SEPARATING PARTICLES OF DIFFERENT MAGNETIC PROPERTIES BY INTEGRATING POSITIVE AND NEGATIVE MAGNETOPHORESES

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ABSTRACT

This paper reports a new method that combines both positive and negative magnetophoreses based on ferrofluids to separate mixtures of particles with different magnetic properties. This scheme is simple, cost-effective and label-free compared to other existing techniques.

KEYWORDS: Separation, Ferrofluid, Magnetophoresis

INTRODUCTION

"Positive magnetophoresis" uses magnetic beads for microfluidic particles and cells manipulation. Because the magnetization of beads is typically larger than its surrounding medium (*e.g.* water), they move towards the location of field maximum. Another magnetic manipulative technique, termed as "negative magnetophoresis", is exactly the opposite of positive magnetophoresis. In this case, magnetizations of particles and cells are less than that of their surrounding medium, typically a magnetic fluid such as a paramagnetic salt solution or a ferrofluid [1, 2]. As such, any non-magnetic object inside these magnetic fluids can be potentially manipulated towards a weaker field direction. In this paper, by replacing water with ferrofluids of tunable magnetizations, beads can now be manipulated based on their magnetization alone, which cannot be realized by using either positive or negative magnetophoreses individually. We combine both positive and negative magnetophoreses together to sort particles of different magnetic properties in a microfluidic system.

THEORY AND SIMULATION

A general expression of the magnetic buoyancy force is $\vec{F} = \mu_0 V\left[\left(\vec{M}_p - \vec{M}_f\right)\cdot\nabla\right]\vec{H}$. Here $\mu_0 = 4\pi \times 10^{-7}$ H/m is permeability of free space, V is volume of the magnetized body, $\vec{M}_p$ is its magnetization, $\vec{M}_f$ is magnetization of the magnetic fluid surrounding the body, and $\vec{H}$ is the magnetic field strength at the center of the body. For demonstration purpose, there are two types of superparamagnetic particles of the same volume with magnetizations of $\vec{M}_{p1}$ and $\vec{M}_{p2}$ in a magnetic fluid with magnetization of $\vec{M}_f$. According to the above equation, the magnitude of magnetic buoyancy force depends on the difference of the magnetization of particles $\vec{M}_p$ and ferrofluids $\vec{M}_f$ and the sign of the equation represents the force direction on the beads. Figure 1(a) describes three possible cases that both positive magnetophoresis and negative magnetophoresis co-exist. Particles can be distinguished and sorted solely based on their magnetizations in a simple microfluidic channel with a permanent magnet, as illustrated in Figure 1(b). Simulation results in Figure 1(c) depicts the distribution of magnetic field and magnetic force on a 4 μm diameter particle within the microchannel, as well as representative trajectories of that particle with different magnetizations in a ferrofluid in 3D. According to the simulation, the particle's trajectory depends on the relative fractions of magnetic volume of both particles and fluid. Here we keep the magnetic volume fraction of the ferrofluid constant at 1%, very close to the measured value of the EMG 408 commercial ferrofluid that will be used in later experiments.

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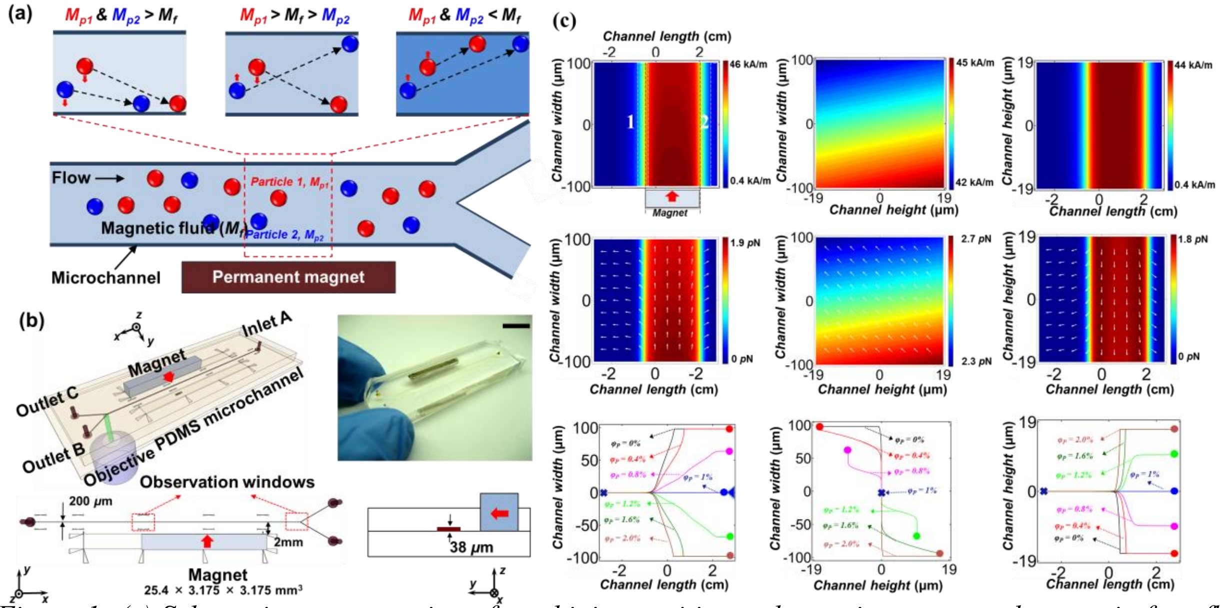

Figure 1: (a) Schematic representation of combining positive and negative magnetophoreses in ferrofluids to separate particles of different magnetic properties. (b) Device illustrations. Scale bar is 10 mm. (c) Three-dimensional simulation of magnetic field and force distribution in the microfluidic channel, and trajectories of 4 μm diameter particles with different magnetic volume fractions.

