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A Numerical Simulation of Arterial Mass Transport in Presence of Magnetic Field-Links to Atherosclerosis

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***Abstract*—**This paper has focused on the most important parameters in the LSC uptake; inlet Re number and Sc number in the presence of non-uniform magnetic field. The magnetic field is arising from the thin wire with electric current placed vertically to the arterial blood vessel. According to the results of this study, applying magnetic field can be a treatment for atherosclerosis by reducing LSC along the vessel wall.

Homogeneous porous layer as a arterial wall has been regarded. Blood flow has been considered laminar and incompressible containing Ferro fluid (blood and 4 % vol. Fe_3O_4) under steady state conditions. Numerical solution of governing equations was obtained by using the single-phase model and control volume technique for flow field.

***Keywords*—**LDL Surface Concentration (LSC), Magnetic field, Computational fluid dynamics, Porous wall.

I. Introduction

RESEARCH indicates that there is one common thread that links all vascular disease: high blood viscosity [1]. The relation of rheological variable to cardiovascular events were at least as strong as those of conventional risk factors (smoking habit, diastolic blood pressure, and low density lipoprotein) [2]. Studies have also shown that the more viscous the blood is, the more injurious it is to blood vessels. The cells that line damaged arteries and veins will attempt to adapt to the assault and offset the impact by actually building up plaque, a condition called atheroma. A safe and reliable method to reduce high blood viscosity is thus important and may be valuable. At present, the only method to reduce the blood viscosity is to take medicine such as aspirin. Based on Tao et al. reports, blood viscosity can be reduced by the use of high magnetic fields of 1 T or above parallel to the blood flow direction. One magnetic field pulse of 1.3 Tesla lasting ~1 min can reduce the blood viscosity by 20%-30%. The strong magnetic field aggregates red cells along the field direction to form short chains. In addition to increasing poly dispersity, etc., for the blood, this change also makes the blood flow similar to a nematic liquid crystal flow with the molecule alignment parallel to the flow direction (Fig. 1): The viscosity along the flow direction is significantly reduced [3].

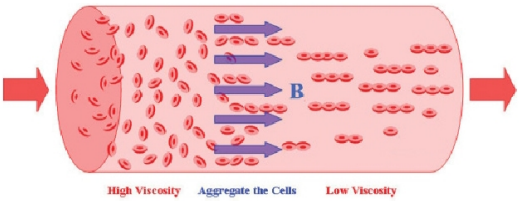

Fig. 1 Aggregated red-cell clusters have the shape that favors the flow dynamics, leading to further viscosity reduction [3]

Atherosclerosis is a disease of large arteries that is characterized by the accumulation of lipids in the arterial wall. The transport process of atherogenic species such as low density lipoprotein (LDL) from the bulk blood flow to and across the arterial wall contributes to lipid accumulation. This transport process is termed “arterial mass transport” and is influenced by blood flow in the lumen and transmural flow in the arterial wall. There are two pathways of LDL transport through the endothelium: by vesicular transcytosis, which is regulated by receptors on the endothelial cells, and through leaky junctions (opened leaky junctions provide pathways for LDL transport), most of which are located at the sites of dying or replicating cells [4].

Because the occurrence of leaky junctions is governed by the adjacent endothelial cells, and because the behavior of the endothelial cells is in turn influenced by the shear stress acting on their surface, LDL transport in the arterial wall is in part governed by local blood flow characteristics that determine the level of wall shear stress [5].

In the previous studies [6], [7] by assuming blood as a ferrofluid it was shown that Using a magnetic field directs to decreasing the LSC about 4%, but position of thin wire which carries an electric current, also its intensity is really important. In those works arterial wall, was treated as a boundary condition. This approach is generally called a “wall-free model,” and has the advantage of being computationally cheap and providing qualitative information on mass transfer in the blood lumen.

The alternative is the fluid-wall model with a single-layered formulation, which treats the intima and media of the arterial wall as one single layer of porous medium with homogeneous transport properties. It takes into account transport processes within the arterial wall without excessive computational expense.

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The main focus in this investigation is to provide a feasibility study of numerically simulating of non-uniform magnetic field effects on the LDL surface concentration (LSC) in the lumen-wall interface and outer layer of porous. FDA (food and drug administration) has approved magnetic strengths up to 8 T for use with humans and human clinical trials have utilized 0.2–0.8 T magnetic field strengths [8]. The magnetic field is generated by an electric current going through a thin and straight wire oriented perpendicular to the longitudinal axis (x) at the position (a and b), as shown in Fig. 2.

