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Rapid mixing in micromixers using magnetic field

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ABSTRACT

In this paper, the rapid mixing of deionized water and Fe_3O_4 ferrofluid in a Y-shaped microchannel using a permanent magnet is studied both numerically and experimentally. The microchannel has a rectangular cross section with 500 μm in width and 1 mm in depth. The process, assumed to be two-dimensional and steady state, is simulated by COMSOL numerical software. In the numerical simulation, the Maxwell equations are solved to obtain the magnetic potential. Then, the magnetic force can be calculated. Knowing the magnetic force, the momentum and transport-diffusion equations are solved. A setup is designed and fabricated to carry out the experiments. The mixing process is photographed by a CCD camera for 5 min until the mixing process reached a steady state condition. The numerical results are compared with the corresponding measurements to validate the simulations. The effect of different parameters such as magnetic field's strength (1280G, 2000G and 3000G), volume flow rate (30 cc/min, 40 cc/min, and 60 cc/min), and mass fraction of nanoparticles (0.0125, 0.025 and 0.05) is investigated on the mixing efficiency. Applying magnetic field considerably improves the mixing efficiency of the micromixer and reduces the mixing length. Increasing the mass fraction of nanoparticles and magnetic field strength increases the mixing efficiency until the magnetization of the ferrofluid reaches its saturated level. Increasing the fluid flow, however, lowers the mixing efficiency and increases the mixing length.

1. Introduction

Microfluidics is the science and technology of designing and manufacturing the systems which operate with a small amount of fluid flowing through small channels. Microfluidics presents an essential capability in controlling the molecular concentration at a specific location and time by its inherent features such as small sizes and laminar flow in microchannels [1]. Recently, microfluidic devices have received much attention due to their frequent applications in biology, pharmacy, biochemistry and other industries. In microfluidic systems with small-sized channels, the viscous effects play a significant role and the flow regime is laminar. Small sizes of microfluidic systems increase the surface-to-volume ratio. As a result, heat and mass transfer efficiencies are improved. The surface-to-volume ratio can reach up to 30,000 m^2/m^3 in these systems [2]. In the case of no turbulence, the fluid mixing will entirely depend on the molecular diffusion considered as a slow molecular phenomenon. In most chemical and biological processes, fast and complete mixing of liquids is essential since it can affect the overall function of the microfluidic system.

Although all microchannels, micropumps, micromixers, and microfilters are considered as the components of the microfluidic systems, the micromixer and mixing phenomenon are of special importance in these systems [1,2]. Liu et al. [3] used a micromixer to facilitate the DNA hybridization process. Their results show a five-time faster process when a micromixer is utilized. Gi Seok Jeong et al. [4] classified the micromixer applications as follows: 1) chemical applications including chemical synthesis, polymerization and extraction, 2) biological applications such as DNA analysis, biological screening enzyme assays, and protein folding, and 3) chemical and biochemical content analysis in conjunction with Nuclear Magnetic Resonance (NMR), Fourier Transform Infrared (FTIR), and Raman spectroscopy. Solvent extraction, occasionally called liquid-liquid extraction, is performed by the micromixer techniques [5]. The extraction process consists of two overall stages: dispersion and phase separation. Mass transfer across the entire phase boundary is the main phenomenon in the extraction process. Effective diffusion and mixing processes are required to attain the saturated phase. Some features of the micromixers especially large surface-to-volume ratio and short mixing length make these devices proper for such processes [5]. Yun and Yoon [6] utilized a novel 3D spiral

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mixer with a flow of 10–70 μl/min to extract DNA from blood/liquid samples. Hessel et al. [7] used the micromixer as a microreactor to produce Phenylboronic acid. Their results suggest that in the case of a good mixing process, the production rate of the acid can be increased by 25%. Increasing the production rate, decreasing the byproducts, enhancement in the quality of the production, and lower energy consumption are also reported in their investigation. Many reactions that are impossible in large dimensions due to their impractical conditions can readily occur in micro-dimensions. For example, due to inflammability of the Toluene fluorination, this reaction should be carried out at $-70\,^{\circ}$C in macro-scales, while a safe non-explosive reaction at $-10\,^{\circ}$C is possible in micro-dimensions [8].

To answer the demands for various mixing processes, different micromixers have been fabricated in recent years. In these devices, the mixing process is mainly resulted from enhanced mass diffusion of the flows. Generally, microfluidic mixing is categorized into the passive and active mixing. In the active microfluidic mixing, an external excitation factor disturbs the sample. In the passive mixing, however, the interface area and interaction time are increased by special design of the microchannel shapes. Active micromixers are more efficient and lead to faster mixing comparing to their passive counterpart. The passive types possess less electrical and mechanical components, and as a result, less complexity. Generally, in passive micromixers, two methods are adopted to improve the mixing efficiency. The first method focuses on intensifying the molecular diffusion. Its underlying mechanism consists of enlarging the interface between the fluids. In the second method, mixing improvement mainly depends on the transport phenomenon and increasing the flow irregularity by changing the geometry or putting some barriers against the flow. The interface enlargement techniques include lamination, re-combination, segmentation, and hydrodynamic focusing of the flow [9–13]. Active micromixers usually utilize acoustic/ultrasonic, dielectrophoretic, electrokinetic, pressure turbulence, electrical hydrodynamic, magnetic, and heating techniques [13].

