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Capture Efficiency of Magnetic Nanoparticles in a Tube under Magnetic Field

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Abstract

In this work, we have performed the computational simulation to calculate the capture efficiency of magnetic nanoparticles flowing within a fluid in a tube under magnetic field. The capture efficiency is calculated by considering the dominant magnetization and fluidic drag forces acting on the magnetic particles. Further, experiments are also performed to calculate the capture efficiency of magnetic particles experimentally in a tube of diameter 6 mm under magnetic field. Iron oxide (Fe₃O₄) nanoparticles were synthesized via co-precipitation method and transported them in a tube with help of peristaltic pump. The value of capture efficiency, calculated through experimental data, is found to be 26 and 50 %, which is slightly differ from its value (30 and 52 %) calculated through mathematical model at 2 and 6 kOe magnetic field, respectively. Subsequently, the experimental results validate the mathematical model results.

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1. Introduction

During the last decade, the application of nanotechnology to medicine for diagnosis and therapy has emerged as a promising new field, often referred to as nanomedicine [Riehemann et al., 2009]. A wide selection of nano-sized constructs has been developed for applications in drug delivery, imaging, and tissue engineering [Doshi et al., 2009].

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Gupta et al., 2014 studied the ferrites based nanostructures for biomedical applications. Nanoparticles (NPs) composed of magnetic iron oxides, i.e., magnetite (Fe_3O_4) and maghemite ($\gamma\text{-Fe}_2\text{O}_3$) (also known as ferrofluids), have received special attention for applications in magnetic drug targeting, contrast enhancement in MRI (magnetic resonance imaging), and hyperthermia treatment [McCarthy et al. 2008]. These ferrofluids have become the primary carriers due to their high saturation magnetization and magnetic susceptibility for magnetic targeting drug delivery. The basic idea of magnetic drug targeting (MDT) is that magnetic nanoparticles are used as controllable carriers of medical agents that are attached to the particles. The concept relies on intravascular injection of magnetic particles, transportation of the particles with the blood flow, and final capture of the particles at the target site under the influence of a magnetic field. The obvious benefits of magnetic drug targeting reside in local drug action and minimization of systemic side effects. This method of targeting is a promising approach for tumour treatment due to its high targeting efficiency. Compared with traditional chemotherapy, the accumulation and retention of the magnetic drug carrier particles can be enhanced by using an external magnetic field, which is focused on the area of the tumor. Driscoll et al., 1984 had studied magnetically targeted drug delivery by tracking each individual particle under the influence of Stokes drag force and magnetic force. Grief et al., 2005 conducted a theoretical analysis of targeted drug delivery using magnetic particles and proposed a two-dimensional network model. Furlani et al., 2009 presented an analytic model for transport and capture of therapeutic magnetic nanoparticles in the human microvasculature for targeted drug delivery applications. However, most existing models do not take into account of the real 3D effect and the interaction between blood flow and magnetic particles, Non-Newtonian behavior of blood and the effect of magnetic forces. Therefore, in order to fully understand and control the local flow behavior of blood and particles through the area of tumor-induced angiogenesis, it is essential to develop a sophisticated model and computational technique for the flow analysis.

In this work, we have performed the computational simulation to calculate the capture efficiency of magnetic nanoparticles flowing within a fluid in a tube under magnetic field. Further, experiments are also performed to calculate the capture efficiency of magnetic particles experimentally in a tube of diameter 6 mm under magnetic field. Iron oxide (Fe_3O_4) nanoparticles were synthesized via co-precipitation method and transported them in a tube with help of peristaltic pump. The capture efficiency as well as accumulation of magnetic nanoparticles in a tube under the influence of magnetic field are studied.