II. Mathematical Model

The blood flow considered as the laminar, incompressible, fully developed, Newtonian viscous flow. Also, it is regarded with a constant viscosity of 0.0038 Pa.s and a density of 1058 Kg/m^3. Thus, blood can be considered to be a magnetic fluid, with the erythrocytes playing the role of the magnetic dipoles and the plasma playing the role of the liquid carrier. This model is consistent with the principles of ferrohydrodynamics (FHD), and the dominant force in the flow field is that of magnetization. However, blood also contains ions in the plasma, which interact with an applied magnetic field. Consequently, blood can be considered to be an electrically conducting fluid that simultaneously exhibits magnetization, and thus, the principles of magnetohydrodynamics (MHD) could also be incorporated into the mathematical model which has been ignored in this study.

The iron oxide in hemoglobin has been considered in the flowing blood as Nano particles (4 Vol % Fe3O4). As known, viscosity and the thermal conductivity of the Ferro fluid are affected by magnetic field, these effects are supposed minimal [9].

The governing equations of the problem are the mass, momentum and concentration conservation, also Darcy's law. By employing suitable boundary conditions, they have solved. For reducing volume of calculation nanofluid (blood) by considering single-phase method added to the mathematical model. Tube length is 125 mm and lumen diameter is 5 mm, also the thickness of porous domain is 0.3 mm.

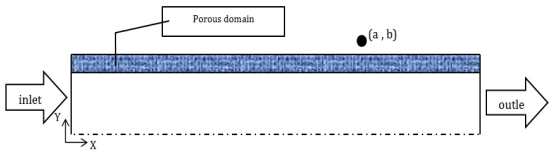

Fig. 2 Schematic of the one homogeneous porous layered structure of an artery wall (not to scale)

A. Fluid Dynamics

Under the assumption of steady-state conditions and incompressible blood with Newtonian rheology, the fluid dynamics in the artery lumen are governed by:

$$\nabla(\rho_e \ \vec{v}) = 0 \tag{1}$$

$$\nabla.\left(\rho_e \ \vec{v}\vec{v}\right) = -\nabla p + \nabla.(\mu_e \ \nabla\vec{v}) + \mu_0(\vec{M}\nabla)\vec{H} \tag{2}$$

$$V.\nabla C = D\nabla^2 C \tag{3}$$

Second term in (2) shows force comes from viscous shearing of the fluid. The last term $\mu_0(\vec{M}\nabla)\vec{H}$ represents the influence of the magnetic force as a body force on the fluid element due to fluid-magnetic pressure which μ_0, M and H are absolute permeability (equal to $4\pi \times 10^{-7}$, [H/m]), applied magnetic field and magnetization) respectively [10]. Magnetic force in this work has produced by long current which was placed perpendicular of the vessel. The components of the magnetic field intensity H_x and H_y along the x and y coordinates, (H= (H_x, H_y)) are given by:

$$H_x(x,y) = \frac{I}{2\pi}\frac{(x-a)}{(x-a)^2+(y-b)^2} \tag{4}$$

$$H_y(x,y) = \frac{I}{2\pi}\frac{(y-b)}{(x-a)^2+(y-b)^2} \tag{5}$$

where I is the magnetic field strength at the point (x=a, y =b) and the magnitude H, of the magnetic field intensity is:

$$H(x,y) = \sqrt{(H_x(x,y))^2 + (H_y(x,y))^2} = \frac{I}{2\pi}\frac{1}{(x-a)^2+(y-b)^2} \tag{6}$$

The transfer of blood-borne solutes such as oxygen, ATP, or LDL is governed by the advection-diffusion equation as (3) in the lumen.

The above mentioned non-linear and coupled partial differential governing equations subjected to the following boundary conditions which are agree with many studies [11], [12]:

- At the inlet:

U_{in}=0.2 m/s, C_o=1300 kg/m^3.

- At the outlet:

The static gage pressure is set to zero and $\partial C/\partial x$=0.

B. Porous Domain

The transmural flow in the arterial wall is modelled by Darcy's Law:

$$u_w = \frac{k_P}{\mu_P}\nabla P_w \tag{7}$$

$$\nabla.u_P = 0 \tag{8}$$

k_P, μ_P and P_w are the permeability of the arterial wall, viscosity of the blood plasma, and pressure within the arterial wall, respectively. The LDL transport in fluid domain is governed by convection-diffuision equation:

$$u_1.\nabla c_1 - D_1\Delta c_1 = 0 \tag{9}$$

where cl and D1 are the LDL concentration and diffusion coefficient in the lumen, respectively.

