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AGGREGATION AND DETECTION OF MAGNETIC NANOPARTICLES IN MICROFLUIDIC CHANNELS

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Incorporating numerical simulation with COMSOL Multiphysics, the aggregation and detection of superparamagnetic nanoparticles in microfluidic channels are investigated. Considering the physical specifications of the implemented microchannels, the parameters which determine the ability of the system for aggregation and detection of the particles are examined and simulated. Based on the simulation results, we propose a new approach for both capturing and detecting of the magnetic nanoparticles passing through microchannels.

Keywords: superparamagnetic nanoparticles, microfluidic channels, nanoparticle aggregation and detection

1 INTRODUCTION

Magnetic particle based microfluidic systems are currently known as very interesting solutions for many different MEMS and BioMEMS applications [1] because superparamagnetic nanoparticles can be used as actuation handles and detection markers at the same time. One of the important issues in the design of such systems is the incorporation of appropriate magnetic detection techniques for the precise investigation of the magnetic particles. In reference [2], the two conventional detection methods, suceptometry and relaxometry, have been reviewed and the frequency mixing technique has been introduced. However, other approaches have also been examined. In reference [3], an integrated system of the microfluidic system and magnetic sensor has been presented. A GMR sensor (Giant Magneto Resistive) has been embedded in the microfluidic chip by using an advanced fabrication process. By introducing an external magnetic field, the particles are guided to be placed above the magnetic sensor for the magnetic detection.

In this work, we investigate the aggregation and detection of magnetic nanoparticles in micofluidic channels using COMSOL Multiphysics. Based on our implemented configuration of microchannels [4] and incorporated magnets, the distribution of the magnetic field and the components of the resulting magnetic forces on the particles are extracted. The finite element simulation of the system which determines the required specifications for aggregation and detection of magnetic particles, is then used for designing the system parameters. Furthermore in this work, a new experimental setup is devised on the basis of our simulation results. Our experimental realization is investigated with respect to both capturing and detection of magnetic nanoparticles passing through microchannels.

2 FINITE ELEMENT SIMULATION OF THE SYSTEM

2.1 Simulation of the magnetic forces on the particles

One of the important goals of the FEM simulation is the precise investigation of the applied magnetic forces on the nanoparticles which determine the place and the structure of their aggregation. For this purpose, we have modelled and simulated our experimental setup in which magnets with small tips are used for the aggregation of the particles. Figure 1 depicts the schematics and dimensions of our microchannel system. Figure 2 shows a fabricated microchannel with a small electromagnet which has been incorporated for achieving aggregation of the particles.

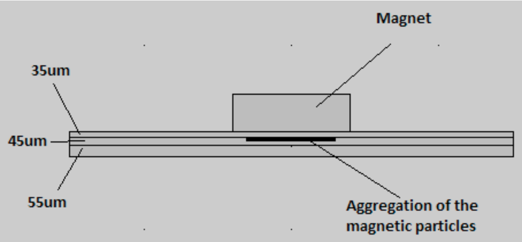

Fig. 1. The schematics of the microchannel system.

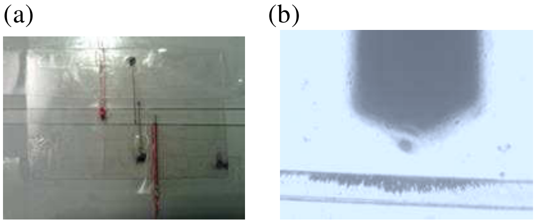

Fig. 2. (a) The microchannel and the small electromagnet wound on a drilling bit core (0.5 mm diameter), (b) the aggregated nanoparticles in the microchannel under the electromagnet.

