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The influence of magnetic field on nanoparticle transport in a micro channel

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The present study focuses on a new solver considering the effect of magnetic field on nanoparticles concentration in a micro size channel. To describe the multi component behavior of blood, the Euler-Euler method is used. Particles are modeled by a concentration equation considering a magnetic drift. The influence of a realistic magnetic field on nanoparticles is investigated. A result for a test case is presented. It shows that the magnetic body force resulting from nanoparticles also influence the hematocrit distribution in the channel.

1 Introduction

Magnetic Drug Targeting is a new approach in nano-medicine based on nanoparticles utilization as drug carriers. Purpose of this method is to minimize the toxic side effect of drugs on healthy tissues by delivering them to a certain location in patient's body. Aim of the present study is to extend the previous work presented in [1]. There, focus of study was the effect of a constant magnetic field gradient on the ability to concentrate particles on a micro channel's wall under consideration of the Fahraeus-Lindqvist effect and local blood cell concentration (hematocrit). In contrast, the current study uses a realistic magnetic field, of which the gradient is computed. Furthermore, the magnetic body force caused by the particles is considered in the momentum equation.

2 Simulation Approach

The developed simulation approach solves the magnetic field, blood flow and nanoparticles transport. Blood flow and nanoparticles do not affect magnetic field, hence it is calculated in advance. Based on solving the magnetic scalar potential,

$$\nabla \cdot (\mu \nabla \psi) = -\nabla \cdot (\mu \mathbf{M}), \quad \mathbf{H} = \nabla \psi, \tag{1}$$

the magnetic field strength H is drived. In this equation local permeability μ and magnetization $\mathbf{M}$ are used. An Euler-Euler approach as developed in [2], based on theory of interacting continua, is used to model blood flow. Transport of phases is described by a scalar transport equation and in comparison to [1], additionally, a magnetic body force $\mathbf{f}_{mag}$ is used:

$$\frac{\partial \phi}{\partial t} + \nabla \cdot \left(\phi \overline{\mathbf{U}}_\phi\right) = 0, \quad \text{RBC: } \phi = \alpha, \quad \text{plasma: } \phi = \beta, \quad \mathbf{f}_{mag} = n_n \left(\frac{1}{2}\mu_0 \chi V_n \nabla(|\mathbf{H}|^2)\right). \tag{2}$$

It depends on volume specific number of particles $n_n = \gamma / V_n$, based on the volume fraction of the nanoparticles $\gamma = c\gamma_{ref}$. Concentration of nanoparticles is c (see eq. (3)), γ_{ref} is a reference (inlet-) volume fraction of nanoparticles, for which studies are performed. V_n is a single particle's volume and $\chi = 20$ is the magnetic susceptibility of iron particles. Further information is given in [1]. Plasma is considered as Newtonian fluid and red blood cells as non-Newtonian, in which viscosity depends on both shear rate and red cell's volume fraction. Interface momentum transfer is described by a laminar drag and lift model. Continuity of the mixture is demanded. All these models are considered in the momentum and continuity equation

$$\frac{\partial \phi \overline{\mathbf{U}}_\phi}{\partial t} + \nabla \cdot \left(\phi \overline{\mathbf{U}}_\phi \overline{\mathbf{U}}_\phi\right) + \nabla \cdot \left(\phi \overline{\mathbf{T}}_\phi\right) = -\frac{\phi}{\rho_\phi} \nabla \overline{p} - \frac{\overline{\mathbf{F}}_\phi}{\rho_\phi} + \phi \mathbf{f}_{mag}, \quad \nabla \cdot \left(\alpha \overline{\mathbf{U}}_\alpha + \beta \overline{\mathbf{U}}_\beta\right) = 0, \tag{3}$$

an exact explanation is given in [1]. Transport of nanoparticles concentration is described by eq. (4). It considers attraction to the magnet, displacement of particles by red blood cells and Brownian diffusion. The equation solved is

$$\frac{\partial c}{\partial t} + \nabla \cdot \left(c\left(\overline{\mathbf{U}} - \mathbf{U}_{Drift}\right)\right) = \nabla \cdot (D_c \nabla c), \quad \mathbf{U}_{Drift} = \mathbf{U}_{Drift,\alpha} - \frac{d_c^2 \mu_0 \chi}{36 \overline{\eta}} \nabla\left(|\mathbf{H}|^2\right), \tag{4}$$

models and parameters are described in [1]. The magnetic field is solved using the *magneticFoam* solver of *OpenFOAM-dev*. For solving the flow *twoPhaseEulerFoam* of *foam-extend-4.0* is modified.

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3 Problem Description and Results

The test case is a 100 μm high and 4mm long micro-channel placed centrally under a magnet in a distance of 500 μm, c.f. fig. 1 (left). In the calculation of magnetic field, parameters for neodymium were set. This corresponds to a magnetization of $\mathbf{M} = 900\mathrm{e}_y$ kA m^{-1} and a relative permeability of $\mu_r = 0.9$, leading to a peak magnetic flux of $|\mathbf{B}| \approx 1$ T inside the magnet. Outside the magnet the magnetization is zero and $\mu_r = 1$. For the magnetic domain 4000×4000 uniform cells are used. As the result in fig. 1 (middle) shows, the magnetic field lines are as expected. Fig. 1 (right) shows the magnitude of the magnetic field gradient and its vectors. In this representation it can be seen that the particles are attracted by poles.

