MAGNETIC DROPLETS – GENERATION AND MANIPULATION IN CONTINUOUS FLOW

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ABSTRACT

We report the generation and downstream manipulation of magnetic droplets in continuous flow. Magnetic droplets were formed using aqueous-based ferrofluids as the dispersed phase and a fluorocarbon oil as the continuous phase. Droplet manipulation was demonstrated with simple permanent magnets using two microfluidic platforms: (i) flow focusing droplet generation followed by their splitting into daughter droplets containing different amounts of magnetic nanoparticles, and (ii) droplet generation at a T-junction and their downstream deflection across a chamber for sorting based on the applied magnetic field and magnetite loading of the droplet. Both systems show great potential for performing a wide range of high throughput continuous flow processes including sample dilution, cell sorting and screening, and microparticle fabrication.

KEYWORDS: Magnetic droplets, Droplet splitting, Droplet deflection, Continuous flow

INTRODUCTION

Droplets have been studied extensively within lab-on-a-chip devices.[1] Operations such as merging, splitting and sorting have been achieved by dedicated channel design or electric forces. The magnetic manipulation of droplets could be advantageous as magnets can be positioned externally. Furthermore, magnetic forces are generally independent of pH and ionic strength. However, so far, magnetic droplets have received relatively little attention with most investigations conducted in millimeter tray systems by manual pipetting of magnetic particle suspensions.[2-5] Here, we explore the on-chip continuous flow generation of magnetic droplets followed by downstream continuous flow splitting or deflection.

THEORY

Droplet splitting at a junction proceeds via two steps: (i) droplet deformation due to pressure from the continuous phase, followed by (ii) droplet breakup; as the droplet is pressed against the branching point, sheer forces dominate and the droplet splits into two daughter droplets and was described by Song *et al.* [6].

Droplet deflection: Magnetically loaded droplets can be manipulated based on their magnetite content and the magnetic field applied. The trajectory of droplets within a microfluidic chamber is the sum of the vector for the applied flow velocity ($\mathbf{u}_{\mathbf{hyd}}$) in the x-direction and the magnetically induced velocity ($\mathbf{u}_{\mathbf{mag}}$) predominantly acting in the y-direction. The magnetically induced velocity ($\mathbf{u}_{\mathrm{mag}}$) in turn is defined by equation (1),

$$\mathbf{u}_{\mathbf{mag}} = \frac{\mathbf{F}_{\mathbf{mag}}}{6\pi\eta r} = \frac{\Delta\chi \cdot N \cdot V_m \cdot (\mathbf{B}\cdot\nabla)\mathbf{B}/\mu_0}{6\pi\eta r} \qquad (1)$$

where $\mathbf{F}_{\mathrm{mag}}$ is the magnetic force acting on a droplet, μ_0 is the permeability of free space ($4\pi\ 10^7$ H m^{-1}), $\Delta\chi$ is the difference in magnetic susceptibility between the magnetic material and surrounding medium, N is the number of magnetic nanoparticles within a droplet, V_{m} is the volume of a magnetic nanoparticle (m^3), $\mathbf{B}$ is the magnetic flux density (T) and $\nabla\mathbf{B}$ is the gradient of the magnetic flux density (T m^{-1}).

EXPERIMENTAL

The continuous phase in both the splitting and deflection experiments consisted of a 10:1 mixture of perfluorodecalin (Fisher Scientific, UK) and 1*H*,1*H*,2*H*,2*H*-perfluoro-1-octanol (Sigma-Aldrich, UK) fluorinated oils. Droplets were formed using aqueous-based ferrofluids EMG 507 and EMG 705 (Ferrotec Ltd., UK) that each contained 10 nm diameter magnetic nanoparticles. EMG 507, used for the droplet splitting experiments, contained a nanoparticle concentration of 1.5×10^{16} particles mL^{-1}. EMG 705, used in the droplet deflection experiments, contained 6.9×10^{16} particles mL^{-1}. Dilution of EMG 705 ferrofluid was performed using purified water in different volume ratios.

