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# Numerical simulation of the continuous biomagnetic separation in a two-dimensional channel

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ABSTRACT

Numerical simulation of magnetically mediated separation of labeled biospecies from a native fluid flowing through a two dimensional channel is presented. The transport of the magnetic biospecies is modeled by coupling the fluid flow with an Eulerian advection–convection concentration equation. A magnetic field is imposed in the separator that causes an accumulation of the magnetic labeled species in the vicinity of the higher magnetic field region. The accumulation of the magnetically labeled species in the highest magnetic field zone presents a scheme for the collection of these species from the heterogeneous samples under the simulation conditions. The axial magnetic forces, as resulted from a dipole-like magnetic field, is found to play a major role in the vortex formation and it complement the downward vertical force in confining the particles to a small region near the point with the highest magnetic strength. The interplay between the particle transfer mediated by magnetophoresis forces and that by normal diffusion is analyzed for high and low inertia flows. The present study predicts that the generated viscous shear stress levels in the interior region of the channel provide a safe transport mechanism for biological cells from the solution.



## 1. Introduction

Magnetic separation is increasingly employed in laboratories for efficient isolation of specific biological and chemical entities from heterogeneous samples. Water purification using magnetic assistance is increasingly utilized to isolate hazardous compounds generated from industrial operations (Qadri et al., 2009; Ambashta and Sillanpää, 2010). These particles are generally surface modified to capture the hazardous compound using electrostatic attraction between the hazardous compound and the surface charge of the magnetic particles. The magnetic separation can reach an efficiency of 98%. The separator design for the hazardous material is required.

Separation of biological compounds has grown over the past few years. Several commercially viable products have been introduced to the market. A typical magnetic carrier for the biological entities separation is coated with a suitable marker that specifically targets the biological species of interest. Magnetic separation has been utilized in many applications such as in removing red blood cells from whole blood mixture (Haik et al., 1999), in isolating rare tumor cells from blood (Pratt et al., 2011; Chalmers et al., 2007), pre-processing technology for polymerase chain reactions through which the DNA of a sample is amplified and identified (Hofmann et al., 2002), determining the location and the number of tagged cells by measuring the magnetic moment of the microsphere tags (Delgratta et al., 1995), MRI contrast enhancement (Livingston, 1996; Elster and Burdette, 2001) and in many other applications. Biomagnetic separation techniques have promising potentials for use in many, yet evolving, applications in the biosciences (Pankhurst et al., 2003).

Magnetic separation relies on using magnetically responsive material that do not retain remnant magnetization at the temperature of operation. The lack of magnetic memory allows for isolation of magnetic material with the aid of an external magnetic field without causing agglomeration due to the intrinsic magnetic interaction among particles in the absence of an applied field. Various polymer-based and protein-based magnetic particles have been synthesized in the last few decades, primarily for applications in drug delivery, immunoassays and separation (Pardoe et al., 2001; Gruttner and Teller, 1999).

Khashan and Haik (2006) and Tzirtzilakis and co-workers (Tzirtzilakis and Loukopoulos, 2005; Tzirtzilakis, 2008; Loukopoulos and Tzirtzilakis, 2004) conducted a series of numerical studies involving the effect of localized steady magnetic field on such biomagnetic fluids. They demonstrate that the presence of the magnetic field influences the biomagnetic fluid patterns and the shear stress at the wall near the magnetic source. Li and Liu (2007) numerically simulated the behavior of a moving magnetic fluid in a channel of two different size vessels 1 mm and 10 mm

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in width, which were exposed to a high gradient magnetic field. They employed a simple numerical simulation model which covers different conditions such as, flow velocity, particle susceptibility, and intensity of magnetic field and its gradient.

Design of magnetic separators is essential to meet the increasing demand of both positive and negative separation devices. An adequate understanding of the transport phenomena of suspended magnetic microparticles or of magnetically tagged biological entities under the effect of an external magnetic field is essential for optimization and preset of biomagnetic separation techniques as in assay/analysis systems. Reported investigation on magnetic separators focus on the bulk efficiency of the separation. The miniaturization of the separators that meet specific demand are being produced based on meso-scale separators. Essential fundamental studies that could contribute to the fundamental understanding of the separation process are of great demand by both the scientific community and the separators manufacturers. Through this study we show the concentration of magnetically responsive particles when subjected to an external magnetic field. Literature describing the biomagnetic fluid motion assumes strong affinity between the carrier fluid and the magnetic particle, preventing the particles from drifting relative to the carrier fluid. In this study the employed model allows for relative drifting between fluid carrier and the magnetic particles, therefore allowing particles to redistribute by coupling the Navier-Stokes equations with advection–diffusion particle concentrations. Our new handling of the carrier fluid–particle interaction contributes to the fundamental understanding of the design parameters that influence the separation, hence improving the separator performance.

## 2. Mathematical formulation

A steady magnetic field is applied to a channel flow containing magnetically responsive tags on biological species. The magnetic label usually has a magnetic core made out of iron oxide nanoparticles (10 nm in size) that is coated with suitable protein to tag the biospecies. The interaction between the applied steady field and the magnetic tags is through magnetization effect.

