LAB-ON-A-CHIP IN SUPERCONDUCTING MAGNETS – A TOOL FOR PARTICLE SEPARATIONS AND BUBBLE MANIPULATION VIA DIAMAGNETIC REPULSION

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ABSTRACT

We report on the integration of microfluidic devices and superconducting magnets to enable temporal and spatial control for the application of high magnetic fields in the study of materials and physical phenomena. Here, we perform the continuous flow separation of two particle populations in high magnetic fields based on diamagnetic repulsion, as well as the manipulation of air bubbles.

KEYWORDS: Bubbles, Continuous flow, Diamagnetic repulsion, Microparticles, Superconducting magnets

INTRODUCTION

Superconducting magnets allow the generation of high magnetic fields that enable the study of unusual phenomena, including atypical crystal growth, the levitation of live species, and the simulation of zero gravity conditions. However, apparatuses inserted into the bores of these magnets are often cumbersome and lack control over the environment in which the species of interest is present. Microfluidic technology enables fine control over the fluidic surroundings, and so offers the potential for performing investigations into unique occurrences with great spatial and temporal resolution. Previously, we demonstrated the handling of polymer particles in the bore of a superconducting magnet, and the effect of a paramagnetic medium on the diamagnetic repulsion of particles from regions of high field [1]. Here, we explore the effect of changing the paramagnetic medium concentration and the magnetic field strength and gradient on the deflection behaviour of polystyrene particles, and demonstrate the continuous flow separation of two particle populations in a free-flow magnetophoresis chip. Furthermore, we present initial findings on the manipulation of air bubbles in high magnetic fields.

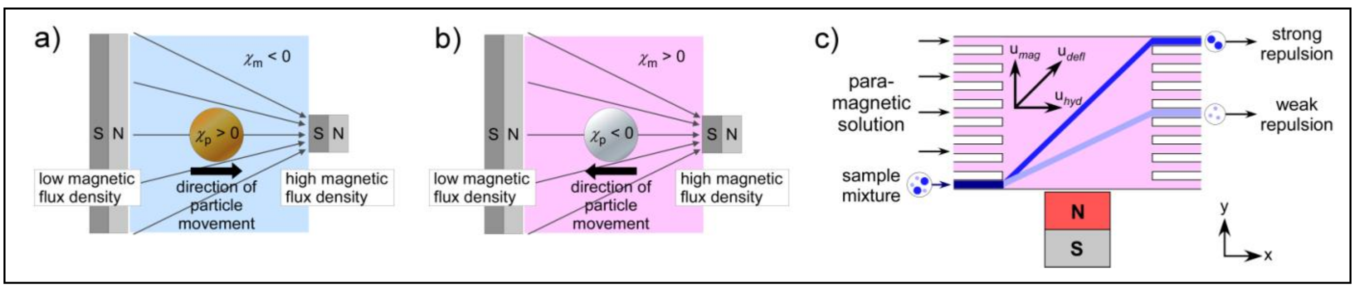

Figure 1: (a) Attraction of a magnetic particle ($\chi_p > 0$) to a magnetic field in a diamagnetic medium ($\chi_m < 0$). (b) Repulsion of a diamagnetic particle ($\chi_p > 0$) from a magnetic field in a paramagnetic medium ($\chi_m > 0$). (c) Continuous flow deflection and separation of diamagnetic species due to their repulsion from the magnetic field.

THEORY

When a particle is placed in a magnetic field it experiences a force ($\mathbf{F_{mag}}$) that is dependent on several factors, including the difference between the magnetic susceptibility of the particle (χ_p) and the surrounding medium (χ_m), the volume of particle material affected by the magnetic field (V), the magnetic flux density ($\mathbf{B}$) and its gradient ($\nabla\mathbf{B}$), and the permeability of free space (μ_0), as shown by Eqn. (1).

$$\mathbf{F_{mag}} = \frac{(\chi_p - \chi_m)\ V\ (\mathbf{B}\cdot\nabla)\mathbf{B}}{\mu_0} \tag{1}$$

When a magnetic particle is placed in a diamagnetic medium (e.g. water), then $\chi_p - \chi_m > 0$, and the particle will be attracted towards the magnetic field (Fig. 1a). However, when a diamagnetic particle is placed in a paramagnetic medium then $\chi_p - \chi_m < 0$, and the particle will be repelled from the region of highest field to the region of lowest field (Fig. 1b). Hence, in the experiments described here the particles and bubbles were suspended in a solution of paramagnetic aqueous manganese (II) chloride in order to achieve repulsion.

