NUMERICAL SIMULATION OF BLOOD FLOW IN A TUBE BY USING THE COMSOL MULTIPHYSICS SOFTWARE

S.F. Salem[1,2], V.V. Tuchin[1,3,4,5]
[1]Department of Optics and Biophotonics, Saratov State University, Saratov 410012, Russia
[2]Department of Physics, Faculty of Science, Benha University, Egypt
[3]Interdisciplinary Laboratory of Biophotonics, Tomsk State University, Tomsk 634050, Russia
[4]Laboratory of Molecular Imaging, Bach Institute of Biochemistry, Research Center of Biotechnology of the Russian Academy of Sciences, Moscow 119071, Russia
[5]Institute of Precision Mechanics and Control of the Russian Academy of Sciences, Saratov 410028, Russia

Abstract. In this work, numerical simulation for biomagnetic fluid (such as blood) flowing through a tube with a rectangular cross section is studied under the influence of the magnetic field. The effects of the magnetic field on the blood stream in a tube are generated outside the tube with a permanent magnet. COMSOL Multiphysics® Modeling Software has been used to numerically solve the motion equations that describe the flow by combining magnetic equations for permanent magnet and Navier-Stokes equation for fluid (blood).
Keywords: Newtonian fluid, non-Newtonian fluid, permanent magnet, computational modeling.

1. Introduction

Blood behaves as a magnetic fluid because of the intercellular proteins, cell membrane, and hemoglobin's complex association with the magnetic field. The blood magnetic property is determined by the state of oxygenation of hemoglobin (a form of iron oxide in red blood cells (RBCs)) [1-4].

Tzirtzilakis E. [5]. Suggested a BFD mathematical model and studied an application in which the three-dimensional, fully developed, viscous flow of a biomagnetic fluid under the influence of a magnetic field was numerically investigated. Using an efficient technique based on a pseudotransient, pressure-linked system implemented on a standard orthogonal grid, numerical results are reached.

Tzirtzilakis E. [6]. In another work the movement of BFD in a channel with symmetric stenosis was studied numerically. The numerical solution of the problem is based on developed numerical finite difference. Results relating to the velocity field show that the downstream flow symmetry of the stenosis breaks and the vortex near the magnetic field source are enlarged.

Tzirakis K. et al. [7]. Presented a mathematical model to explain the exposed biomagnetic fluid flow to a magnetic field which accounts for both the electrical and magnetic properties of the biofluid. This is done by applying the forces of Lorentz and magnetization to the equations of Navier-Stokes and considering the case of laminar, incompressible, viscous, steady flow of Newtonian biomagnetic fluid.

Alexandru M. et al. [8]. Provided the mathematical model and numerical simulation findings for complex arterial blood flow-structural coupled models unique to magnetic drug targeting (MDT). In their approach, the computational domains are created using image-based reconstruction techniques, which provide a more realistic definition.

Blood in this work is regarded as Newtonian and non-Newtonian fluid. Using COMSOL Multiphysics ® Modeling Software numerically solved the motion equations describing the flow by using magnetic equations for permanent magnet and Navier-Stokes equation for fluid (blood).

2. Formulation of the problem

Biomagnetic fluid (blood) flowing through a tube is analyzed using the rectangular cross-section. Blood flow in this model was considered as a steady laminar flow of viscous and incompressible fluid. Blood motion is considered in two dimensions (x, y) with corresponding components of velocity in Cartesian coordinates (u, v). The magnetic field which a permanent magnet produces is situated outside the tube. The problem-solving model domain contains two domains: first, the tube domain that contains biomagnetic fluid such as blood, and the second domain of a permanent magnet and surrounding medium is air. The magnet is located on a distance =2mm between the surface of magnet and the tube surface as shown in (Fig.1).