C.Nano Fluid

Many of the researchers have studied the heat transfer characteristics of nanofluids in last decade experimentally as well as computationally. There have been concerns that if the nanofluids behave as a single phase fluid or it has to be treated as a two-phase mixture. Using a single phase model for nanofluid simplifies the application of computer simulation technique as only the material properties in the Navier-Stokes and energy equations need to be modified with appropriate correlations. For nanofluids within the single phase approximation, the appropriate expression for density, specific heat, thermal conductivity, and viscosity need to be prescribed [13].

$$\rho_n = \alpha_p \rho_p + (1-\alpha_p)\rho_f \quad (10)$$

$$\mu_n = \left(1+\frac{5}{2}\alpha_p\right)\mu_f \quad (11)$$

The governing equations of the flow field are solved numerically by using the one phase homogeneous model and control volume technique.

In the non-dimensional form;

$$Re\ v \cdot \nabla c = (1/Sc)\nabla^2 c \quad (12)$$

where c is the normalized concentration of the species of interest, the Schmidt number is defined as Sc = ν/D and D is the diffusivity. The Peclet number is the product of Re and Sc, which indicates the relative importance of convective versus diffusive mass transfer effects.

III. Numerical Method

In this study, the set of non-linear differential equations was discretized with the control volume technique. For the convective and diffusive terms a High resolution method was used and convergence criteria of 1e-6 in root mean square have been applied. A structured grid has been used to discrete the computational domain. It is finer near the walls where the velocity and concentration gradients are large. Several different grid distributions have been examined to ensure that the calculated results are grid independent. In the Fig. 3 (A) dimensionless LSC on the outer porous layer has shown based on the Table I, and mesh 6 (110000 elements) has selected.

After that, the Fig. 3 (b) indicates the comparison of the present dimensionless concentration profile along the wall, with the result of reference study [14], as seen this is in line with available data.

IV. Results

The magnetic field is generated by an electric current going through a thin and straight wire oriented perpendicular to the longitudinal axis (x) at the position (a, b). Properties of the studied base fluid (blood) and nanoparticle have been presented in Table II.

TABLE I
ALL MESH TYPES USED IN THE MESH DEPENDENCY EXAMINATION

Mesh types	Node number	Element number
Mesh 0	98546	48000
Mesh 1	72904	35000
Mesh 2	185064	91000
Mesh 3	237864	117000
Mesh 4	290664	143000
Mesh 5	201824	99000
Mesh 6	224624	110000
Mesh 7	246624	121000

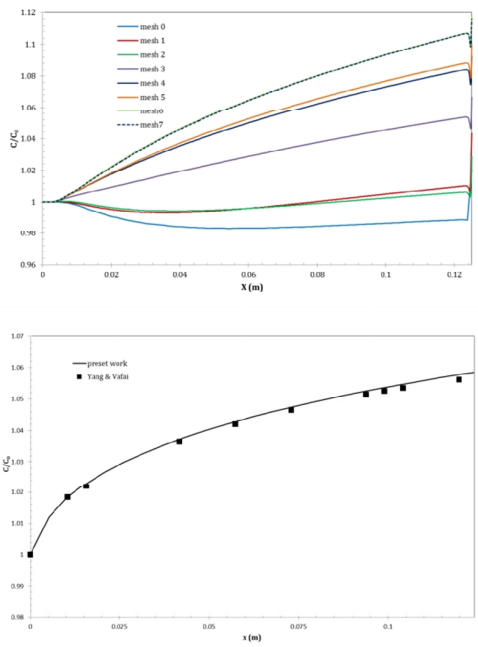

Fig. 3 (a) Grid examination, (b) Comparison of LSC resulted in this paper and work of [14]

TABLE II
PROPERTIES OF THE STUDIED BASE FLUID (BLOOD) AND NANOPARTICLE

Properties	Nano particle (Fe_3O_4)	Base fluid (blood)	Effective
ρ [kg/m³]	5200	1050	1216
μ [Pa.S]	-	0.0035	0.00385

Initially, finding the place for applying a magnetic field to the blood vessel is necessary. As seen in Fig. 4, in the presence of a magnetic field produced by wire intensity of 30A (which is about 0.5 Tesla), the best place is b=2.9 mm. The wire is such a needle, which was placed outer the tissue to disappear the negative effects of magnetic field on the blood hemodynamics.

