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Analysis of MHD micro-mixers with differential pumping capabilities for two different miscible fluids

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ABSTRACT

In this study, newly devised is a magneto-hydrodynamic (MHD) micro-mixer capable of differential pumping of two different miscible fluids, and numerically investigated are the mixing performance and the mass flow rates of the two fluids. By artfully applying different potentials to different electrode pairs, Lorentz-force with different sizes can be created, driving the liquids in a desired direction for pumping, and inducing fluid circulation at a cross-section for mixing. The results show that the micro-mixer proposed in this study can achieve high mixing performance for electrolytes, together with differential pumping capabilities for the two different miscible fluids. The effect of the total difference in potential applied to the electrodes in pumping section on the mixing performance is numerically analyzed. Also, rectangular and H-shaped cross-sections for pumping section have been examined to explore the geometrical effect on the differential pumping capability.

1. Introduction

Microfluidic systems and devices, such as bio-detection, biotechnology, chemical reactors and environmental monitors, have emerged as a necessary tool for Laboratory-on-a-Chip (LOC) in different fields in the last two decades (Qian and Bau, 2005). A micro pump is needed to pump the fluid, such as blood, DNA, and saline buffers, in many different applications. Meanwhile, an efficient micro-mixing scheme is required to ensure that a full mixing of various reagents and species can be achieved within small space and time scales (Suh and Kang, 2010; Qian and Bau, 2009). In many microfluidic applications, the characteristic length associated with a micro-device is small so that the flows are laminar and well-ordered. Also, turbulence that may enhance mixing is not available.

For the fluid with low diffusivity the diffusion effect alone cannot provide a sufficiently fast way for mixing. The ratio of the rate of advection of the flow to the rate of molecular diffusion in a given mixing problem is measured by a non-dimensional number called the Peclet number for mass transfer. For fluids in microfluidic devices the Peclet number for mass transfer is often quite large, whose values are normally in the range of 10^3–10^5, so that mass transfer is expected mainly due to the advection rather than the diffusion. Therefore, the mixing process must be employed with artificial vortices created in the fluid flow (Affanni and Chiorboli, 2008).

Magneto-hydrodynamics (MHD) can provide us with a relatively convenient way for pumping and mixing. Firstly, an MHD micro-pump is one of the most important microfluidic systems that generates continuous flow without moving parts, and is suitable for biomedical applications. Recently, a number of researchers constructed MHD micro-pumps with silicon (Jang and Lee, 2000), ceramic substrates (Zhong and Bau, 2002), and polymer such as PDMS (Khan et al., 2016), and showed an efficient operation of the MHD pump fabricated with simple processes. Also, demonstrated is that these pumps are able to move liquids in micro-channels. Kosuke et al. (2014) experimentally and numerically studied MHD micro pumps for micro total analysis system (μ-TAS) with the applied magnetics flux density of 0.32 T, indicating that flow situation remains Poiseuille flow and Hartmann flow is not observed in the channel because of the weak MHD interaction. Das et al. (2013) illustrated unique applications of these pumps such as sample injection, fluid flow in a packed bed, and on-chip assay develop-

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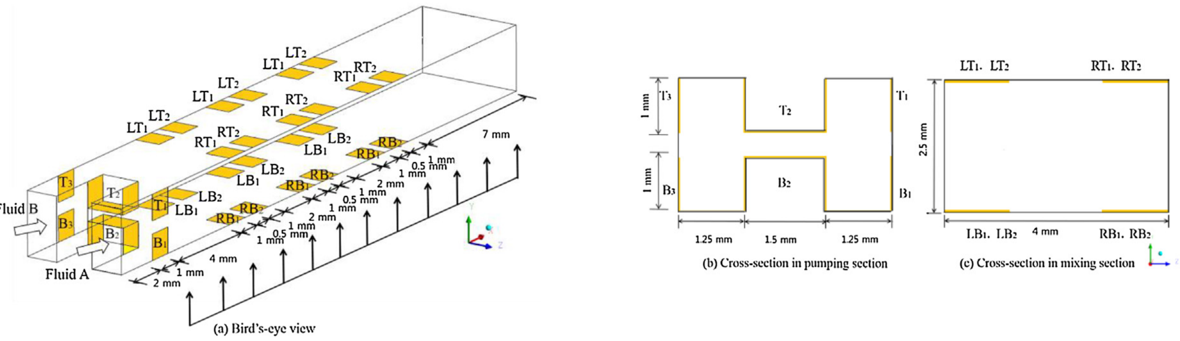

Fig. 1 – Duct geometry with three sets of electrodes in mixing section, and the coordinate system in Cases 1 and 2.

ment, all of which are relevant to point-of-care diagnostic device design and fabrication. Secondly, a great deal of attention has been paid to the design of more efficient mixers in microfluidic systems (Bau et al., 2001; Gleeson and West, 2002; Park and Song, 2012; Cerbelli et al., 2009), which triggers the formation of cross-sectional vortexes and velocity recirculation by exploiting the coupling of momentum transport with MHD effects. Gleeson and West (2002) examined the MHD mixing of two fluids in an annular micro-channel, using asymptotic analysis and numerical simulation. Park and Song (2012) numerically investigated the effect of multiple electrode pairs on the mixing performance of a micro-mixer using DC-biased ACEO, and found that the mixing performance strongly depends on both the number of electrode pairs and the flow rate of the working fluid.