As the particles are introduced into a microfluidic chamber they exhibit a velocity in the x-direction due to the applied hydrodynamic flow, while the repulsive force from the magnet causes them to experience a velocity in the y-direction ($\mathbf{u}_{\mathbf{mag}}$). Thus, the particles have velocities in both the x-direction and y-direction, with the resultant deflection velocity ($\mathbf{u}_{\mathbf{defl}}$) being the sum of these, as shown in Eqn. (2) (Fig. 1c). Hence, if the applied flow rate ($\mathbf{u}_{\mathbf{hyd}}$) is kept constant, the extent of deflection ($\mathbf{u}_{\mathbf{defl}}$) depends only on $\mathbf{u}_{\mathbf{mag}}$, which in turn depends on the $\mathbf{F}_{\mathbf{mag}}$ values on the particles. Therefore, different sized particles experience different forces (due to their V values), resulting in different $\mathbf{u}_{\mathbf{mag}}$ velocities and allowing their separation.

$$\mathbf{u}_{\mathbf{defl}} = \mathbf{u}_{\mathbf{mag}} + \mathbf{u}_{\mathbf{hyd}} \tag{2}$$

EXPERIMENTAL

Two microfluidic chip designs were used for these experiments, both fabricated in glass to a depth of 20 μm using conventional photolithography and wet etching techniques. Chip design A was employed for particle experiments, and featured an 8 x 3 mm^2 separation chamber, five inlets, a branched waste outlet system, and a single particle outlet channel (Fig. 2a). Chip design B was used for bubble deflection, and featured a 6 x 6 mm^2 chamber, a branched bubble inlet system, and a branched outlet system (Fig. 2b). The appropriate chip was fixed onto a rail, with a CCD camera and an LED also attached to allow visualization inside the chamber. The rail was then inserted into the bore of a superconducting magnet, such that the chip was situated at a position of 146 mm from the centre of the bore where the value of $(\mathbf{B}\cdot\nabla)\mathbf{B}$ was largest, and thus the greatest amount of force experienced by the particles or bubbles. The particle and bubble experiments were performed as follows:

Particle deflection: 10 μm and 5 μm polystyrene particles were suspended in aqueous manganese (II) chloride solution and pumped through inlet 1 of chip design A, with $MnCl_2$ solution pumped through the remaining inlets. The concentration of $MnCl_2$ salt was varied, as were the strength and gradient of the magnetic field ($(\mathbf{B}\cdot\nabla)\mathbf{B}$), to determine the effects on the deflection behaviour in the magnet bore, and the results were applied to the separation of the two particle populations.

Bubble deflection: Air bubbles in 0.48 M $MnCl_2$ were introduced into the chamber of chip design B at a flow rate of 400 μL h^{-1}, and their deflection behaviour studied at a magnetic flux density of 10 T, giving a $(\mathbf{B}\cdot\nabla)\mathbf{B}$ value of 347 T^2 m^{-1}.

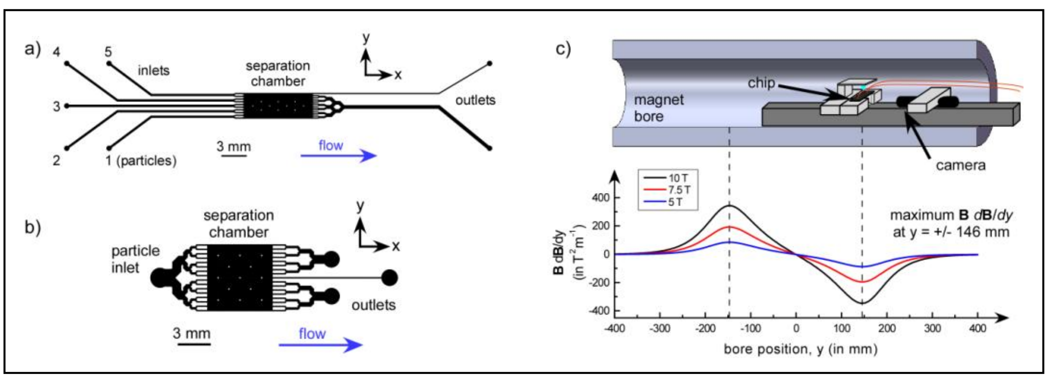

Figure 2:

(a) Schematic of chip design A, used for particle experiments.

(b) Design of chip B, used for bubble deflection experiments.

(c) Bore of a superconducting magnet, into which chips were inserted on a rail.

RESULTS AND DISCUSSION

Particle deflection: When introduced into the chip, it was observed that the larger 10 μm particles were deflected to a greater extent than the smaller 5 μm particles in all scenarios, as expected by Eqn. (2). The magnetically induced velocities ($\mathbf{u}_{\mathbf{mag}}$) of the particles were determined in $MnCl_2$ concentrations of 0.24, 0.38 and 0.48 M, with the magnetic flux density at 10 T, and the flow rate at 50 μL h^{-1}, where it was found that higher concentrations yielded higher $\mathbf{u}_{\mathbf{mag}}$ values (Fig. 3a). The particles were then suspended in 0.48 M $MnCl_2$ and pumped through the chip at 50 μL h^{-1}, with the particle deflection behaviour studied at magnetic flux densities of 5, 7.5 and 10 T, corresponding to $(\mathbf{B}\cdot\nabla)\mathbf{B}$ values of 347, 195 and 87 T^2 m^{-1}, respectively. Here, it was shown that higher field strengths resulted in greater deflection velocities (Fig. 3b). Finally, these findings were applied to the separation of a mixture of 5 and 10 μm polystyrene particle populations in 0.48 M $MnCl_2$, at a magnetic flux density of 10 T, and at a flow rate of 70 μL h^{-1}. The 5 μm particles exited the chamber via outlets 4 to 7, and the 10 μm particles via outlets 9 to 12, respectively (Fig. 3c), demonstrating the use of the setup for performing separations based on the intrinsic properties of the particles, a process that could also be applied to biological specimens.