EXPERIMENTAL

Two types of ferrofluids are used in the microfluidic experiments. One of them is a custom-made water-based magnetite nanoparticle ferrofluid stabilized by sodium oleate surfactant. A second ferrofluid is a commercial water-based magnetite nanoparticle ferrofluid (EMG 408, Ferrotec Co., Bedford, NH) stabilized by anionic surfactants. Magnetizations of both ferrofluids are measured using a Vibrating Sample Magnetometer (VSM). Two fluorescent polystyrene non-magnetic particles (green 4.2 μm diameter and green 7.3 μm diameter), and four fluorescent superparamagnetic particles (red 2.6 μm diameter, green 2.8 μm diameter, green 7.9 μm diameter, and green 8.2 μm diameter) are used in the experiments.

RESULTS AND DISCUSSION

We first demonstrate the separation of 7.3 μm non-magnetic particles (red fluorescent) and 7.9 μm magnetic particles (green fluorescent, saturation magnetization ~2,939 A/m) in the ferrofluid stabilized by sodium oleate (saturation magnetization ~ 571 A/m, 0.1% magnetic volume fraction), as shown in Figures 2(a). An observation window is located at before the left edge of the magnet (window 1), and another at the outlets (window 2), as indicated in Figure 1(b). The top image of Figure 2(a) records particles' trajectories close to the inlet at window 1. Both particles are observed in fluorescent mode flowing together across the channel width. The middle image of Figure 2(a) records particles' trajectories close to the outlets at window 2. Between windows 1 and 2, the force on non-magnetic particles is pointing in positive y-direction due to negative magnetophoresis, while the force on magnetic particles is pointing in negative y-direction due to positive magnetophoresis. This leads to the spatial separation of two types of particles at the outlets, which is also confirmed by the simulation result in the bottom plot of Figure 1(c). Similar separation phenomenon still exists at an increased flow rate of 3 μl/min, as shown in Figure 2(a). Second, we also demonstrate the separation of 4.2 μm non-magnetic particles (green fluorescent) and 2.6 μm magnetic particles (red fluorescent, saturation magnetization ~10,019 A/m) in the same ferrofluid and observe the similar separation, as shown in Figure 2(a). As the flow rate raising up to 3 μl/min, the width of 4.2 μm particles increases due to the shorter residual time in channel.

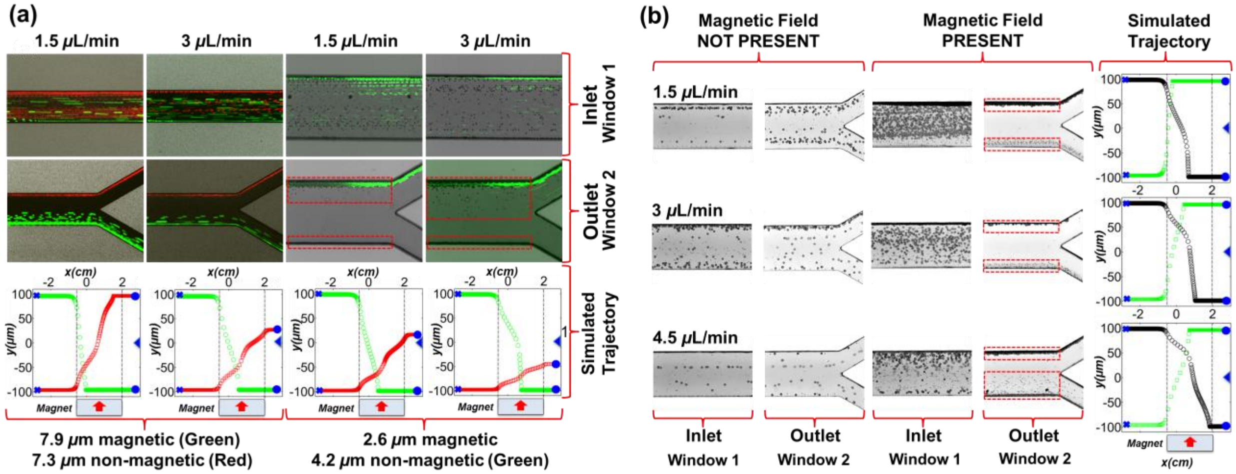

Figure 2: (a) Experimental composite micrographs of the separation process between non-magnetic and magnetic particles and simulated particles' trajectories. (b) Experimental composite micrographs of the separation process between particles with different magnetic properties and simulated particles' trajectories.

Experimental results of separating of 8.2 μm magnetic particles (saturation magnetization ~2,939 A/m) and 2.8 μm magnetic particles (saturation magnetization ~10,019 A/m) in the EMG 408 ferrofluid (saturation magnetization 4,953 A/m) in a microfluidic system are shown in Figure 2(b). The ferrofluid's saturation magnetization falls roughly halfway between the ones of 8.2 μm and 2.8 μm particles, making it ideal to separate them. Figure 2(b) show the comparison at 1.5 ~ 4.5 μl/min flow rates. When the magnetic field is not present, magnetic particles flow together and exit the channel through both outlets. As soon as the magnetic field is present, a clear migration of 2.8 μm particles towards the stronger field direction and 8.2 μm particles towards the weaker field direction occurs, which is the evidence that both positive and negative magnetophoreses exist in the system. This is also confirmed by the simulated particle trajectories in the right column of Figure 2(b).

CONCLUSION

We have developed a new separation method based on particles' magnetic properties through combining positive and negative magnetophoreses in a ferrofluid. This method is expected to separate particles with smaller difference in their magnetic properties than the case demonstrated in this paper.

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