2. Mathematical Model

2.1. Equation of particle motion

The fluid flow along with magnetic particles is assumed to be flowing in a cylindrical tube. The magnetic particles are assumed to be uniformly distributed throughout the fluid. The blood is flowing in the axial direction and an external magnetic field is applied perpendicular to the flow direction. The flow behaviour of magnetic particles in a fluid under the influence of applied external magnetic field depends upon many factors including the applied magnetic force, fluidic drag, particle/fluid interactions, inertia, buoyancy, gravity, Brownian motion, and interparticle effects that include magnetic dipole interaction. In our mathematical model, we considered only dominated magnetic and fluidic force.

The equation of motion for particle under the applied external magnetic field can be written as

$$m \frac{d^2 r}{dt^2} = F_m + F_f \quad (1)$$

where m is the mass of the particle. F_m and F_f are the magnetic and fluidic drag forces. The fluidic drag force for a particle is determined by Stoke's law

$$F_f = 6\pi\mu r_p (u_f - u_p) \quad (2)$$

where u_f and u_p are the velocity of fluid and particle, respectively. Here μ and r_p are the viscosity of fluid and radius of the particle.

The magnetic force on the particle is given by

$$F_m = \mu_0 V_p (M \cdot \nabla) H \quad (3)$$

where M is the magnetization, μ_0 is the magnetic permeability of vacuum, V_p is the volume of the particle and H is the applied magnetic field. The particle acceleration can be neglected under this assumption and particle velocity can be calculated as

$$u_p = u_f + u_m = u_f + \frac{F_m}{6\pi\mu r_p} \quad (4)$$

where $u_m = \frac{F_m}{6\pi\mu r_p} = u_0 \frac{F_m}{F_f}$ is the magnetic velocity in the direction of the magnetic field.

2.2. Capture Efficiency

The capture efficiency (η) of magnetic nanoparticle is defined as the ratio between the total number of particles deposited along the vessel walls and the total number of released particles.

$$\eta = \frac{n_{in} - n_{out}}{n_{in}} \quad (5)$$

Here, n_{in} and n_{out} is the number of particle entering and leaving the vessel. The Magnetic Drug Targeting has a major challenge to produce a large magnetic force to capture particles of very small size. For this purpose, we have to choose the magnetic materials such as to maximize the capture efficiency. An important quantity η scales with the characteristic values of parameters such as the flow velocity (u_0), vessel radius (R), and applied magnetic field (H). We have taken $u_p = u_f + u_m$ and simplify the analysis by assuming that u_m is perpendicular to u_f .

With $l \sim u_m t$ the distance over which particles are displaced during a time $t \sim L/u_0$ in the direction of a magnetic force of spatial extent of the order L , one obtains a scaling for the capture efficiency as $\eta \sim l/R \sim (L/R)(u_m/u_0)$.

Introducing the particle magnetization number

$$Mn_p = \frac{u_m}{u_f} = \frac{F_m}{F_f} \quad (6)$$

The 'particle magnetization number' Mn_p can be written in terms of characteristic integral quantities as

$$Mn_p = \frac{2\mu_0 r_p^2 M H}{9\mu u_0 L}$$

The scaling relation obtained from the analysis is $\eta \sim \sqrt{\alpha Mn_p}$

For simple tube geometries, it is deduced theoretically that the particle capture efficiency scales as $\eta \sim \sqrt{Mn_p}$

or it can be written as [Haverkort et al., 2009]

$$\eta \sim r_p \sqrt{\frac{2\mu_0 MH}{9\mu u_0 L}} \quad (7)$$

We use the model derived above to study the capture efficiency of carrier particles with embedded magnetite nanoparticles. With the characteristic ratio of the particle magnetization force and the drag force. This relation is found to hold quite well for the carotid artery. In this model, the capture efficiency is calculated by using equation 7 by assuming, $\mu = 3.5 \times 10^{-3}$ Pa-s, $u_0 = 0.1$ m/s, $M = 10^6$ A/m and $r_p = 100$ nm.