For the numerical simulation of the system, we have modelled our structure using COMSOL Multiphysics. For

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the determination of the different magnetic force components on the particles, we have followed the approach of reference [5] in which equation (1) is considered for the derivation of the magnetic field along the channel.

$$\boldsymbol{F}_m = \frac{V\chi}{\mu_0}(\boldsymbol{B}\cdot\nabla)\boldsymbol{B} \tag{1}$$

Figure 3 depicts the distribution of the magnetic field around the magnet and the channel because of a 2 mm × 2 mm permanent magnet. Figure 4 visualizes the *x* component of the magnetic flux density which is used in equation (1) for the derivation of the magnetic force on the particles.

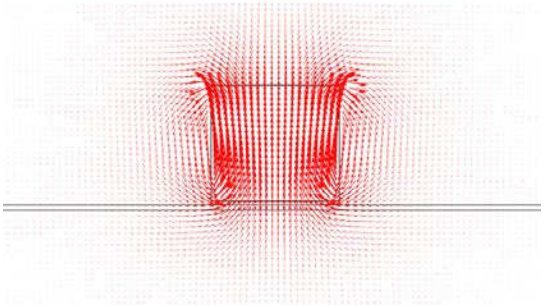

Fig. 3. A 2mm×2mm permanent magnet above the channel and distribution of the magnetic field.

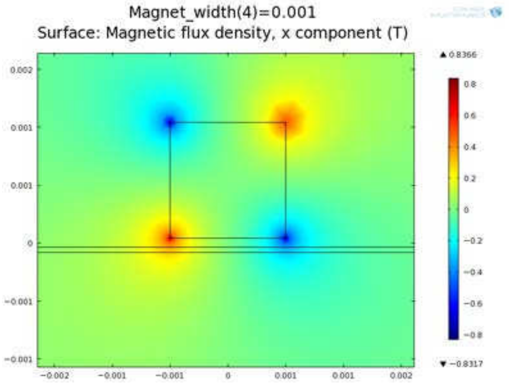

Fig. 4. The distribution of the x-component of the magnetic flux density because of the permanent magnet.

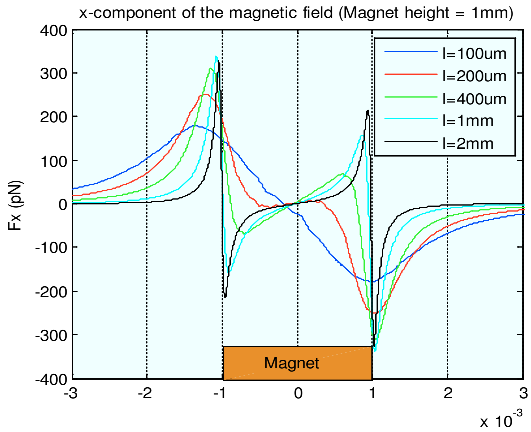

Fig. 5. The *x* component of the magnetic force applied by the permanent magnet to the magnetic particles for a magnet with 1 mm height and different lengths.

It should be noted that the position of the particles aggregation can be obtained from Fig. 5. According to [5], when there is a zero crossing of the *x* component of the magnetic field, a stable position is obtained at which the particles aggregate. In addition, Fig. 5 shows that for a permanent magnet with a fixed height, there are different positions for the aggregation of the particles if the length of the magnet is changed. It can be deduced that for magnets with tips smaller than 100 µm, there is just one position for the aggregation of the particles. On the other hand, when the size of the magnet tip is larger than 100 µm, two aggregation positions are found.

2.2 Simulation of the magnetic field perturbation caused by the particles

An important issue in designing the detection system for the investigation of the magnetic nanoparticles is the understanding of the field perturbation obtained because of the particles. The considered model for investigation of this perturbation is depicted in Fig. 6.

Because of the very small sizes of the particles relative to the dimensions of the magnet and the microchannel, the meshing of the structure in COMSOL for 3D simulation of the magnetic field in the presence of the magnetic particles is rather difficult. Therefore, we have considered a different approach for derivation of the effect of the particles on the distribution of the magnetic field. In this approach we modeled the distribution of the particles as a uniform magnetic box. The permeability of this homogeneous magnetic matter was chosen precisely such that the equivalent box has the same effect on the perturbation of the magnetic field as the densely packed distribution of magnetic particles. By sweeping the permeability of the box and comparing the field with that of the particles, we found that the equivalent box should have a permeability which is about 5 times lower than the permeability of the individual particles. Figures 6 and 7 illustrate the distribution of the magnetic particles and the equivalent box of the magnetic particles (with 5 times lower permeability).