The macroscopic interaction of magnetic tags with an external non-uniform magnetic field is determined by the force acting on each particle. Under the action of a static and non-homogenous magnetic field **H**, a non-conducting particle with linear magnetization will magnetize. The magnetization takes the form of a net magnetic moment m leading to a net force $\mathbf{F}_{mag}$ in the direction of increasing field strength. If the particle is placed in a medium which is essentially non-magnetic, i.e. its permeability does not deviate appreciably from that of vacuum $\mu_o$, the force can be written as (Neuringer and Rosensweig, 1964; Rosensweig, 1985; Engel and Freidrichs, 2002; Furlani, 2006).

$$\mathbf{F}_{mag} = \mu_o(\mathbf{m}\cdot\nabla)\mathbf{H} \tag{1}$$

For a particles with volume $V_p$, the force can be expressed in term of the volume Magnetization **M** as

$$\mathbf{F}_{mag} = \mu_o V_p(\mathbf{M}\cdot\nabla)\mathbf{H} \tag{2}$$

For particles (with superparamagnetic core) in the linear magnetization region, the magnetization can be related to the applied **H**-field via the constitutive relation, $\mathbf{M} = \chi\mathrm{H}$ where $\chi$ presents the particle's volume-averaged magnetic susceptibility as attained by its magnetic content. With $\nabla\times\mathbf{H} = 0$, the above equation can be rewritten with respect to $H^2(=\mathbf{H}\cdot\mathbf{H})$ as

$$\mathbf{F}_{mag} = \frac{1}{2}\mu_o V_p \chi \nabla H^2 \tag{3}$$

The above "per particle" force expression is deemed valid under the condition of weak inter-particle interactions, i.e. the effect a dipole magnetic moment induced by one particle has on the magnetization of a neighboring particles as well as on the applied magnetic field itself are marginal. The interaction with the leading importance is the one that results in enhancing the particle's magnetization (where it alone) by an additional magnetization induced by the neighboring magnetic dipole fields. This induced magnetization, however, is inversely proportional to inter-particle separation cubed (i.e. $\mathrm{Min}\sim 1/s3$), where the inter-particle separation s can be approximated with respect to the volumetric particles density n as; $s\sim n^{-1/3}$.

Simulating magnetic interaction with particles that are not-permanently magnetic but closely spaced would require more considerations to the fact that particles would attract one another and agglomerate together and to the fact that viscous action as modeled with Stokes approach would become invalid. Also, the modeling of the dynamic viscosity and density used in the momentum conservation of the continuum mixture of fluid and particles would become more involved. The magnetic force as modeled here would only work properly for magnetic particles under the dilute condition. In this study, weak inter-particle magnetic interaction as a simplifying assumption is deemed justifiable in the dilute limit by which we require that *s* is never less than two particle diameters in the whole problem domain.

The dynamics of the magnetic separation process of particles in dispersion involves reconciliation between several kinds of forces. The magnetically forced particles move relative to the carrier fluid flow and therefore, exchange momentum with it. Viscous drag by the fluid, on the other hand, sets up in an attempt to dampen this relative motion. In the same time, this transfer of momentum alters the fluid flow which feeds back as a change in the viscous drag experienced by the particles as well as in their motion. The motion of these particles changes as they accelerate to set up a new force balance between drag and magnetic forces. Gravitational body force on the micron-sized particles, though typically denser than the fluid, can be as one order of magnitude smaller than magnetic force and therefore can be neglected. For a magnetic particle moving relative to the carrier fluid, under the effect of non-homogenous magnetic field, the viscous-magnetic force balance is assumed to be established rather very quickly. This significant simplification is easily tolerated by the fact that Reynolds number based on the typically used particle's radius is much less than unity. This means that the particle passes through a very short acceleration phase (in the order of microseconds), before it attains a constant terminal velocity pertaining to the balanced drag and other external forces.

The magnetic force causes a motion of magnetic particles (magnetophoresis) with respect to the carrier fluid. The magnetic particle concentration increases wherever the magnetic intensity is high. The mechanism of molecular diffusion of particles, as described by Fick's law, causes diffusion from regions with high concentration to those with low concentration.

The interaction between the different mass transfer mechanisms, by advection, magnetic migration and normal diffusion, results in a redistribution of the suspended particles and, consequently, in altering the intensity of the volume magnetic force acting upon the fluid. In the absence of any surface or volumetric particle reactions, the mass and, therefore, the volume of the suspended solid particles are conserved. In the framework of continuum approach one can use this mass conservation of particles to derive a transport equation for the temporal and spatial-varying volumetric particle density. If the particles density is normalized using a reference particle density to obtain a dimensionless concentration $c(x, y, t)$, a concentration equation can presented as

$$\frac{\partial c}{\partial t} + \nabla\cdot\mathbf{J} = 0 \tag{4}$$