electric field, and magnetic field, etc.[2,3] The mixing efficiency of passive mixers is limited due to many restrictions such as the structure and manufacture. However, active mixer can avoid these restrictions. The electromagnetic hydrodynamic force mixer is such a kind of active mixers which have been studied for many years.

The minute magneto hydro-dynamic (MHD) phenomenon was first observed by Ritchie in 1833.[4] This MHD technique has been used to pump and control liquid metals in the field of plasma physics widely. One of the first demonstrations of MHD pumping of saline solutions in micro channels was presented by Jane and Lee in 2000.[5] So far, more and more researches have been performed theoretically and experimentally to improve the micro-mixing efficiency. These researches mainly focused on the effect of the Lorentz force on the fluid flow. The mixer designed by Jane and Lee, Lemoff and Lee, with the directions of Lorentz force along the axes of the pipes (the primary aim was to drive fluid) has little mixing effect.[6] In the mixers designed by Bau and Yi, with directions of Lorentz force perpendicular to the axis of the pipes, certain mixing effects by disturbing of the fluids were found.[7] Then in the mixer designed by Qian and Bau, the direction of the Lorentz can be tuned into the axes and the normal to the pipe, which can achieve the purpose of both driving and mixing.[8]

In this Letter, we improve the efficiency of micro-mixing. The electrodes at the mixer bottom are orthogonal in the axes of the pipe. The direction of the magnetic field is upward, then the direction of Lorentz force is perpendicular to the axis of the pipe. There are the outlet and inlet at both the ends of the micro pipe, respectively. Due to the action of the Lorentz force, the secondary flow and the eddy are formed, which makes the interface of the fluids fold and stretch. The interface becomes much longer and wider, which improves the efficiency of diffusion and mixing. Micro particle image velocimetry (micro-PIV) technology is used to measure the flow in the experiments. The theoretical model is developed and numerical simulation is conducted for the investigation of the MHD mixer. Our numerical results agree well with the experimental results, and show that the efficiency of mixing is improved.

Combined with the experiment, a mathematical model of the mixer should be established. We describe a three-dimensional model of the MHD stirrer. A rectangular duct is constructed with length L, width W and height H. A schematic depiction of the top view of the conduit is shown in Fig. 1. The x, y, and

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$z$coordinates indicate the conduit's axis, width and height, respectively. Several individually controlled electrodes are denoted by A, B, C, D and E. Here A, C, D are connected with the negative electrode of the dc power; B and D are connected with the positive electrode, the direction of current is opposite in the adjacent stages of AB, BC, CD and DE, as well as the directions of Lorentz force. The device is placed in a uniform and static magnetic field. The flux density of the magnetic field is $B = B\hat{e}_z$, where $\hat{e}_z$ is a unit vector in the z-direction. When the current is imposed on the solution, the Lorentz force is produced due to the interaction between the electric field and the magnetic field. According to Ohm's law, Lorentz force in the fluid can be written as

$$\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B} = \sigma(\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B}) \times \boldsymbol{B}, \tag{1}$$

where σ is conductance, $\boldsymbol{J}$ is current density, $\boldsymbol{E}$ is electric intensity, $\boldsymbol{V}$ is velocity vector, and $\boldsymbol{B}$ is magnetic field strength.

For incompressible and viscous flow, the Navier–Stokes equations can be written as follows:

mass conservation equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \tag{2}$$

momentum conservation equations

$$\frac{\partial u}{\partial t} + \nabla \cdot (u\boldsymbol{V}) = \nabla \cdot (\upsilon \nabla u) - \frac{1}{\rho}\frac{\partial p}{\partial x} + F_x, \tag{3}$$

$$\frac{\partial v}{\partial t} + \nabla \cdot (v\boldsymbol{V}) = \nabla \cdot (\upsilon \nabla v) - \frac{1}{\rho}\frac{\partial p}{\partial y} + F_y, \tag{4}$$

$$\frac{\partial w}{\partial t} + \nabla \cdot (w\boldsymbol{V}) = \nabla \cdot (\upsilon \nabla w) - \frac{1}{\rho}\frac{\partial p}{\partial z} + F_z, \tag{5}$$

where ρ and p refer to the density and pressure, respectively; u,v and w are the components of velocity in the x, y, z direction, υ is the dynamic viscosity coefficient, $\boldsymbol{V}$ is the velocity vector; F_x, F_y and F_z are the components of electromagnetic force, respectively.

