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Performance investigation of MHD micro-mixers with different pumping capabilities for two different miscible fluids

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ABSTRACT

In this study, a magnetohydrodynamic (MHD) micro-mixer with differential pumping capabilities for two different miscible fluids is newly proposed and numerically investigated. Lorentz-force can be created with different potentials applied to different electrodes, producing a differential pumping for the two fluids, and inducing a cross-sectional fluid circulation for mixing. The results show that the micro-mixer proposed can achieve high mixing performance for electrolytes. Here, the effect of the ratio of the potential difference in pumping section on the ratio of the mass flow rate of the two fluids is obtained in the form of an exponential function.

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 [1]. In microfluidic systems, the fluid moves in devices with micron size, which can analyze and treat the blood with only around 10 μl. Even though the reagent quantities are reduced and the reaction time is shorter in microfluidic systems, it makes biological tests more effective [2,3]. Usually, a micro pump is needed to pump a fluid, such as blood, DNA, and saline buffers, in many different applications. Meanwhile, in order to promote chemical reactions and bioassays, it is necessary to fully mix various reagents. Generally, the characteristic length associated with micro-device is small so that the flows are laminar and well-ordered. For the fluid with low diffusivity the diffusion effect alone cannot provide a sufficiently fast way for mixing. Also, turbulence that may enhance mixing is not available because of flows with low Reynolds number in micro-devices [4].

The importance of the convective stirring mechanism relative to the 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 fairly large, whose typical values fall in the range of 10^3–10^5, so that concentration change is expected mainly due to the convection rather than the diffusion. Therefore, the stirring process must be utilized with artificial vortices created in the fluid flow [5].

Magneto-hydrodynamics (MHD) can provide us with a relatively convenient way for pumping and mixing for electrically conducting fluids. 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 [6], ceramic substrates [7], and polymer such as PDMS [8], of which PDMS is the most widely used material for microfluidic system due to its chemical stability and simple fabrication [9,10], and showed an efficient operation of the MHD pump. Also, demonstrated is that these pumps are able to move liquids in micro-channels. Das et al. [11] illustrated unique applications of these pumps such as sample injection, fluid flow in a packed bed, and on-chip assay development, 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 [12–15], which triggers the formation of cross-sectional vortexes and velocity recirculation by exploiting the coupling of momentum transport with MHD effects. Gleeson and West [13] examined the MHD mixing of two fluids in an annular micro-channel, using asymptotic analysis and numerical simulation. Gleeson et al. [14] developed a quantitative analysis of the regimes in an annular MHD-driven micro-mixer proposed by Cerbelli et al. [15].

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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. Derakhshan and Yazdani [16] provided a three-dimensional numerical model, and investigated the effects of magnetic field strength, electric current, geometrical parameters of the MHD micropump, electrode length and electrode location on its performance. Kosuke et al. [17] numerically investigated the influences of the channel height and the strength of externally applied magnetic field on the fluid temperature in the channel. The numerical results indicated that the increase in fluid temperature with the operation of the MHD pumps is less than 1 K when the magnetic flux density and the channel height are more than 0.3 T and 0.3 mm, respectively. Lee et al. [18] 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 micromixer 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, we newly propose 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 induce mass flow imbalance of two different miscible fluids, based on differential pumping capabilities of the two fluids. More precisely, the formation of cross-sectional velocity recirculation obtained in this study leads to the enhancement of mixing performance. Meanwhile, by varying the applied potentials of the electrodes in pumping section, the size of Lorentz forces for the two different miscible fluids in pumping section become different, consequently yielding different mass flow rates of the two different miscible fluids. In this study, the effect of the magnitude of the voltages imposed on the electrodes in mixing section on the mixing performance is considered. Also, the effect of the number of electrode sets in mixing section on the mixing performance is analyzed. Furthermore, ten cases (Case 0 to Case 9) with different potential differences of the electrodes in pumping section for the two different miscible fluids are considered. The obtained results including the information of velocity distribution, 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 is obtained.