Acoustic stimuli are used to move the fluids through the micromixers. Moroney et al. [14] reported the acoustic mixing with Flexible Plate Waves (FPWs). Liu et al. [3] used acoustically-induced micro-streams to perform the mixing process in a microchamber. They employed a piezoelectric disk to excite the trapped bubbles in the top layer of the chamber with the frequency of 5 KHz. Ultrasonic mixing, because of the sound energy, rises the temperature. This can pose some problems in chemical and biochemical applications. Many biological fluids are sensitive to the temperature rise. Moreover, 50 KHz ultrasonic waves lead to the cavitation problem which harms the biological samples [13].

Dielectrophorsis (DEP) is the polarization of the particles in a non-uniform alternating electric field. The electric field induces the dipole moment on the particles. The interaction between the induced electric charges caused by the dipoles and the electric field leads to a resultant force that makes the particles to get far or close to the electrodes [13]. Deval et al. [15] and Lee et al. [16] suggested dielectrophoretic micromixers. Electrokinetic micromixers apply an electrokinetic excitation force and induce periodic turbulence in the flow field. Their function can be improved by enlarging the interfacial area, elongating the contact duration or making irregular flow fields. Both square and sinusoidal excitation waves with a frequency in the range of 0.1–5 Hz can be applied to these micromixers.

In pressure-disturbance micromixers, the flow turbulence is accomplished by velocity pulsing [17]. Commonly, micromixers consist of a single main channel and some side channels. The fluid in the main channel is excited using the velocity pulsating of the fluids in the side channels. Consequently, stretching and folding of the fluids in the main and side channels increase mixing of the species.

In electrical hydrodynamic-disturbance micromixers, rather than pressure sources, electrodes are installed along the mixing channel [13]. A set of Titanium wires is installed perpendicular to the mixing length. Switching the voltage as well as the frequency in the electrodes results good mixing in less than 0.1 s for a small Reynolds number of 0.02. In the presence of an external magnetic field, applying a DC voltage to the electrodes causes the Lorentz forces, which in turn improve the mixing process. The Lorentz force makes the liquids to turn and fold in the mixing channel. This approach can only be applied to the electrolyte solutions.

Another approach to enhance the mixing efficiency is to use the magnetic nanoparticles. Since, in a ferrofluid, the magnetic particles can be influenced by an external magnetic field, higher mixing efficiency between the ferrofluid and another sample solution can be obtained. The advantages of using a ferrofluid and a magnetic field generated by a permanent magnet can be stated as follows. While having a high mixing efficiency it requires no source of electricity for the electromagnet and it does not generate any heat in the sample. As a result, this method is preferred for biological applications. These micromixers have applications in biological sensors. Generally, biological reagents have low diffusion coefficients especially when the solution contains macromolecules such as DNA and proteins or large particles such as bacteria or blood cells. The rapid mixing within ferrohydrodynamic micromixers may be utilized to overcome the diffusion barrier in the integrated biosensors. Water-based ferrofluids have this potential to be bio-compatible and utilized in highly-sensitive pathogen detectors [18]. In this type of micromixers, the mixing time is reduced which in turn removes the need for long mixing channels.

Wen et al. [19] numerically studied the mixing of ferrofluid and deionized water in an active micromixer under the effects of magnetic fields. In their study, the magnetic field was generated using an electromagnet. The effects of AC and DC currents as well as the magnetic field's strength on the mixing efficiency were investigated in the transient state. From their results, when applied magnetic field had a peak of 60 Oe (Oersted), the mixing efficiency reached 95% in less than 2 s. In addition, no considerable difference between the AC and DC currents was observed. Tsai et al. [20] experimentally investigated mixing of the water and Fe3O4 ferrofluid in a Y-shaped micromixer. In their work, a permanent magnet with strength of 2200G was directly installed beneath the micromixer channels. Mao et al. [18] also presented a fast micromixer with ferrofluids which was constructed based on the manufacturing standards of micro devices. In their model, the nanoparticles are excited in very low voltages. Kitenbergs et al. [21] used magnetic micro-convection phenomenon to improve the mixing efficiency in a Y-shaped micromixer. The results showed that the relative mixing efficiency over a large distance of 0.5 mm reached to 45% in 0.4 s with a magnetic field less than 15 mT. Hejazian et al. [22] investigated the mass transport of fluorescein dye in a microchannel using diluted ferrofluid and an external non-uniform magnetic field. The body force due to the magnetic susceptibility gradient led to a secondary flow and compelled dye molecules to follow the same path of the magnetic nanoparticles toward the magnet, thereby improving mass transport process. Cao et al. [23] proposed a high throughput active micromixer using a hybrid magnetic field consisting of a static gradient magnetic field generated by micro-magnets and an external AC uniform magnetic field. The simulation results showed that proposed micromixer achieved a mixing efficiency up to 97% in 8 s at a distance of 600 μm from the mixing channel inlet.

In this study, the mixing of Fe_3O_4 ferrofluid and deionized water in a Y-shaped micromixer using a magnetic field of a permanent magnet is investigated both numerically and experimentally. The