Figs. 4 (a) and (b) show the nondimensionalized LSC on the lumen-tissue interface and upper layer of tissue, respectively.

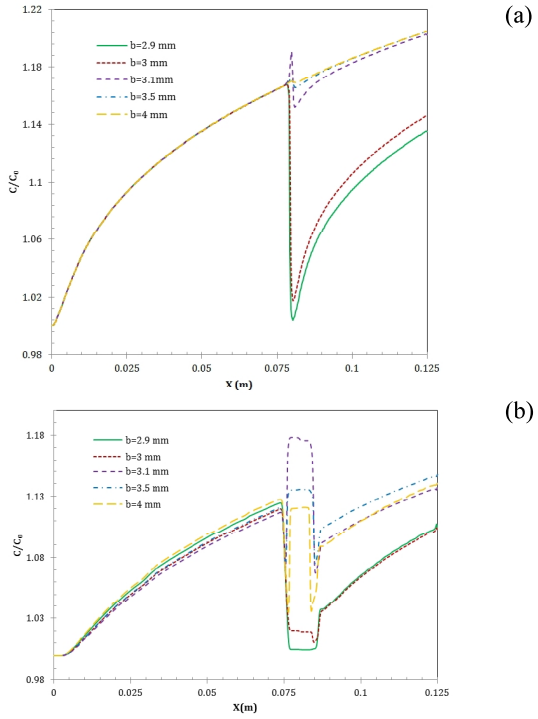

Fig. 4 (a) LSC distribution along the lumen-tissue interface for different b, (b) LSC distribution along the upper tissue wall for different b

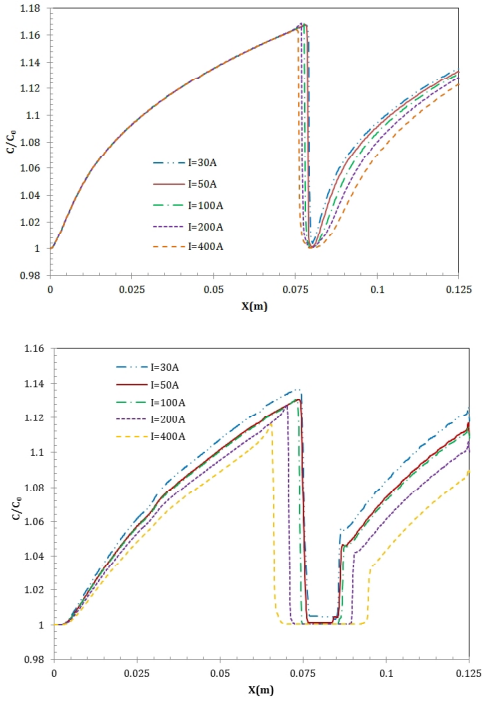

Fig. 5 Behavior of LSC in the presence of a magnetic field by different wire intensity in the lumen-tisssue interface (a) and upper layer of porous domain (b)

Fig. 5 illustrates the behavior of LSC in the presence of a magnetic field by different wire intensity in the interface of the lumen-tisssue (Fig. (5-a)) and upper layer of porous domain (Fig. (5-b)).

When inlet Reynolds number increases, the particle settlement time on the blood vessel wall reduces thus the LSC plunge. Fig. 6 shows augmentation of inlet velocity causes to fall in the LSC along the wall. Similarly, observed that applying magnetic field can be affected the flow pattern more in low Reynolds numbers. As known, More Re number arise from high momentum in flow field which can damps the magnetic force effect.

