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Capturing Magnetic Nanoparticles with Different Permanent Magnet Shapes in a Microchannel System

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Abstract

This study examines the influence of different permanent magnet geometries (cube, ring, disc, and Halbach array) on capturing magnetic fluorescent nanoparticles (Synomag,70m) for magnetic drug delivery. Magnetic flux density mapping was performed with a custom setup using a 3MTS Teslameter, ensuring precise magnetization profiling around each magnet. A calibration curve for fluorescence intensity developed through regression analysis of Synomag nanoparticle concentrations, enhanced imaging accuracy. Python line profiling revealed that the Halbach array achieved the highest capture efficiency, reaching a concentration of 10 mg/ml, compared to 5.7 mg/ml for the cubic, 4 mg/ml for the disc, and 2 mg/ml for the ring magnet, under a flow velocity of 10 mm/s. Our results highlight the critical role of magnet design in magnetic nanoparticle capture and distribution, with the Halbach array excelling in high-concentration applications and cubic/disc magnets favoring even distribution. The Halbach array likely excels because it creates a high magnetic field strength and a steep gradient (∇B) in the region near its surface. This combination ensures efficient particle capture by balancing the drag forces from the fluid flow with a localized, focused magnetic force, making it highly effective in the given flow configuration.

I. Introduction

The ability to manipulate magnetic nanoparticles with external magnetic fields has made them valuable for targeted drug delivery, allowing precise localization of therapeutic agents to target sites within the body. Despite significant advances in magnetic nanoparticle synthesis and surface functionalization [1], a research gap remains in optimizing the design, shape, and configuration of external magnetic systems used to manipulate these particles effectively [2]. Addressing this gap could enhance the precision and efficiency of magnetic guidance, capture, and release in biological environments, thereby improving the overall efficacy of nanoparticle-based therapeutic and diagnostic systems. In addition, optimizing magnetic field strengths and gradients could further refine the control over nanoparticle behavior in complex biological environments. In this work, we assessed how different permanent magnet systems influence the capturing of nanoparticles in a straight microchannel.

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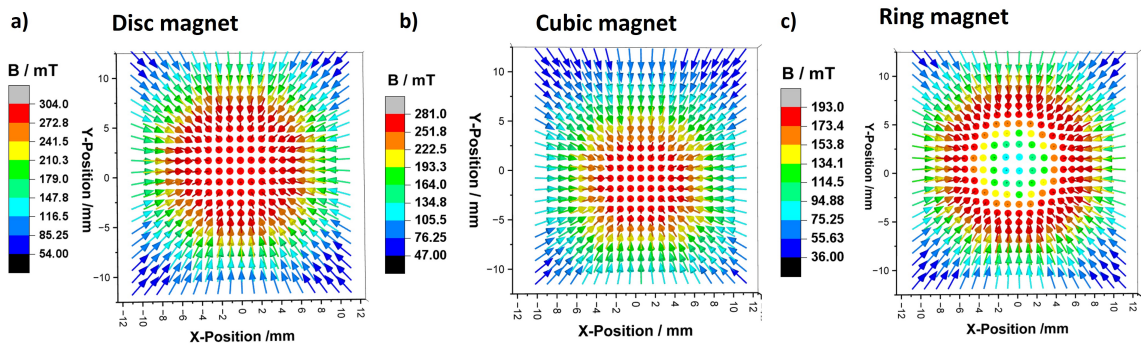

Figure 1: The magnetization profile around each permanent magnet shape (disc, cubic, and ring) was measured using a custom-built setup that incorporated linear motors and a 3MTS Teslameter for a precise spatial resolution.

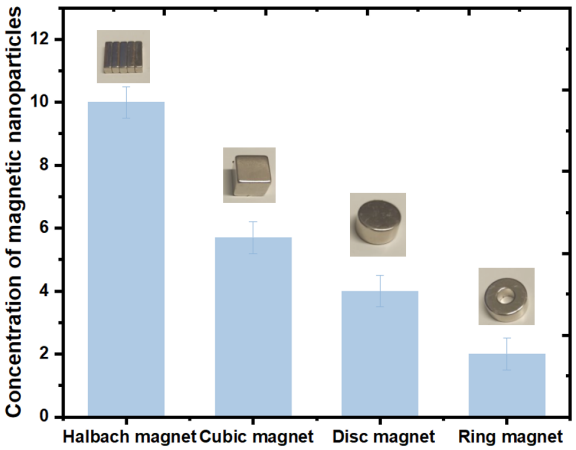

Figure 2: The maximal concentration of magnetic nanoparticles captured by various magnets inside the microchannel chip at a flow rate of 10 mm/s.

II. Methods and materials

In this experiment, fluorescent microscopy was used to observe the capturing of magnetic nanoparticles inside a single straight-channel chip. Fluorescence intensity was calibrated through regression analysis to correlate it with magnetic nanoparticle concentration, while imaging parameters were optimized for accuracy. Initial preprocessing steps, including image alignment and greyscale linearization, were conducted using AxioVision Lab. Python-based line profiling evaluated particle accumulation through intensity profile analysis, providing detailed insights into the spatial distribution and capture efficiency of nanoparticles within the magnetic field. A custom-built setup, featuring linear motors and a 3MTS Teslameter, was used to measure the magnetization profiles of permanent magnets for a precise spatial resolution [3].

III. Results and discussion

Figure 1 shows the magnetic field distribution of the used magnets except for the Halbach array. It corresponds to the closest distance between magnets and the channel achieved by the experiments. The disc magnet exhibited the highest maximum field strength at 304.0 mT, with a more gradual field decay, providing a broader effective area for nanoparticle capture. The cubic magnet displayed a highly centralized field with a steep gradient, reaching a maximum field of 281.0 mT at the center. In contrast, the ring magnet generated a distinct field pattern with a peak of 193.0 mT, showing a lower intensity in the central area but maintaining a concentrated ring-like distribution.

These differences in field distribution are expected to impact the efficiency of magnetic nanoparticle capture and concentration, suggesting that each magnet type may be optimally suited for different biomedical applications requiring specific field localization or gradient characteristics.

Figure 2 reveals that the Halbach array captures the most particles, yielding an estimated magnetic nanoparticle concentration of 10 mg/ml, followed by the cubic magnet at 5.7 mg/ml, the disc magnet at 4 mg/ml, and the ring magnet at 2 mg/ml, confirming the superior efficiency of the Halbach array in nanoparticle trapping.

IV. Conclusion

Different permanent magnet systems have been tested for their efficiency in capturing magnetic fluorescent nanoparticles in a microchannel. The Halbach array demonstrated the highest particle capture efficiency, followed by the cubic, disc, and ring magnets. These results suggest that the unique field distribution and characteristics of each magnet type play a crucial role in nanoparticle capture and concentration. By optimizing the design and configuration of magnetic systems, it is possible to

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enhance the precision and effectiveness of nanoparticle-based therapeutic and diagnostic applications, particularly in targeted magnetic drug delivery.

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Author's statement

The authors state no conflict of interest.

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