Problem formulation

PBS (phosphate buffered saline) solution, which is an electrolyte, is usually used in LOC as a working fluid for real experiments of the protein analysis, and it is also used as medium for the fixation of protein. The properties of PBS solution are outlined in Table 1. A micro-mixer with rectangular cross-section proposed in this study is shown in Fig. 1, where totally fourteen individual electrodes are installed. Here, the combined effect of six electrodes (denoted by T_1, T_2, T_3, B_1, B_2 and B_3) functions as a pump, 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 as a mixer. Uniform magnetic field is applied in the y-direction with the intensity of 0.2 T.

Table 1
Material property of PBS solution.

	PBS solution
Density (kg/m^3)	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}

In the present study, in order to investigate the effect of the magnitude of the voltages imposed on the electrodes in mixing section on the mixing performance, additional cases with lower voltages applied to the electrodes in mixing section (that is, Case 0* and Case 5* in comparison with Case 0 and Case 5, respectively) are considered. Moreover, in order to examine the effect of the number of electrode sets in mixing section on the mixing performance, two subcases (Case 0-1, Case 0-2 for Case 0; Case 0*-1, Case 0*-2 for Case 0*; Case 5-1, Case 5-2 for Case 5; Case 5*-1, Case 5*-2 for Case 5*) with one-set, and two-sets of electrodes in mixing section are considered with an aim to investigate the difference in mixing performance. The detailed information about the comparison of mixing index in each subcase is shown in Tables 3–6. Furthermore, in order to investigate the mass-flow imbalance of Fluid A and Fluid B, ten cases (Case 0 to Case 9) with various input voltage of electrode T_2 are considered, respectively, as shown in Table 2. The detailed discussion about the mass flow rates of Fluid A and Fluid B in each case is presented in Table 7.

Fig. 2(a) shows the schematic depiction of the electrodes on the top wall in Case 0-1. The electric current flows from T_3 to T_2, and from T_2 to T_1 (denoted by J_p, which means the current for pumping), which induces the x-directional Lorentz force (denoted by F_p, which implies the force for pumping). In Case 0, the voltage difference between T_3 and T_2 is the same as the voltage difference between T_2 and T_1, which means the pumping capability for Fluid A is the same as the pumping capability for Fluid B. The electric current flows from LT_1 to LT_2, and from RT_1 to RT_2 (denoted by J_m, which denotes the current for mixing), which yields the z-directional Lorentz force (denoted by F_m, which implies the force for mixing).

Fig. 2(b) shows the schematic depiction of the electrodes on the bottom wall in Case 0-1. Also, the electric current flows from B_3 to B_2 and from B_2 to B_1, which induces the x-directional Lorentz force for pumping. The electric current flows from LB_2 to LB_1 and from RB_2 to RB_1, which induces the negative z-directional Lorentz force for mixing. At the cross-section located in the gap between the electrode LT_1 and LT_2 (say, in the y–z plane at x = 0.00625 m) the fluid is expected to be forced to flow in a clockwise direction (see Fig. 2(c)) under the influence of the Lorentz force therein, which may enhance mixing performance.

In Case 5-1, similarly, x-directional Lorentz force induced by the current flows from T_3 to T_2 and from T_2 to T_1 functions as a pump for the whole micro device. However, in Case 5-1 the input voltage of T_2 is -0.05 V, which means the potential difference between T_3 and T_2 (0.15 V) is three times that between T_2 and T_1 (0.05 V). Accordingly, the x-directional Lorentz force in the fluid region between T_3 and T_2 is larger than that in the fluid region between T_2 and T_1, and consequently the mass-flow imbalance of Fluid A and Fluid B may be induced in the current device (see in Figs. 2(d) and (e)). The working principle of mixing performance in Case 5-1 is the same as that in Case 0-1. Also, a clockwise flow recirculation in fluid region between the electrode LT_1 and LT_2 is expected to enhance the mixing performance.

The ratio of the inertial effect to viscous effect in the flow field can be described by the Reynolds number, $R_e = \rho UL/\mu$, where ρ is density of the fluid, U is the average flow velocity in the duct, L is the characteristic length, and μ_f is the dynamic viscosity of the fluid. The ratio of the characteristic time of diffusive effect to that of convection effect is denoted by the Peclet number for mass transfer ($Pe_m = UL/D$, where D is diffusion coefficient.). The Reynolds