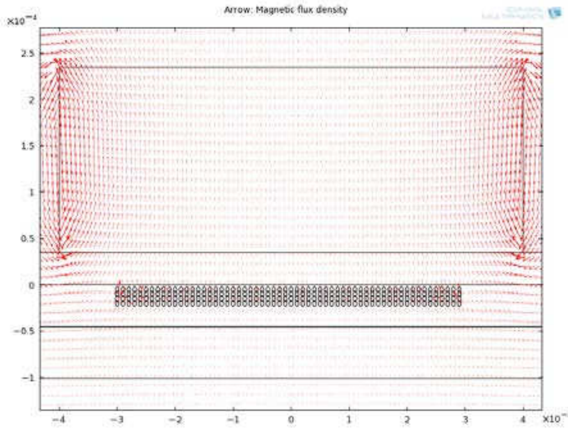

Fig. 6. The perturbation of the magnetic field due to the magnetic particles.

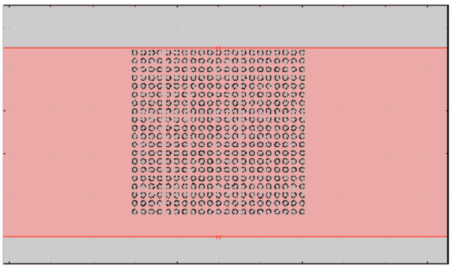

Fig. 7. The assumed distribution of the magnetic particles in the microfluidic channel.

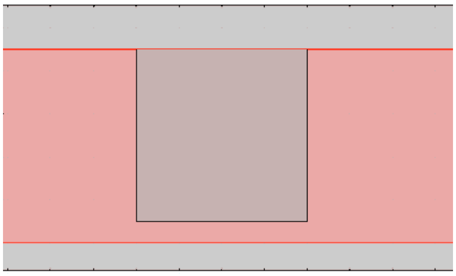

Fig. 8. The model describing the magnetic particles as an equivalent box with 5 times lower permeability than that of an individual particle.

Based on the equivalent box approximation, we have investigated the perturbation of the field due to the magnetic particles. Figure 9 shows the three-dimensional simulation of the particle-induced magnetic field perturbation. The parameters used in the simulation are listed in Table. 1.

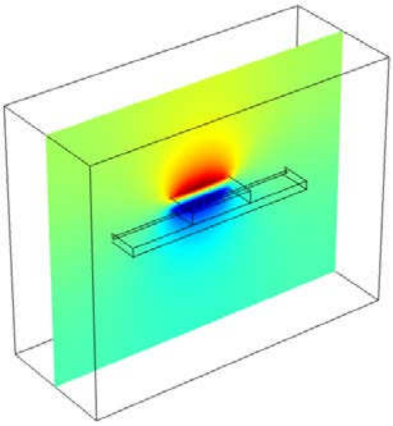

Fig. 9. Three-dimensional simulation of the perturbation of the magnetic field because of the particles.

Table 1. Parameters used in the simulation.

Quantity	***Value***
Susceptibility of particles	1
Diameter of the magnetic particles	1.2 µm
Distribution of particles	closed-pack
Measured distance below the substrate	45 µm
Magnet dimensions	200 µm×200 µm×1 mm
Magnetization	800 kA/m

Figure 10 shows the simulated magnetic flux density with and without the magnetic particles. In this figure it is obvious that the relative changes of the field due to the magnetic particles is very small (about 0.003). It is also evident that the changes occur in a very small spatial region of about 30 µm.