The flow is non-slip at all solid boundaries:

$$u(x, \pm\frac{W}{2}, z) = u(x, y, 0) = u(x, y, H) = 0. \tag{6}$$

The inlet velocity and the reference pressure are uniform at the inlet,

$$u\Big(-\frac{L}{2}, y, z\Big) = U\widehat{e_x}. \tag{7}$$

The electric potential ψ satisfies the Laplace equation

$$\nabla^2\psi = 0. \tag{8}$$

The electric field strength vector can be expressed as

$$\boldsymbol{E} = -\nabla\psi. \tag{9}$$

According to the theory of the electric field, we have

$$\boldsymbol{E} = \frac{\boldsymbol{U}}{l} = E_x\hat{e}_x + E_y\hat{e}_y, \tag{10}$$

where $\boldsymbol{U}$ is the voltage, l is the distance between the two electrodes. Thus components of electromagnetic force can be calculated by

$$F_x = \sigma\left(E_yB_z - V_xB_z^2\right), \tag{11}$$

$$F_y = -\sigma\left(E_xB_z + V_yB_z^2\right). \tag{12}$$

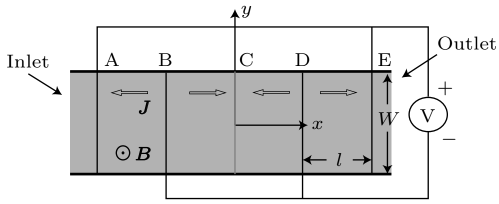

Fig. 1. The schematic illustration of micro-channel.

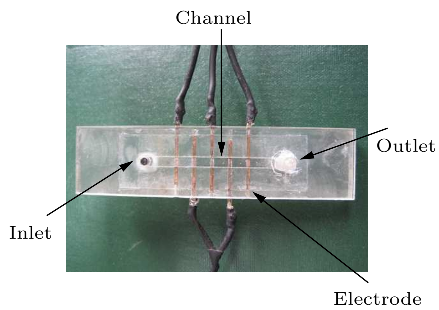

Fig. 2. The micro-channel used in the experiment.

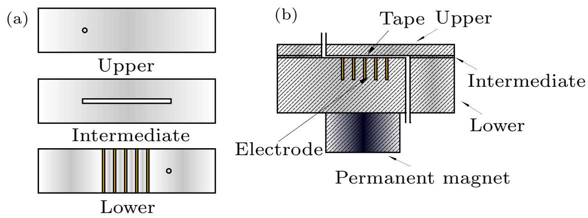

Fig. 3. Schematic diagram of the MHD mixer: (a) various layers of tapes, (b) a cross section of the MHD mixer.

Figure 2 shows the micro channel used in the experiment. Figure 3 presents the schematic diagram of the micro mixer. The mixer is a sandwiched structure with three plate layers. The length and width of mixer are 80 mm and 20 mm, respectively. The thickness of the upper plate is 1 mm. There is a round hole at one end of this plate. The thickness of the lower plate is 5 mm. There are some grooves at the plate and a round hole at the other end of this plate too. The width and the depth of the groove are 1 mm and 2 mm, respectively. A few copper rods are embedded in the grooves, which are used as electrodes. The surfaces of the copper rods are gold-plated. The thickness of the intermediate plate layer is 0.2 mm, a pipe is located in the middle part, the pipe's length is 40 mm and its width is 2 mm. The intermediate layer has glue on both sides, which can bond the upper layer and the bottom layer together. The hydraulic diameter of the micro channel is 360 μm. The round hole in the upper plate is used as inlet and the other in the lower plate as outlet. A cylinder permanent Neodymium magnet ($Nd_2Fe_{14}B$) is put under the device to produce the magnetic field. The dimensions of the magnet are significantly larger than the dimensions of the device to generate an approximately uniform magnetic field.

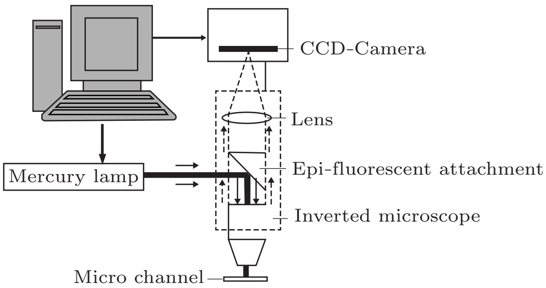

Fig. 4. The light path of the micro-PIV.

