Two-Dimensional Analysis of the Enhanced Magnetic Bioseparation in Microfluidic Systems

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ABSTRACT

The separation of magnetically-labeled bioparticles in a microfluidic system is dependent on the characteristics of the particles and the carrier fluid as well as the external magnetic field. To discuss the influence of these factors, a microfluidic design is proposed for implementing greatly enhanced capture efficiency using two arrays of soft-magnetic elements. One array of the elements are integrated into the bottom of the microfluidic separation chamber, while the other array of elements are encapsulated above the chamber. The combination of these two arrays of the soft-magnetic elements, which are magnetized using an external permanent magnet, greatly enhances the capture efficiency as compared with the conventional system wherein only one array of elements are used. The magnetic field provided by these two arrays of elements is reciprocal to each other, which enables the Kelvin force with the same complementarity. This novel peculiarity narrows the chamber size and enhances separation as well. The enhanced capture efficiency is analyzed using a computational model that takes the particle-fluid momentum transfers into account. Besides, a closed-form magnetic analysis, which is more efficiency and accurate than other numerical methods in calculating Kelvin force, is adopted to describe the spatial distribution of the magnetic field. Furthermore, the influence of the flow rate and the volume fraction of the particles on the capture efficiency is also discussed.

Keywords: Microfluidic, magnetic bioseparation, soft-magnetic elements

1 INTRODUCTION

Magnetic nanoparticles, which can be functionalized to target biomaterials such as cells, genes, and proteins, are always used to separate or sort specific biomolecules by attracting them with an external magnetic field [1]. Moreover, these targeted biomolecules can be released on demand by removing the magnetic field [2]. In recent years, the integration of the magnetic separation and the microscale systems has advanced greatly due to their rapid and efficient analysis of low-volume biomolecules [3].

Magnetic functionality can be obtained by encapsulating the magnetic element into a microfluidic system. With skillful design of the magnetic elements, the microfluidic system can implement high separation efficiency. The passive or active magnetic elements are always adopted in the microfluidic systems. Smistrup *et al* suggested an active magnetic elements (e.g. coils) that were integrated into a microfluidic devices to offer a switchable Kelvin force for controlling the behavior of the magnetic bead [4]. However, the Kelvin force in this system was extremely weaker than that in the system using passive magnetic elements (e.g. permanent magnet). Furlani *et al* introduced a soft-magnetic microstructure, which could be magnetized by using external magnetic field, into the microfluidic devices for improving the capture efficiency [5]. Moreover, one peculiarity of this system was that the elements could be returned to unmagnetized state once the field was removed, which enabled its reutilization.

Many groups have investigated the separation process of the microfluidic system, and even discussed the influence of the particle properties and the magnetic elements on the capture efficiency of the magnetic nanoparticles [6]. Most theoretical studies have been carried out to discuss the behavior of the nanoparticles by using one-way or two-way particle-fluid coupling model [7]. In the one-way model, the flow is assumed to be stationary, and irrelevant to the motion of the particles. However, it is worth noting that the two-way model takes the interaction between the nanoparticles and fluid into consideration, which can describe the perturbation of the flow.

In this paper, we propose a special design of magnetic microstructure, which is comprised of two arrays of soft-magnetic elements that are integrated into the bottom and the top of the microchannel, respectively. An equivalent magnetic charge method is adopted to calculate the distribution of magnetic field of the magnetic microstructure, which can separate the nanoparticles from the direction of the carrier fluid [8]. According to the analysis of the magnetic field, the Kelvin force on the nanoparticles is derived using effective moment method, in which the nanoparticles is modeled as magnetic point dipoles [9]. Taking the effects of the particles on the flow into account, the two-way particle-fluid coupling model is used to investigate the behavior of the nanoparticles.

Besides, the influence of the initial flow rate and the volume fraction of the particles on the capture efficiency is also discussed.

2 THEORY

2.1 Magnetic Field

Firstly, let us briefly describe the equivalent magnetic charge method, which is introduces by Furlani. As shown in Fig. 1(c), a rectangular permanent magnet can be reduced to a distribution of equivalent "magnetic charge". The magnetic field of the rectangular permanent magnet can be obtained by calculating the magnetostatic field equations wherein the magnetic charges are regarded as source term [10]. Then, the distribution of the magnetic field of a rectangular permanent magnet as shown in Fig. 1(b), in which the length of the magnet is assumed to infinite, is calculated. It should be noted that the coordinate of Fig. 1(b) is different to that of Fig. 1(a).