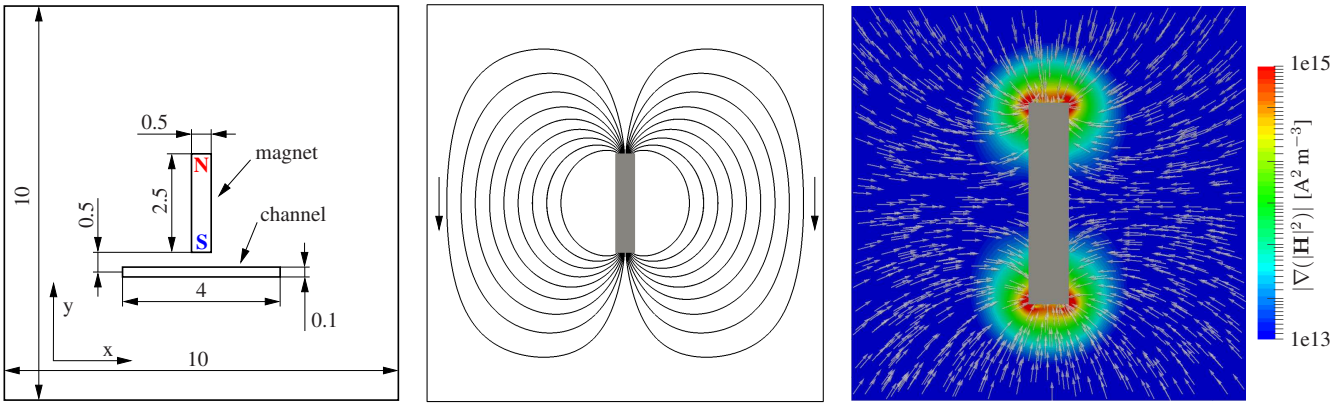

Fig. 1: Left: magnet and flow channel configuration and dimensions in millimeter. Middle: magnetic field lines generated for $\mathbf{H}$. Right: vectors of the magnetic field gradient and its magnitude in the proximity of the magnet.

For simulation of the flow $|\nabla(|\mathbf{H}|^2)|$ is mapped onto the channel's mesh, which consists of using 50 cells over the height and 1000 over the length. The boundary conditions set are the same as named in [1]. In the simulation presented, the outflow velocity is set to 1 cm s^{-1}, which is a typical value for artrioles. The reference nanoparticle fraction is $\gamma_{ref} = 5.5e-4$ and the inlet concentration is $c = 1$.

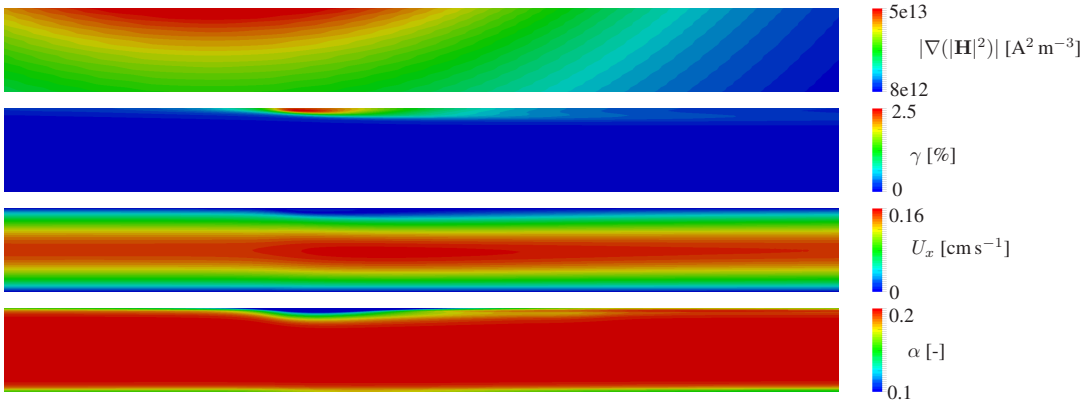

Fig. 2: From top to bottom: mapped magnetic field gradient, steady state volume fraction of nanoparticles, horizontal velocity and red blood cells volume fraction. The presented domain is reduced to proximity of the magnet.

Fig. 2 shows that nanoparticles are concentrating at the wall in the region with a high magnetic field gradient slightly downstream due to convection. Below, the horizontal velocity is increased as expected for a reduction of the flow channel's height. It is known that the Fahreus effect reduces the red blood cells concentration at the wall, which is also visible in the simulation. It was discovered that this effect is increased by the nanoparticles body force. The chosen value for γ_{ref} represents a limit case. For values above that, the concentration at the wall will increase infinitely. This effect was already discovered in [1]. Considering that there is already a balance of red blood cells and plasma ($\alpha + \beta = 1$), it should be seen critical that a third phase occurs with reaching a volume fraction of 2.5%. Additionally the absorption of nanoparticles should be considered. This demands the development of a boundary condition.

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