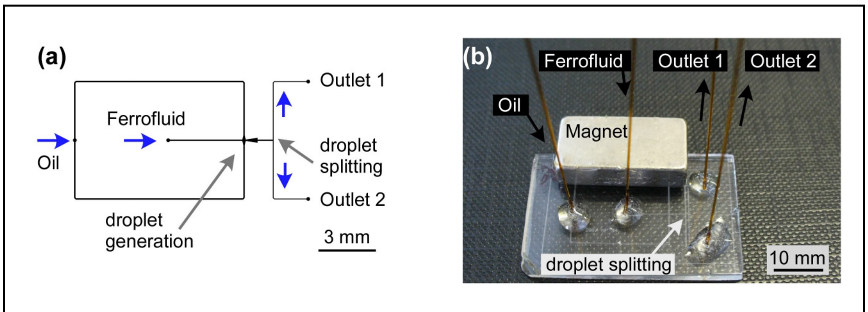

Figure 1: Generation and downstream splitting of magnetic droplets: (a) Chip design A featuring flow-focusing junction for droplet generation and splitting zone. (b) Photograph of experimental setup with NdFeB magnet.

Two microfluidic chip designs were used for the droplet splitting (chip design A) and deflection (chip design B) experiments, respectively. Both chips were fabricated in glass to a depth of 30 µm using conventional photolithography and wet etching techniques. Surface modification of the glass with trichloro(perfluorooctyl)silane was performed to produce hydrophobic channel walls for the generation of water-in-oil droplets.

Chip design A (figure 1a) featured a branched oil inlet that fed two identical 100 µm wide channels, which converged on a single, central 100 µm wide ferrofluid inlet channel to produce droplets via a flow focussing mechanism. Once the droplets were formed they were directed through a 2 mm long central channel to a T-junction that branched into two 50 µm wide sub-channels, towards outlets 1 and 2, for droplet splitting. Three different NdFeB magnets were employed, namely, a 20 x 10 x 5 mm^3 (magnetic flux density on surface of magnet **B** = 640 mT) which was placed on top of the chip at a distance of 1.2 mm from the droplet generation channel as shown in figure 1b, a 5 x 3 x 3 mm^3 block magnet (**B** = 530 mT) and an 8 mm diameter x 4 mm thick disc magnet (**B** = 460 mT). For splitting experiments in chip design A, the ratio of ferrofluid-to-oil flow rates was maintained at 1:10; ferrofluid flow rates ranged from 0.05 to 0.5 µL min^{-1}, and oil flow rates from 0.5 to 5 µL min^{-1}.

Chip design B featured a T-junction for droplet generation, fed by a ferrofluid inlet channel (100 µm wide) and an oil inlet channel (150 µm wide) (figure 2a). Droplets were formed at the T-junction and traversed a short serpentine channel before entering a 6 x 2 mm^2 deflection chamber supplied by an oil inlet, and featuring four exit channels with exit 1 directly opposite the droplet inlet channel and exit 4 furthest away. The ferrofluid and oil flow rates in the T-junction were 2 µL h^{-1} and 26 µL h^{-1}, respectively, while the oil flow rate in the chamber was 330 µL h^{-1} to match the flow velocity of the droplet inlet channel. The effect of two disc magnets on droplet behaviour in the chamber was studied with the magnet position shown in figure 2b. One magnet was 20 mm diameter x 5 mm with **B** = 290 mT, the other 10 mm diameter x 3 mm with **B** = 330 mT.