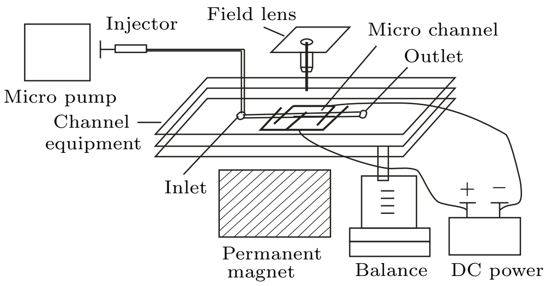

Fig. 5. Experimental device structure diagram.

Figure 4 shows the light path of the Micro-PIV. Fluorescence imaging technique is used in the experiments. The setup consists of four main components: an illumination system, an optical system, a coupled charge device (CCD) camera and a personal computer (PC). A mercury lamp is used as the illumination source for the fluorescence measurement. The wavelength of this mercury lamp is 532 nm. A Nikon inverted microscope (Leica DM ILM) with a set of epi-fluorescent attachments is used as the optical system. The filter cube is used to select the specific emission wavelength of the sample and to remove traces of excitation light. The interline transfer CCD camera (Dantec Floesecce 2 M) records the images. The magnification of the objective lens is 10×. The exposure time for recording the images is 4×10^4 μs. The camera can record two frames of the flow fields and then digitizes them in the same image buffer.

The experimental device designed to study the mixing process of the micro flow is shown in Fig. 5. In this device, the fluid flow is driven by the syringe pump (Longer pump LSP01-1A). The initial velocity is 2 mm/s, and the corresponding Reynolds number is 8.

NaCl saturated solution is used as the working medium. The conductivity of the solution is 13 s/m, and its viscosity is considered to be $10^{-6}\,m^2s^{-1}$, the voltage of dc power supply is 3 V, the magnetic field intensity is 0.4 T. Initially, a tracer is used to visualize the change of the interface and vortex. Then experiment is conducted using the Micro-PIV. The sampling rate of the CCD is 24 frames per second. The velocity field can be obtained by analyzing the images and the displacement of the tracer particles.

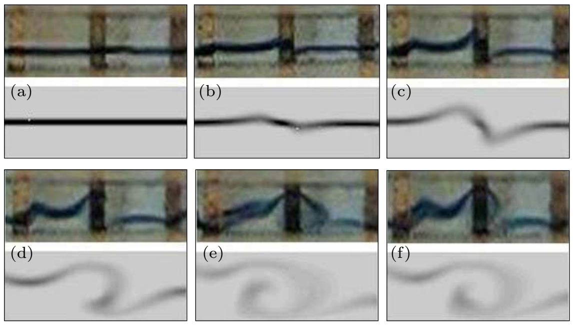

Fig. 6. The comparison of experimental (upper) and numerical (lower) interfaces variations with time within one period: (a) $t = 0$ s, (b) $t = 1$ s, (c) $t = 2$ s, (d) $t = 3$ s, (e) $t = 4$ s, (f) $t = 5$ s.

The software Fluent is adopted to simulate the mixing process in the micro-channel. The electric field is solved by user-defined scalar (UDS), and the Lorentz force is solved by user-defined function (UDF). The inlet velocity is 2 mm/s, the wall is no-slip condition. The hexahedron-structured grids are used to compute the flow field, and the number of grids is about 1100000. The unsteady, pressure-coupled, implicit solver is adopted. Figure 6 shows the comparison of experimental (upper) and numerical (lower) results for the variation of interface with time in one period.

At $t = 0$, no Lorentz force is applied, the interface between two fluids is a straight. The Reynolds number is 8, the flow is laminar with a clear interface in the experiment. The directions of the electric current of both AB and BC are opposite to each other, the Lorentz force at the stage of AB is in the direction of Y-axis positive but at the stage of BC, it is opposite. There is a transverse flow in the direction normal to the wall. With time going on, the transverse flow turns to be clearly and is shown in Fig. 6(b). Both the simulation and experimental results show that the staggered flow in the Y direction is gradually intensified when $t = 1$ s and $t = 2$ s. Due to the interaction between main flow and the staggered flow, the fluid interface becomes fold, as shown in Fig. 6(d). Then, due to the driving effect of pressure, the upper fluid moves to the upper wall, and the lower fluids moves down, a secondary flow appears, and a vortex is formed, the vortex center is near the B point as shown in Figs. 6(e)–6(f). The vortex makes the interface of two fluids deformed and stretched, which enhances the fluid mixing. Figure 7 indicates that the interface length increases very fast with the passage of time. At $t = 5\,\mathrm{s}$ the length of the interface is three times as the length at the initial time.