3. Results and Discussion

Fig. 1 shows the capture efficiency (η) plot of magnetic particles, calculated using equation 7, at different magnetic fields. The curve indicates that capture efficiency increases as we increase the magnetic field. The value of capture efficiency is found to be 22, 30, 37, 43, 48, 52, 56, 60, 64 and 67 % at the magnetic field 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 kOe, respectively. This is because as the magnetic field increases, the magnetization force, which is attractive in nature and responsible to attract or capture the magnetic particles increases and results the capture of large number of magnetic particles due to high strength of attractive magnetic force.

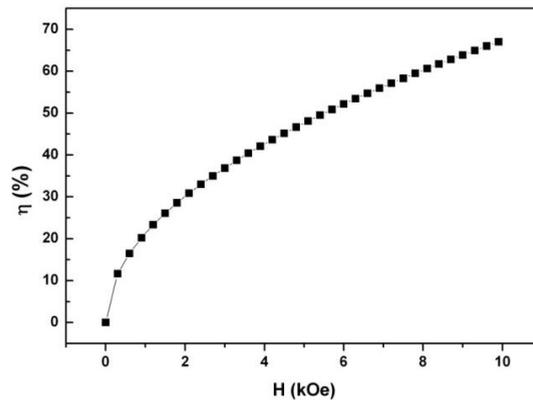


Fig. 1. Capture efficiency (η) of magnetic nanoparticles at different magnetic field (0-10 kOe).

We have also synthesized the Fe_3O_4 nanoparticles by co-precipitation method [Kim et al., 2001]. The X-ray diffraction (XRD) pattern of Fe_3O_4 nanoparticles is shown in Fig. 2 (a), which shows the pure phase formation of Fe_3O_4 without any impurity. The size of Fe_3O_4 magnetic particles was measured by Scanning Electron Microscopy (SEM) image as shown in Fig. 2 (b). The average diameter of the particles is found to be 20 nm. The Magnetization versus field hysteresis loop of Fe_3O_4 powder were recorded by Vibrating Sample Magnetometer (VSM) and shown in Fig. 2 (c). According to hysteresis loop, the Fe_3O_4 nanoparticles are superparamagnetic in nature as the magnetization is zero in absence of magnetic field. The saturation value of magnetization for Fe_3O_4 nanoparticles is found to be 50 emu/gm.

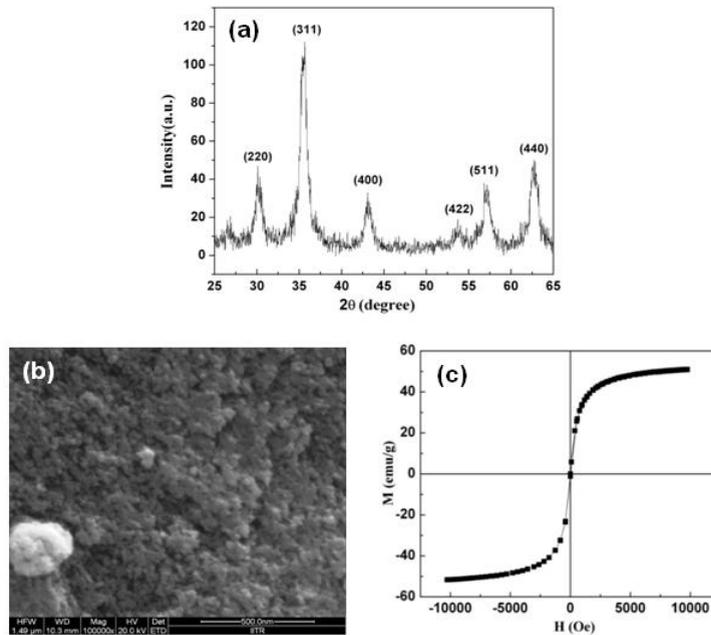


Fig. 2 (a-c). X-ray diffraction pattern (a), SEM micrograph (b) and M-H curve (c) of as synthesized Fe_3O_4 nanoparticles.