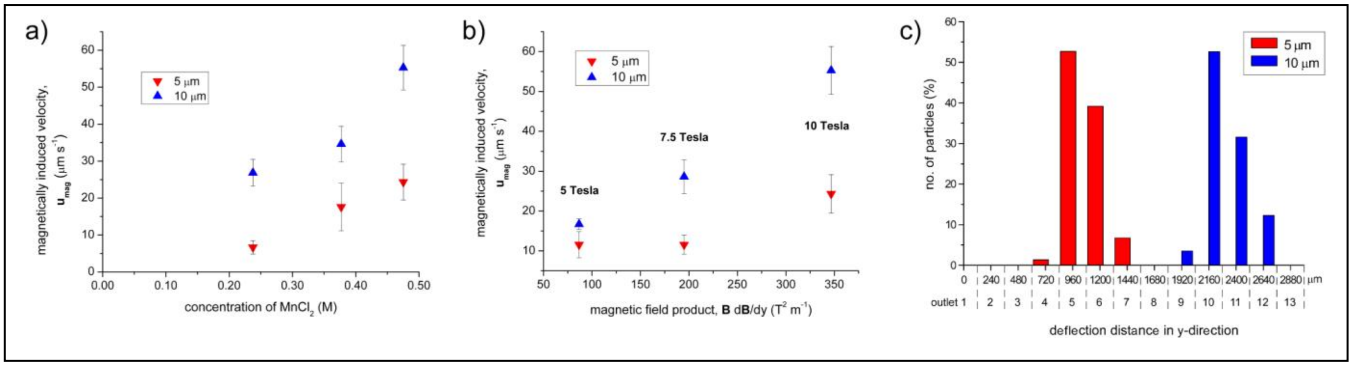

Figure 3: Diamagnetic repulsion of polystyrene particles. (a) Effect of $MnCl_2$ concentration on the magnetically induced velocity ($\mathbf{u}_{mag}$) of the two particle populations. (b) Effect of the magnetic field strength and gradient ($(\mathbf{B}\cdot\nabla)\mathbf{B}$) on the $\mathbf{u}_{mag}$ velocities of the particles. (c) Separation of 5 μm and 10 μm in continuous flow via diamagnetic repulsion.

Bubble deflection: Air bubbles were introduced into the chamber of chip design B, whereupon they were deflected away from the centre of the magnet via diamagnetic repulsion. By moving the rail between the two points of greatest $(\mathbf{B}\cdot\nabla)\mathbf{B}$ inside the magnet (Fig. 4), the bubbles could also be made to deflect first one way and then the other in the y-direction. Small bubbles of 34 μm diameter (equivalent to 18 pL) experienced $\mathbf{u}_{mag}$ velocities of 64 ± 12 μm s^{-1}, whilst bubbles of nearly 10 times larger diameter, 336 μm (1770 pL), exhibited greater velocities of 147 ± 40 μm s^{-1}. These initial results show great promise for performing repulsion-based continuous flow processes on bubbles, such as the deposition of particles and biomolecules onto their surfaces [2].

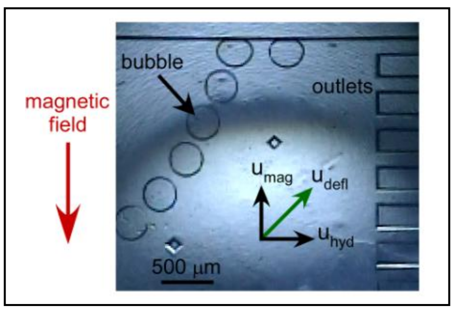

Figure 4: Superimposed photographs showing the deflection of an air bubble across the chamber of chip design B, due to its diamagnetic repulsion from the region of highest magnetic field over 6 seconds. The magnetically induced velocity ($\mathbf{u}_{mag}$) of the 336 μm diameter (1770 pL) bubble was 147 ± 40 μm s^{-1}.

CONCLUSION

We have demonstrated the application of microfluidic devices inside superconducting magnets, and used the effect of diamagnetic repulsion to study polystyrene particle deflection behaviour in varying concentrations of paramagnetic medium and with different magnetic field strengths and gradients. From these results, we have also performed separations of two particle populations in continuous flow, and have achieved the deflection of air bubbles. These results show great promise for the use of microfluidics in the study of a number of interesting effects that can only be achieved in the unique environment of such high field superconducting magnets.

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