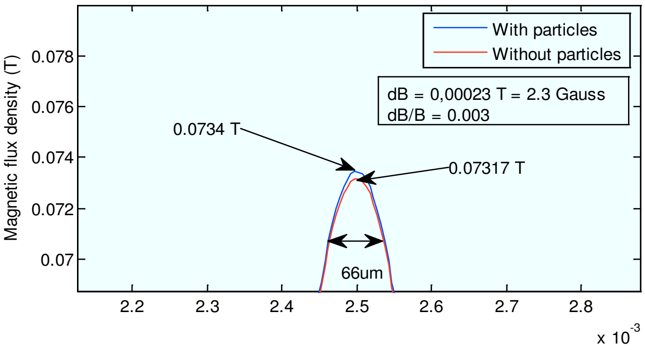

Fig. 10. Magnetic flux density with and without particles.

For investigating the influence of the measurement distance between the magnetic sensor and the channel, we have examined the magnetic field of the previous structure at different distances with respect to the channel. Figure 11 shows the magnetic field along the x axis for different distances. Figure 12 shows the measured magnetic flux density just below the aggregation of particles under the channel, as a function of this distance. This figure shows that by increasing the distance between the magnetic sensor and the channel, the magnetic field decreases exponentially. The magnetic field just 200 µm below the substrate is below 0.1 of its magnitude at the bottom of the substrate. This observation shows the importance of using a small size magnetic sensor and placing it at a very short distance from the channel in order to be useful for such applications.

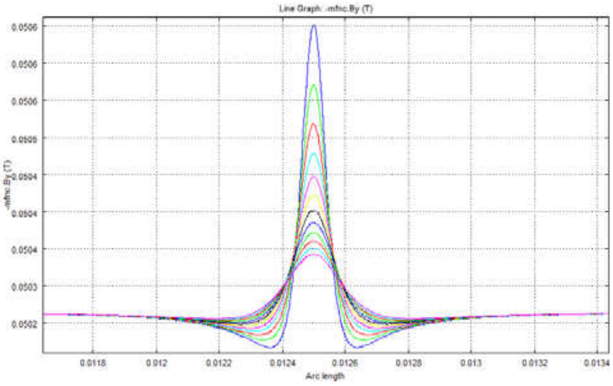

Fig. 11. Magnetic flux density along x-axis at different distances (with the difference of 10um between each).

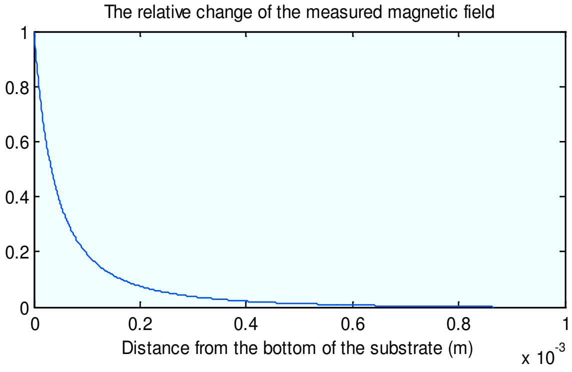

Fig. 12. Magnetic flux density at the center of the aggregation at different distances.

3 A NEW METHOD FOR THE AGGREGATION AND DETECTION OF MAGETIC NANOPARTICLES

Based on our simulations and observations, we propose a new method for both capturing and detection of magnetic nanoparticles passing through microchannels. Figure 13 depicts the schematics of the considered arrangement of the system. Figure 14 shows the implemented coils and electromagnets for the realization of the frequency mixing technique for microfluidic channels. In this system, an electromagnet is used for the aggregation of the particles. The implemented electromagnet consists of a 500 µm diameter ferromagnetic core with a solenoid wound around it. According to [3], in the frequency mixing technique, the nonlinearity in the magnetic characteristics of the particles is the source of the resulting detection signal. For this reason, all these systems are made from nonmagnetic materials. In our new approach where we incorporate a ferromagnetic core in our system, we should consider and cancel its nonlinear frequency mixing effect on the detected signal. In order to solve this problem of introducing a magnetic core, a second core arranged symmetrically is being used at the location of the other pickup coil. By precisely adjusting the location of the second magnetic core and using the subtraction feature of the gradiometer-type pickup coils, we can cancel the unwanted signal contribution in the output signal due to the magnetic core. For incorporating the frequency mixing technique, two excitation coils with different excitation frequencies are needed which are typically realized as cylindrical coils around the channel [3]. In this work we utilize a set of Helmholtz excitation coils, schematically shown in Fig. 13. It should be noted that these coils are placed in such a way that the two pickup coils are arranged in a symmetric position in their center. Figure 15 shows the result obtained from the aggregation experiment. The incorporated electromagnet proved suitable for our purpose as the capturing of the particles was successful.