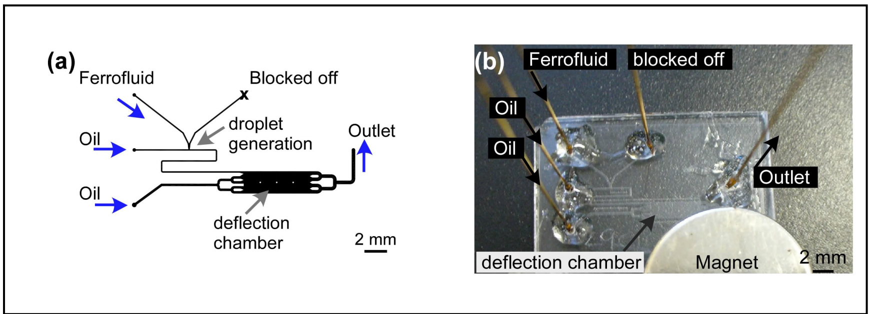

Figure 2: Generation and downstream deflection of magnetic droplets: (a) Chip design B featuring T-junction for generation and 2 mm wide chamber for deflection of droplets. (b) Experimental setup with disc magnet.

RESULTS AND DISCUSSION

Droplet splitting: An example for droplet splitting behavior is shown in figure 3 with flow rates of 1 µL min^{-1} for the ferrofluid and 5 µL min^{-1} for the oil phase. In the absence of a magnetic field (figure 3a), ferrofluid droplets were formed and found to split into two equal daughter droplets at the downstream junction. When a magnet was placed next to the channel, the magnetite concentrated in one half of the primary droplet (figure 3b). At the splitting junction, droplets flowing into outlet 1 were enriched in magnetic particles, whereas droplets flowing into outlet 2 were depleted. Based on grey-scale analysis it can be estimated that the nanoparticle concentration in the enriched droplets was about 2 x 10^{16} particles mL^{-1}, whereas the depleted droplets featured 1 x 10^{16} particles mL^{-1}.

Splitting behavior was investigated at different flow rates as described in the experimental section. Generally, it was found that more enrichment was achieved at slower flow rates (data not shown). Furthermore, the effect of different magnetic fields was studied. As an example, data obtained for a ferrofluid flow rate of 0.5 µL min^{-1} and an oil flow rate of 5 µL min^{-1} is shown in figure 3c. As expected, the greater field magnitudes and gradients from the large block magnet and disc magnet result in a stronger enrichment effect than the weaker field from the small block magnet.

Droplet deflection: In the absence of a magnetic field (figure 4a), the droplets were found to follow the direction of laminar flow and exited the 2 mm wide deflection chamber directly opposite the inlet. When a magnetic field was applied, ferrofluid droplets were pulled towards the magnet. The extent of deflection was studied as a function of magnetic field strength (figure 4b,c) and magnetite loading (figure 4d).

CONCLUSION

The continuous generation and downstream splitting and deflection of aqueous magnetic droplets was achieved. Splitting of magnetic droplets was investigated by studying different parameters such as the flow rate and the magnetic field strength. This effect could be used to add or remove magnetic functionality as desired. This system could be used for recovery of magnetic material, such as catalysts or solid supports, after a reaction in the mother droplet and the guided to further processing downstream. Magnetic droplets could also be polymerized for continuous flow production of magnetic microparticles with controlled sizes and with controlled distribution of magnetite within the particle. Another system for the manipulation of magnetic droplets was developed by deflecting the magnetic droplets across a 6 x 2 mm^2 chamber.

The device was tested using different magnet strengths, positions and the magnetic content of the droplets to guide them to desired outlets. The system could be used to perform a variety of high throughput chemical and biological analyses in mobile magnetic reaction vessels, where the droplets would be maneuvered to different outlets by changing the magnet position or changing the magnetite loading of the droplets.