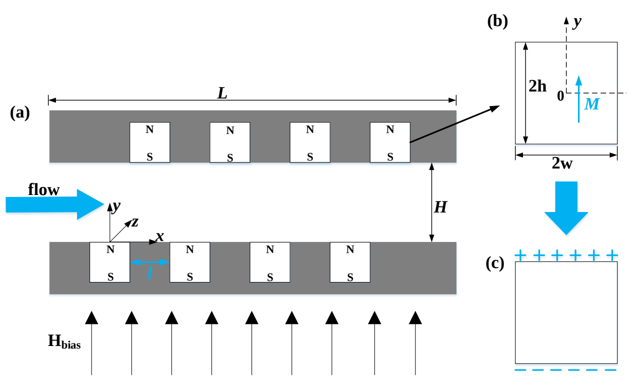

Figure 1: The schematic diagrams of the cross-section of a microchannel (a) and one of the element (b), and the equivalent magnetic charge (c).

The width, height and magnetization of the element are denoted by $2w$, $2h$ and M, respectively. The magnetic flux density ($\boldsymbol{B}$) can be described by the superimposition of radial (B_x) and axial (B_y) components as shown in (1), where $\boldsymbol{e}_x$ and $\boldsymbol{e}_y$ are the unit vector in x and y direction, respectively.

$$\boldsymbol{B}=B_x\boldsymbol{e}_x+B_y\boldsymbol{e}_y \tag{1}$$

The x and y component of the magnetic flux density can be described using (2) and (3), respectively.

$$B_x=\frac{\mu_0 M}{4\pi}\left\{\begin{array}{l}\ln\left[\dfrac{(x+w)^2+(y-h)^2}{(x+w)^2+(y+h)^2}\right]\\ -\ln\left[\dfrac{(x-w)^2+(y-h)^2}{(x-w)^2+(y+h)^2}\right]\end{array}\right\} \tag{2}$$

$$B_y=\frac{\mu_0 M}{2\pi}\left\{\begin{array}{l}\tan^{-1}\left(\dfrac{2h(x+w)}{(x+w)^2+y^2-h^2}\right)\\ -\tan^{-1}\left(\dfrac{2h(x-w)}{(x-w)^2+y^2-h^2}\right)\end{array}\right\} \tag{3}$$

2.2 Kelvin Force

Regarding the magnetic nanoparticles as magnetic point dipoles, the Kelvin force on a magnetic nanoparticle can be obtained using an effective moment $\boldsymbol{m}_{p,\mathrm{eff}}$ as shown in (4),

$$\boldsymbol{F}_m=\mu_f\left(\boldsymbol{m}_{p,eff}\cdot\nabla\right)\boldsymbol{H} \tag{4}$$

where μ_f is the permeability of the fluid and $\boldsymbol{H}$ is the external magnetic field at the center of the particle. According to the self-demagnetization and saturation magnetization of the magnetic nanoparticles, a special model of effective moment is given as [11]

$$\boldsymbol{m}_{p,eff}=V_p f(H)\boldsymbol{H} \tag{5}$$

where V_p is the volume of the particle, and the function $f(H)$ is

$$f(H)=\begin{cases}\dfrac{3(\chi_p-\chi_f)}{(\chi_p-\chi_f)+3} & H<\left(\dfrac{(\chi_p-\chi_f)+3}{3\chi_p}\right)M_{sp}\\ M_{sp}/H & H\geq\left(\dfrac{(\chi_p-\chi_f)+3}{3\chi_p}\right)M_{sp}\end{cases} \tag{6}$$

The χ_p and χ_f are the magnetic susceptibilities of the particle and fluid, respectively. M_sp is the saturation magnetization of the particle. Then, the Kelvin force can be rewritten as

$$\boldsymbol{F}_m=F_{mx}\boldsymbol{e}_x+F_{my}\boldsymbol{e}_y \tag{7}$$

where

$$F_{mx}=\frac{V_p}{\mu_0}f(H)\cdot\left[B_x\cdot\frac{\partial B_x}{\partial x}+B_y\frac{\partial B_x}{\partial y}\right] \tag{8}$$

$$F_{my}=\frac{V_p}{\mu_0}f(H)\cdot\left[B_x\cdot\frac{\partial B_y}{\partial x}+B_y\frac{\partial B_y}{\partial y}\right] \tag{9}$$

2.3 Two-way Particle-fluid Coupling Model

The Newton's law is adopted to describe the behavior of the nanoparticles,

$$m_p\frac{d\boldsymbol{u}_p}{dt}=\boldsymbol{F}_m+6\pi\eta R_p\left(\boldsymbol{u}-\boldsymbol{u}_p\right)+V_p(\rho_p-\rho)\boldsymbol{g} \tag{10}$$

where $\boldsymbol{u}_p$, ρ_p, R_p and m_p are the velocity, density, radius and mass of a nanoparticle, $\boldsymbol{u}$, ρ and η are the velocity, density and viscosity of the carrier fluid.