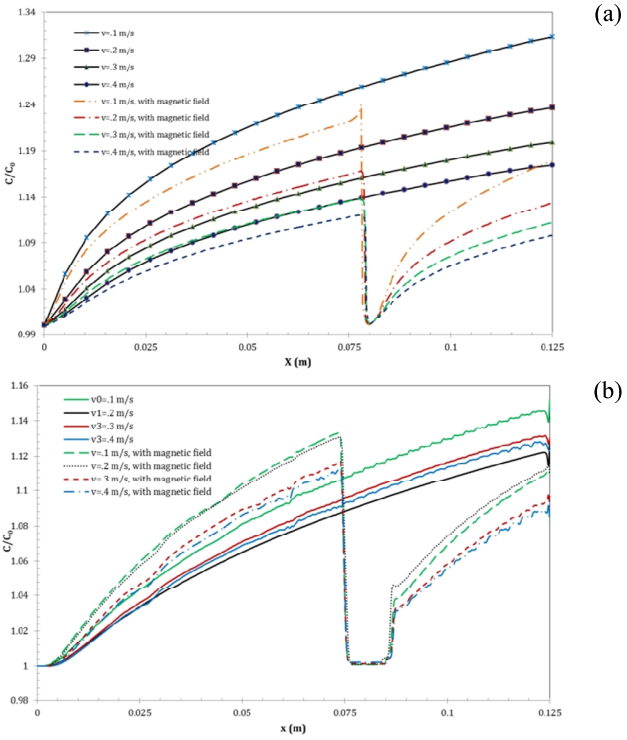

Fig. 6 Magnetic field effect on the LSC along the wall for different Re number; (a) In the lumen-tissue interface, (b) The upper layer of porous domain

Fig. 7 shows LSC along the wall for different Schimdt number 1.6e+5, 3.3e+5 and 6.6e+5 with and without magnetic field effect. Sc number is calculated based on the constant viscosity and the diffusion coefficient. LDL particles are formed into various sizes and different amounts of fatty acids, thus the diffusion coefficient of these particles will vary in the fluid. Diffusion coefficient is according to the Fick law, depends on the particle size, temperature and viscosity of the fluid. This relationship can be revealed under Stokes - Einstein equation as:

$$D_E = \frac{K_B T}{6\pi\mu R} \quad (13)$$

Particle radius R, Boltzmann constant K_B =1.38e-23, viscosity and temperature of fluid are μ and T, respectively. In

this regard, larger LDL particles in the blood have a low diffusion coefficient and high Schmidt number. Small particle diffusion (large Schmidt number) leads to decrease the boundary layer thickness; Also, the concentration gradient in the vessel wall enhances.

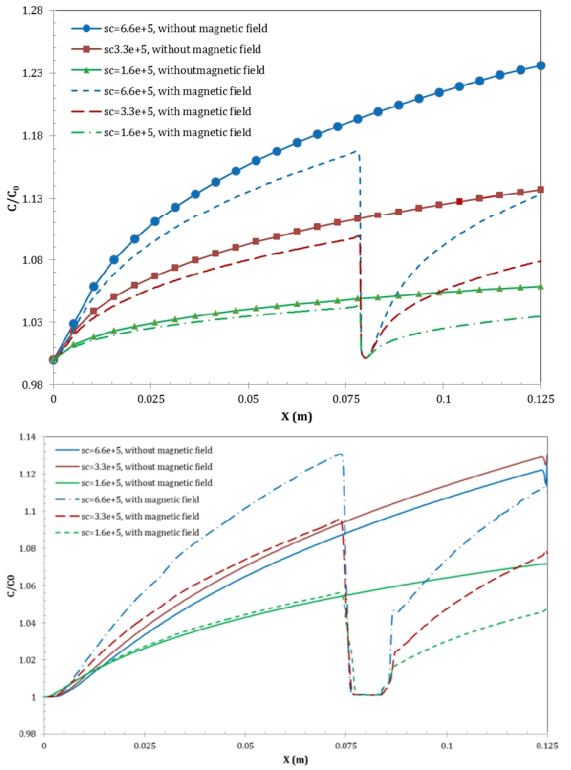

Fig. 7 LSC along the wall for different Schimdt number; (a) In the lumen-tisssue interface, (b) The upper layer of porous domain

V. Conclusions

This paper has focused on the most important parameters on the LSC uptake; inlet Re number and Sc number in the presence of non-uniform magnetic field. The magnetic field is arising from the thin wire with electric current placed vertically to the arterial blood vessel.

- Using a magnetic field directs to decreasing the LSC, but position of thin wire which carries an electric current, also its intensity is really important.
- By increasing the inlet Re number LSC uptake is becoming less. Applying a magnetic field can be affected flow pattern more in low Reynolds numbers. More Re number arise from high momentum in flow field which damps the magnetic force effect.
- Numerical solution of governing equations was obtained by using the single-phase model and control volume technique for flow field. As well, this numerical study is incredibly economical in comparison with in-ex vivo experimental observations accordingly, it seems a logical way for treatment of atherosclerosis. However, in the author's knowledge, it is a golden opportunity for healing of atherosclerosis, but also experimental work is needed to confirm these results.
- It is a motivating recommendation to investigate the impact of magnetic field on the formed plaque due to atherosclerosis in the blood vessel wall. In future work, we try to answer this question; magnetic field can disintegrate or diminish the plaque? Also, hemodynamic parameters how affected by this situation?

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