The prepared Fe_3O_4 magnetic particles were mixed in a fluid as simulated blood (75 % water + 25% Glycerol) with its concentration 15 % (V/V) and density of whole fluid is maintained as 1060 kg/m^3 . The simulated blood suspended with magnetic nanoparticles in inlet beaker was pumped into outlet beaker through the glass tube (simulated blood vessel) by a peristaltic pump with flow rate 2 ml/min. The diameter and length of glass tube is taken 6 mm and 30 cm, respectively. The glass tube is kept between an electromagnet to apply the magnetic field from 2-6 kOe perpendicular to the direction of fluid flow. It is observed that the magnetic particles start to accumulation at the centre of tube as the magnetic field is applied. The accumulation of magnetic nanoparticles increases as we increase the magnetic field.

Fig 3 (a-b) shows the images of magnetic nanoparticles accumulated at 2 and 6 kOe magnetic field, respectively. Images show that the more particles are accumulated at 6 kOe magnetic field as compared to 2 kOe field. This is because as the magnetic field increases, the magnetic force, which is attractive in nature and responsible to attract or capture the magnetic particles increases and results the more accumulation of particles due to high strength of attractive magnetic force.

Further, we have calculated the capture efficiency (CE) of magnetic particles through weighing the captured particles by using the formula

$$CE(\eta) = \frac{\text{weight of captured particles}}{\text{weight of total particles suspended in the fluid}} \times 100 \quad (8)$$

The value of capture efficiency, calculated through experimental data using equation 8, is found to be 26 and 50 % at 2 and 6 kOe magnetic field, which is slightly differ from its value (30 and 52 %) calculated through mathematical model at 2 and 6 kOe field, respectively. Therefore, the experimental results validate our model.

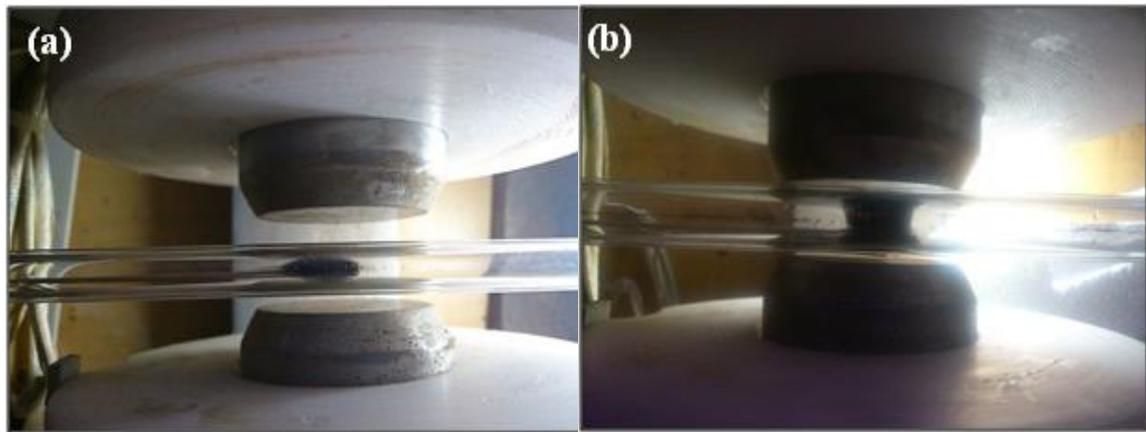


Fig. 3. Image of captured magnetic nanoparticles in a tube at different magnetic field: (a) $H=2$ kOe and (b) $H=6$ kOe.

4. Conclusions

In summary, the computational simulations are performed to calculate the capture efficiency of magnetic nanoparticles flowing within a fluid in a tube under magnetic field. The capture efficiency is calculated by considering the dominant magnetization and fluidic drag forces acting on the magnetic particles. It is observed that the capture efficiency increases from 22 to 67 % as we increase the magnetic field from 1-10 kOe. Further, experiments are also performed to calculate the capture efficiency of magnetic particles experimentally in a tube of diameter 6 mm. The capture efficiency, calculated through experimental data is found to be 26 and 50 % at 2 and 6 kOe, which is close to the value (30 and 52 %) observed though model results. Consequently, the experimental results validate the model results.

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