The Eulerian approach is used to model the dynamics of the incompressible fluid, which can be described by using Navier-Stokes equations [7]

$$\nabla\cdot\boldsymbol{u}=0 \tag{11}$$

$$\rho\left(\frac{\partial\boldsymbol{u}}{\partial t}+\boldsymbol{u}\nabla\boldsymbol{u}\right)=-\nabla P+\nabla\cdot\left(\eta\nabla\boldsymbol{u}\right)-\boldsymbol{f}_p \tag{12}$$

The term $\boldsymbol{f}_p$ is a force density which denotes the influence of the nanoparticles on the carrier fluid,

$$-\boldsymbol{f}_p=\frac{1}{m_p}\sum_p 6\pi\eta R_p\left(\boldsymbol{u}_p-\boldsymbol{u}\right)\dot{m}_p\Delta t \tag{13}$$

where $\dot{m}_p$ is the mass flow rate of each parcel, and Δt is the residual time that a parcel spends in the computational cell. The two-way particle-fluid coupling analysis is implemented by using the discrete phase model (DPM) in the ANSYS FLUENT program.

In all simulation of this work, the parameters are shown in Table 1.

Description	Parameters	Value
Width	$2w$	100 μm
Height	$2h$	100 μm
Distance	l	100 μm
Length of microchannel	L	1 mm
Height of microchannel	H	200 μm
Magnetization of magnet	M	8.6×10^5 A/m
External magnetic field	H_{bias}	3.9×10^5 A/m
Particle saturation magnetization	M_{sp}	4.3×10^4 A/m
Particle radius	R_p	0.5 μm
Particle magnetic susceptibilities	χ_p	1.4
Fluid magnetic susceptibilities	χ_f	0
Fluid viscosity	η	0.001 N s/m^2
Particle density	ρ	1800 kg/m^3
Fluid density	ρ_p	1000 kg/m^3
Fluid permeability	μ_0	1.257×10^{-6} H/m

Table 1: All of the parameters in this paper.

3 RESULTS AND DISCUSSION

The distribution of the magnetic flux density in the microchannel is calculated using the equivalent magnetic charge method. As shown in Fig. 2, the B_x obtains maximum in proximity to the center of the soft-magnetic elements, which are encapsulated at the top and the bottom

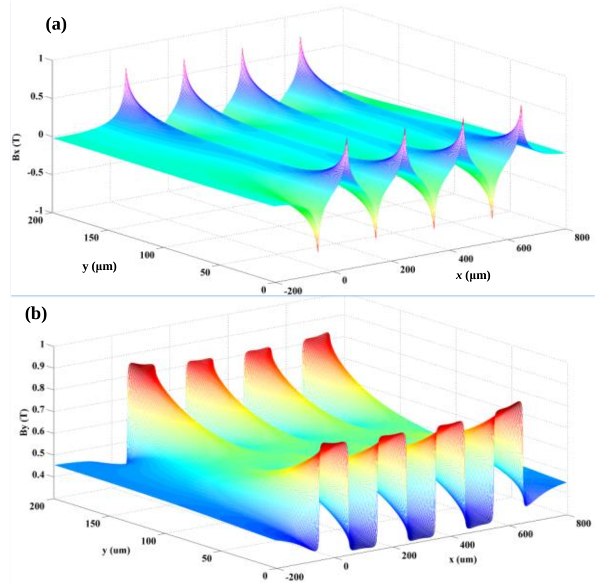

Figure 2: The distribution of the magnetic flux density in the microchannel, (a) B_x (b) B_y.