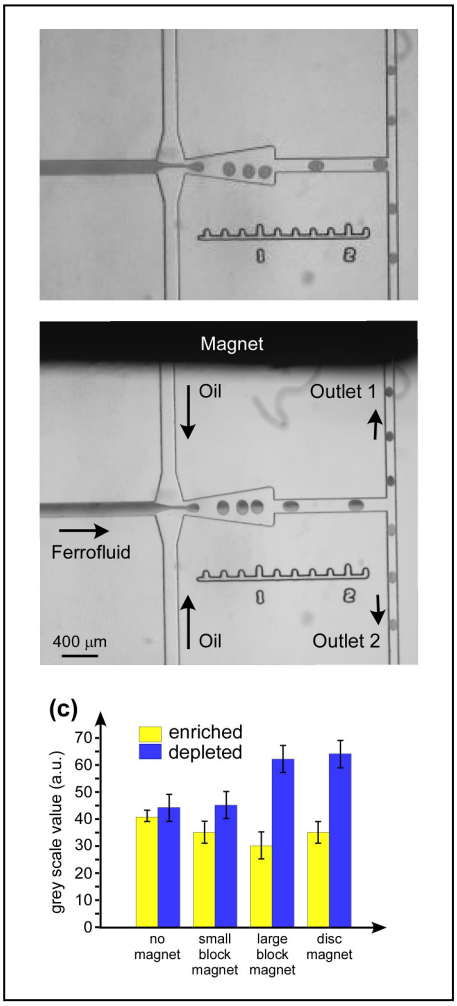

Figure 3 (left): Droplet splitting: (a) without magnet, daughter droplets feature equal magnetite loading. (b) With magnet, ferrofluid was concentrated in one half of the primary droplet, resulting in daughter droplets enriched and depleted in magnetite.(c) Extent of enrichment under different magnetic field conditions.

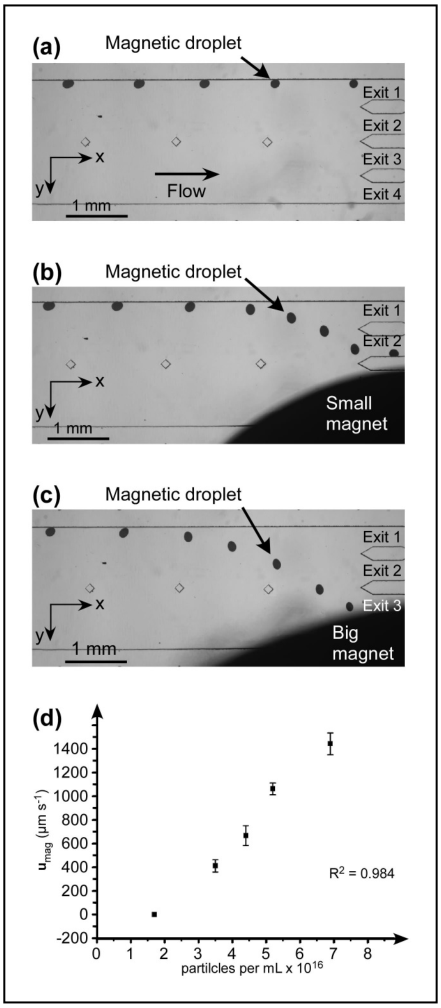

Figure 4 (right): Droplet deflection: (a) No magnetic field: droplets exit via outlet 1. (b) Field from small magnet: droplets deflected to exit 2. (c) Field from larger magnet: droplets deflected further to exit 3. (d) The magnetically induced velocity of the droplets as a function of ferrofluid concentration for, a 20 mm Ø x 5 mm disc magnet.

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REFERENCES

[1] A Huebner *et al.*, "Microdroplets: A sea of applications", *Lab Chip*, **2008**, *8*, 1244.
[2] J Pipper *et al.*, "Clockwork PCR including sample preparation", *Angew. Chem. Int. Ed.*, **2008**, *47*, 3900-3904.
[3] T Ohashi *et al.*, "A simple device using magnetic transportation for droplet-based PCR", *Biomed. Microdev.*, **2007**, *9*, 695.
[4] H Tsuchiya *et al.*, "On-chip polymerase chain reaction microdevice employing a magnetic droplet-manipulation system", *Sens. Actuat. B*, **2008**, *130*, 583.
[5] U Lehmann *et al.*, "On-chip antibody handling and colorimetric detection in a magnetic droplet manipulation system", *J. Microelectr. Eng*., **2007**, 84, 1669.
[6] H Song *et al.*, "A Microfluidic System for Controlling Reaction Networks in Time", *Angew. Chem. Int. Ed.*, **2003**, *42*, 768.

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