Furthermore, the numerical method based on computational fluid dynamics has become an important and effective way to analyze MHD flows. Some investigations about the influence of design parameters of an MHD pump such as channel geometry and magnetic field strength have been performed by numerical method. Aoki et al. (2012) presented 3D numerical MHD simulation for Newtonian fluid as well as experimental data, where it is to be noted that the applied voltage, fluid's electric conductivity and magnetic field intensity have a significant influence on the velocity profile. Kiyasatfar and Pourmahmoud (2014) provided a code based on finite difference method, and investigated the effects of magnetic field strength, applied electric current and channel size on mass flow rate as well as thermal behavior, showing that for low electrical conductive fluid such as a PBS solution the maximum velocity increases linearly with an increasing in the magnetic flux density or in the applied electric current. Lee and Kang 2009 proposed a chaotic mixing mechanism suitable to the micro-mixer for LOC, and investigated the fluid flow by numerical simulation and experimental method. It was confirmed that the proposed micro-mixer was able to achieve high mixing efficiency. However, up to now an MHD micro-mixer with different pumping capabilities for two different miscible fluids has been rarely investigated.

In the present study, newly proposed is an MHD micro-device, where judicious application of different electric potentials to different electrodes can create a cross-sectional fluid circulation for mixing as well as can induce a differential pumping of two different miscible fluids, resulting in the mass flow imbalance of the two fluids. More precisely, the formation of cross-sectional fluid recirculation obtained in the mixing section of the proposed device leads to the enhancement of mixing performance, while with different potentials applied to the electrodes in pumping section the sizes of the Lorentz force exerted in the two different fluids in pumping section become different, consequently yielding different mass flow rates of the two different fluids.

In the first stage, five subcases are considered in Case 1 to examine the effect of the total potential difference in pumping section on the mixing index. Then, two cases (Cases 2 and 3) with different shapes of the cross-section in pumping part are numerically investigated to examine the effect the geometry and electrode locations on differential pumping capabilities. Furthermore, subcases with different potential differences of the electrodes in pumping section in Cases 2 and 3 for the two different miscible fluids are considered. The obtained results including the information of velocity, pressure, current density, and concentration of the fluid are visualized, with the values of mixing index, in detail. The effect of the ratio of the applied potential differences of the electrodes in pumping section for the two different miscible fluids on the ratio of the mass flow rates of the two different miscible fluids in Cases 2 and 3 is obtained.

2. Problem formulation

In the current study, newly proposed is an MHD mixer with H-shaped cross-section in pumping section and with rectangular cross-section in mixing section, as shown in Fig. 1. PBS (phosphate buffered saline) solution, which has been used in LOC as a working fluid in real experiments of the protein analysis, is to be used here. The properties of PBS solution are outlined in Table 1. Here, the combined effect of the voltage applied to six electrodes (denoted by T_1, T_2, T_3, B_1, B_2 and B_3) functions for pumping, and the arrangement of eight electrodes (denoted by LT_1, LT_2, LB_1, LB_2, RT_1, RT_2, RB_1, and RB_2) works for mixing. A situation with three sets of electrodes in mixing section is considered, based on the previous work (Xiao and Kim, 2016), which indicated that the degree of the fluid mixing performance increases with an increase in the number of the electrode set used. Uniform magnetic field is applied in the y-direction with the intensity of 0.2 T.

For the purpose of examining the mixing performance, five subcases with different input voltages of electrodes T_1, T_3, B_1 and B_3 in pumping section are considered in Case 1 (outlined in Table 2). Furthermore, in order to investigate the mass-flow imbalance of Fluid A and Fluid B, eight subcases with various input voltages of electrode T_2 are considered in Case 2, as shown in Table 4. The detailed discussion about the mass flow rates of Fluid A and Fluid B in each subcase of Case 2 is presented in Table 5. In Case 3, the cross section of the whole device is rectangular (including pumping section and mixing section), which is considered with an aim of exploring the geometrical effect in pumping section. Seven subcases with various input voltages of electrode T_2 are considered in Case 3, which can be seen in Table 6. The detailed discussion about the mass flow rates of Fluid A and Fluid B in each subcase of Case 3 is presented in Table 7.

Table 1 – Material properties of PBS solution.

Density (kg/m3)	1000
Conductivity (S/m)	1.5
Viscosity (kg/s m)	6×10^{-4}
Relative permeability	1
Relative permittivity	72
pH	7.4
Diffusion coefficient (m^2/s)	1×10^{-10}