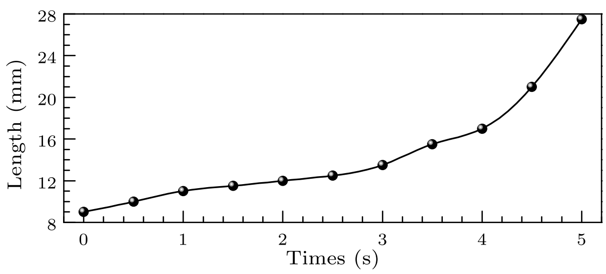

Fig. 7. The curve for the interface length changing with time.

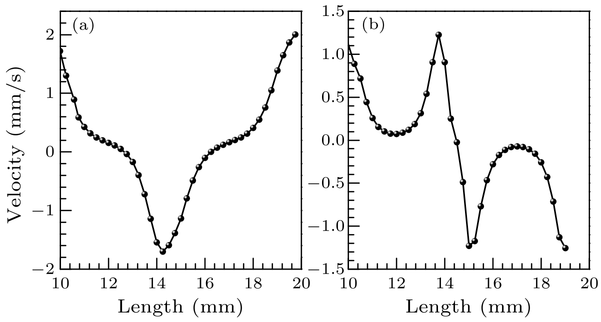

Fig. 8. The graph of the velocity vary with position: (a) the velocity in the direction of X, (b) the velocity in the direction of Y.

Figure 8 shows that the numerical results of the velocity at $y = 0$, $z = H/2$ in the period of AC stage. Due to the effect of the Lorentz force, in AB stage, the velocity in the direction of X decreases first and then rises in the opposite directions. So does the BC stage, but it is opposite for the BC stage. For the velocity in the Y direction, the direction of velocity in AB stage is also different from that in BC stage, but their magnitude is the same. The electricity density round the electrode is larger, which brings on the bigger Lorentz force. Thus in AB stage the velocity in the direction of Y decreases first and then rises. BC stage has the same trend.

In order to describe the mixing of the fluids, the mixing efficiency can be quantified using the following mixing efficiency index,

$$\sigma(x) = \left(1 - \frac{1}{C_\infty}\sqrt{\sum_{i=1}^{N}\frac{(C_{Ai} - C_\infty)^2}{N}}\right) \times 100\%, \quad (13)$$

where C_{Ai} is the mass fraction for the medium A in the ith cell,N is the number of the all cells. Furthermore, C_∞ is the mass fraction for the medium A, when the media completely mixing. In this study, the velocity and flux of two media are in equalization. Therefore, both the mass fractions of two kinds of media are $C_\infty = 0.5$, when the media are completely mixing, and the mixing efficiency is $\sigma(x) = 100\%$. However, for the initialization state, $\sigma(x) = 0\%$. The effect of time for mixing efficiency is shown in Fig. 9, where the B curve indicates the mixing efficiency of two media, after a period of flow (the AC stage depicted in Fig. 1). The C curve indicates that the mixing efficiency of two media, after two period of flow (the AE stage depicted in Fig. 1). Figure 9 shows that the mixing efficiency of two media is low at the stage of initialization, along with the time increasing, the mixing efficiency goes higher, after a period, $\sigma(x) = 57\%$, after two periods, $\sigma(x) = 76\%$, which means that the two media mix well after two periods.

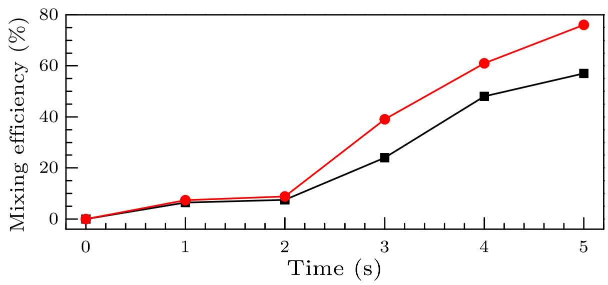

Fig. 9. The mixing efficiency versus time.

In summary, a magneto-hydrodynamic mixer that does not require any interior electrode has been developed. The mixer consists of a conduit filled with an electrolyte solution and the mixer is posited in the magnetic field. Ingenious arrangement of electrodes which are posited on the base of the conduits is used. By appropriate adjustment of the potential differences, the Lorentz force is generated in the designed direction, which then makes a secondary flow. The interface between the fluids is stretched largely, and at $t = 5\,\mathrm{s}$, the length of the interface is three times as the length that without Lorentz force and the mixing efficiency can reach 76%. A good mixing efficiency can be achieved. The mixer described here has some problems which contain bubble formation and electrode corrosion. Most of these problems can be reduced and eliminated altogether with appropriate selection of electrolytes, electrode materials.

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