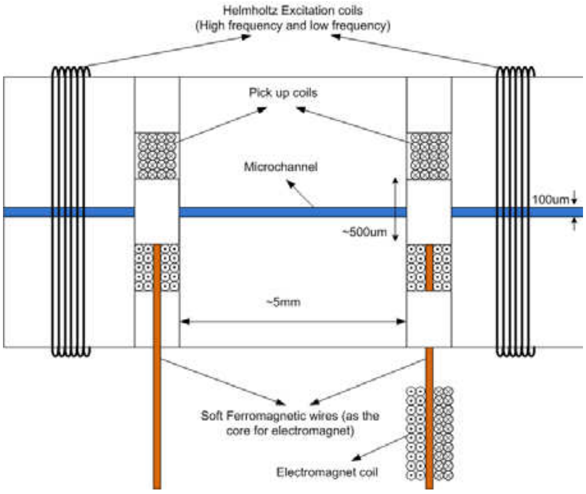

Fig. 2. The schematics of the measurement system.

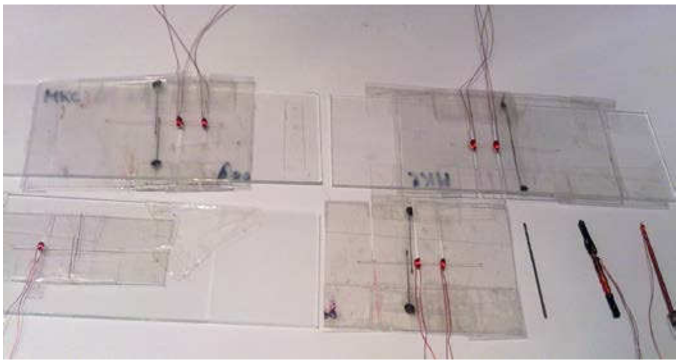

Fig. 14. The implemented coils and electromagnets for the realization of the frequency mixing detection technique in microfluidic channels.

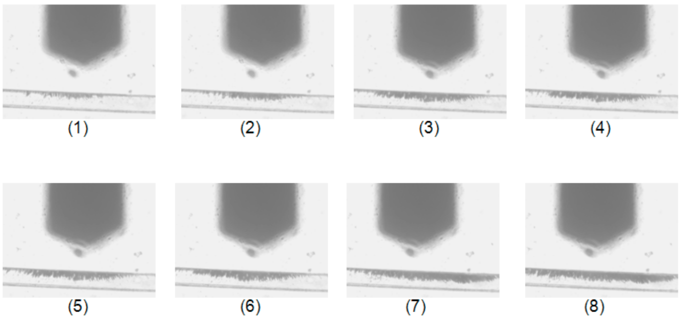

Fig. 15. The aggregation of the magnetic nanoparticles in the microchannel under the realized electromagnet. The aggregation levels of (1) to (9) correspond to different applied currents in the electromagnet.

3 CONCLUSION

In this work, the important parameters for designing of an aggregation and detection system for superparamegnetic nanoparticles have been numerically investigated. Based on the obtained results, a new setup for both capturing and detection of the particles is proposed. Its suitability for achieving aggregation of the particles is experimentally observed. The experimental realization of the complete system including nonlinear magnetic detection and its characterization with respect to magnetic particle quantification is in progress.

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