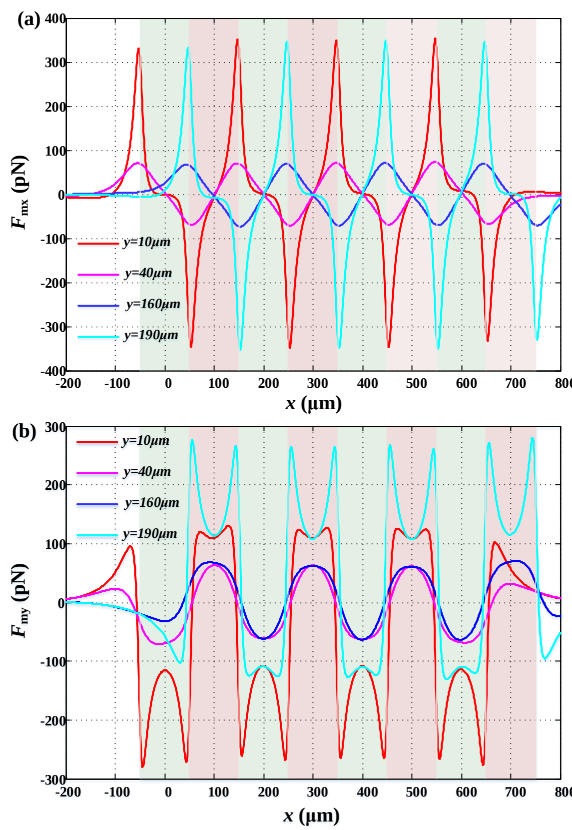

Figure 3: The distribution of the Kelvin force field along the longitude of the microchannel, (a) F_x (b) F_y.

of the microchannel, respectively. At the surface of one element array, the B_x varies from maximum (or minimum) to the minimum (or maximum) at the region between the center of two adjacent elements. The B_y obtains maximum at the surface of the elements and drops to minimum at the area between two adjacent elements as shown in Fig. 2(b).

Then, we analyze the Kelvin force on a magnetic nanoparticle as a function of y with the change of x. In Fig. 3, the pink and green represent the corresponding area that the bottom and the top magnetic elements in the microchannel, respectively. In Fig. 3(a), for a given y, the F_{mx} changes from maximum to minimum from the left margin to the right margin of one element, which denotes that the nanoparticles are attracted towards the surface of the elements. More importantly, the staggered two arrays of elements enable enhancing capture efficiency as compared with the conventional system wherein only one array of elements are adopted [7]. With the increase of y, the F_{mx} decreases firstly and then increases from $y=H/2$, which implies that the particles captured near the outlet of the microchannel are mostly from the center of the inlet. In Fig. 3(b), F_{my} attracts the nanoparticles towards the surface of the elements at the region that above the elements, while in the region between two adjacent elements, the nanoparticles are expelled to the microchannel. The combination of the F_{mx} and F_{my} enables more particles to be captured at the surface of the elements.

(a)
(b)
(c)

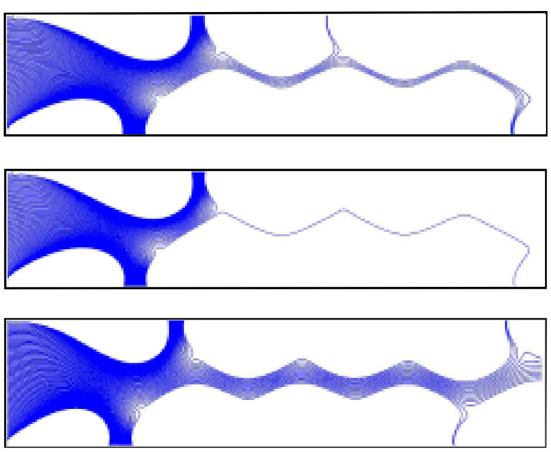

Figure 4: The trajectory of the nanoparticles with (a) v_0=3mm/s, ϕ_0=0.028%, (b) v_0=3mm/s, ϕ_0=0.14%, (c) v_0=5mm/s, ϕ_0=0.14%

Based on the discussion of the Kelvin force, we use the two-way particle-fluid coupling model to predict the trajectory of the nanoparticles in the microchannel. From Fig. 4(a) and (b), we can obtain that the capture efficiency in the two models are 100%. However, with the increase of the particle volume fraction, more nanoparticles are captured near the leading elements, which implies a strengthened interaction between the particles and fluid. As the initial flow rate varies from 3mm/s to 5mm/s, the capture efficiency decreases from 100% to 85% due to the enhanced fluid viscous force and their shorter time in microchannel.

4 CONCLUSION

A special design of magnetic microstructures is proposed for enhancing capture efficiency in microfluid system. The equivalent magnetic charge and the effective moment are adopted to analyze the magnetic field of the magnetic element arrays and the Kelvin force on a magnetic nanoparticle. Moreover, a two-way particle-fluid coupling model is adopted to predict the impact of the nanoparticles on the carrier fluid. Besides, we also discuss the influence of the flow rate and particle volume fraction on particle trajectory.

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