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Rapid Micromixer Via Ferrofluids

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Abstract

Performances of a micromixer based on ferrofluids are predicted numerically. A permanent magnet is used to induce transient interactive flows between a water-based ferrofluid and water. The external magnetic field causes the ferrofluid to expand significantly and uniformly toward miscible water, associated with a great number of extremely fine fingering structures on the interface in the upstream and downstream regions of the microchannel. These pronounced fingering patterns, which mimic the experimental observations of Wen et al. (2009), increase the mixing interfacial length dramatically. Along with the dominant diffusion effects occurring around the circumferential regions of the fine finger structures, the mixing efficiency increases significantly. The mixing efficiency can be as high as 95% within 2.0 s and a distance of 3.0mm from the inlet of the mixing channel, when the applied peak magnetic field is 145.8 Oe. The proposed mixing scheme not only provides an excellent mixing, even in simple microchannel, but also can be easily applied to lab-on-a-chip applications with an external permanent magnet.

Keywords: Magnet; Magnetic field; Micromixer; Ferrofluids;

1.Introduction

Rapid mixing of two or more analytes is essential for many miniaturized total analysis systems, known also as ‘‘lab-on-a-chip’’ device, used in microreactors for complex chemical synthesis, biochemical analysis, immunoassays, and DNA analysis. However, the characteristic Reynolds number for microchannel flow is very small. The flow is laminar and the mixing is dominated by diffusion. In the absence of turbulent flow, complete and homogeneous mixing of fluids might take very long time, and requires large channel length, especially for analyte solutions containing large molecules such as DNA and proteins. The mixing of two solutions containing large molecules becomes very inefficient because the diffusion coefficients are in the order of 10^{-10} m^2/s or less. This flow nature poses a great challenge to the design of a micromixer. Numerous micromixers have been designed in order to enhance the micromixing. In general, micro-scale mixing methods can be categorized into passive and active schemes. Recently, active micromixers utilizing only ferrofluids and magnetic force represent another emerging important class of mixing possibility [2-4]. In this study, the work of Wen et al. [1] is continued. A numerical effort is made to predict the performances of the micromixer based on ferrofluids, designed by Wen et al. [1].

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2. Governing equations and Simulations

Consider a two-dimensional (2D) Y-type micromixer as shown in Figure 1. The flow channel dimensions, fluid properties and flow velocities in the experiments [1] were adopted in the current simulations. The two miscible fluids, DI water and the commercial water based ferrofluid (EMG 605, Ferrotec Corp., USA), were injected into the inlets with the same flow rate of 0.05 μL/min. The corresponding average velocity for each stream is $2.22\text{x}10^{-4}$ m/s. The saturated magnetization of this particular ferrofluid is 200 G (3.6 % vol. Fe_3O_4, average particle diameter of 100 Å). The viscosity, density and magnetic susceptibility of the ferrofluid are 5 mPa·s, 1.18 g/ml and 0.55, respectively, at 300 ^{o}K. The microhannel width is 150 μm and depth is 25 μm. The corresponding Reynolds numbers for DI water and the ferrofluid are 0.02 and 0.004, respectively. Note that a permanent magnet was placed parallel and 1 mm adjacent to the mixing channel in the simulations, instead of an electromagnet as in the experiments. The permanent magnet was chosen so that the same peak magnetic strength of 145.8 Oe in the experiments of 2.5V, 3.3A, 45Hz in [1] was matched.

The system of equations governing the micromixer flows of the ferrofluids are as follows:

$$\nabla \cdot \vec{v} = 0 \tag{1}$$

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + \left(\vec{v}\cdot\nabla\right)\vec{v}\right) = -\nabla p + \eta\nabla^2\vec{v} + \vec{F}_m - \rho g\vec{i}_y \tag{2}$$

$$\frac{\partial c}{\partial t} + \left(\vec{v}\cdot\nabla\right)c = D\nabla^2 c \tag{3}$$

$$\nabla\cdot\vec{B} = 0 \quad \vec{B} = \mu_0\left(\vec{H} + \vec{M}\right) \quad \nabla\times\vec{H} = 0 \tag{4}$$

where Eq. (1) is the continuity equation for incompressible fluid, Eq. (2) the momentum equation, Eq. (3) the concentration equation, and Eq. (4) the Maxwell equations for electrically nonconductive media. In Eqs. (1)-(4), ρ and η are the mass density and dynamic viscosity of the mixture, respectively, g the gravitational acceleration and p the pressure. Inside the ferrofluid, the magnetic body force density is $\vec{F}_m = \mu_0\left(\vec{M}\cdot\nabla\right)\vec{H}$, where μ_0 is permeability in vacuum, $\vec{H}$ the strength of external magnetic field and $\vec{M}$ the magnetization of ferrofluids. When the magnetization $\vec{M}$ is aligned with the applied magnetic field $\vec{H}$ or $\vec{H}$ is large enough, $\vec{M}$ is modeled as $\vec{M} = \chi\vec{H}$ where χ is the average magnetic susceptibility of ferrofluids. By replacing $\vec{B} = \nabla\times\vec{A}$ in Eq. (4), the x and y components of the body force density becomes

$$F_x = \frac{\chi}{\mu_0\mu_r^{\,2}}\left(\frac{\partial A_z}{\partial y}\frac{\partial^2 A_z}{\partial x\partial y} + \frac{\partial A_z}{\partial x}\frac{\partial^2 A_z}{\partial x^2}\right)$$
$$F_y = \frac{\chi}{\mu_0\mu_r^{\,2}}\left(\frac{\partial A_z}{\partial x}\frac{\partial^2 A_z}{\partial x\partial y} + \frac{\partial A_z}{\partial y}\frac{\partial^2 A_z}{\partial y^2}\right) \tag{5}$$

where $\vec{A}$ is the magnetic potential and μ_r is relative permeability.

Note that during the mixing process,

$$\rho = c\rho_m + \left(1 + c\right)\rho_0 \tag{6}$$

and viscosity variations of the mixture are assumed as

$$\eta = \eta_m e^{R\left(1-c\right)} \qquad R = \ln(\eta_0/\eta_m) \tag{7}$$

where R is a viscosity parameter [5] and subscripts m and 0 represent pure ferrofluid and water, respectively.