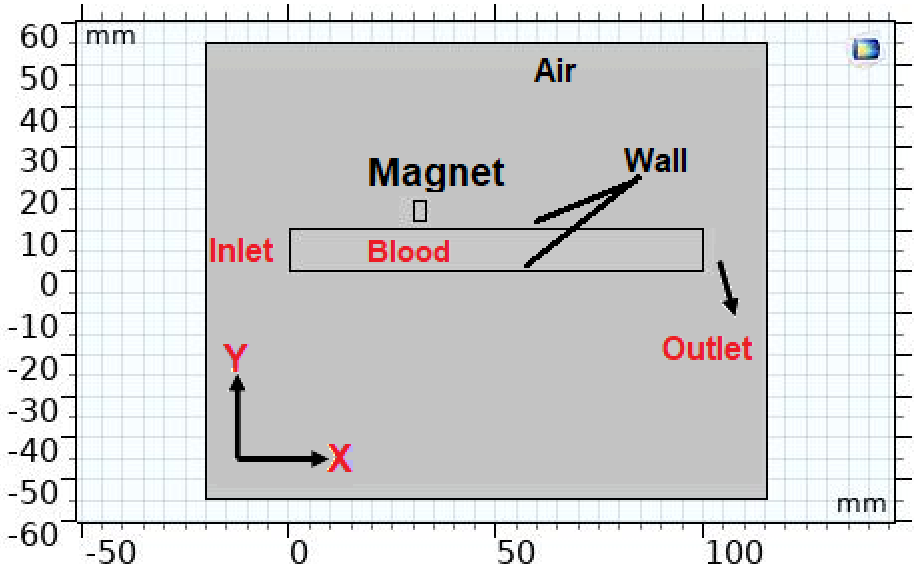

Figure1: Geometric domains for the model. The tube domain is rectangular cross section with dimensions 100 mm ×10 mm, the permanent magnet with dimensions 3 mm ×5 mm (A).

3. Equations of motion and results

3.1 Used modules of the COMSOL Multiphysics® Software

To provide calculations, the equations describing the problem were solved numerically by using two different modules of the COMSOL Multiphysics® Software. These modules include:

1. AC/DC module to calculate the magnetic field of the permanent magnet.
2. CFD module for laminar fluid flow such as blood. The flow of blood in this problem is described by Navier-Stokes equation, which considers blood as a Newtonian and non- Newtonian fluid.

3.2 Magnetic field

A stationary magnetic field produced by a permanent magnet implanted at a specific location is described by the magnetostatic equations for the static magnetic field derivered from the Ampere-Maxwell equation [9]:

$$\nabla \times \overline{H} = \overline{J}, \tag{1}$$

Gauss law for magnetic flux density is given by:

$$\nabla \cdot \overline{B} = 0, \tag{2}$$

and the magnetic flux density in different domains can be described by the relation between $\overline{B}$ & $\overline{H}$, which is given by theses formulas:

for the blood stream $$\overline{B} = \mu_0 \left(\overline{H} + \overline{M_b}(H)\right), \tag{3}$$

for the permanent magnet $$\overline{B} = \mu_0 \mu_r \overline{H} + B_{rem}, \tag{4}$$

for the air $$\overline{B} = \mu_0 \overline{H}, \tag{5}$$

where μ_0 is the magnetic permeability of air and it is constant $\mu_0 = 4\pi \times 10^{-7}$ N/A^2; μ_r, is the relative magnetic permeability of the permanent magnet; H is the magnetic field strength; B is the magnetic flux density; B_{rem} is the remanent magnetic flux density; $M_b(H)$ is the magnetization vector of the blood stream (A/m), which is a function of magnetic field, H.

3.3 Equations of motion for the fluid (blood)

The motion of blood through the tube can be expressed by incompressible Navier-Stokes equations [10-12]:

$$\rho \frac{\partial \overline{u}}{\partial t} + \rho\left(\overline{u} \cdot \nabla\right)\overline{u} = -\nabla P + \eta \nabla^2 \overline{u} + \overline{F}, \tag{6}$$

where $\overline{u}$ is the velocity vector; ρ is the density; ∇p is the pressure gradient; η is the blood dynamic viscosity; $\overline{F}$ is the external force per unit volume.

For non - Newtonian blood flow, the rheological properties of blood such as effective viscosity are governed by a power law model [13].

$$\eta = m\left(\gamma^{\bullet}\right)^{n-1}, \quad (7)$$

where $\gamma^{\bullet}$ (1/s) represents the shear rate, η represents an apparent or effective viscosity as a function of the shear rate (Pa·s), where m=0.035 Kg. $m^{-1}.s^{-1}$ and n=0.6 are the constants coefficients depending on the type of fluid. Since blood is known as a shear-thinning fluid, thus the power index (dimensionless), n<1.

3.4 Boundary conditions for the fluid (blood)

The blood flow was known to be a continuous flow, which would flow from the inlet into the tube and leave the outlet channel. Velocity for the inlet section and a fixed pressure for the outlets were applied as a result. The velocity profile for blood in x-axis and the flow at zero velocity in y- direction at the tube's inlet. No slip condition was presumed for all the tube walls, i.e. (u= 0) as in (Fig.1).

The inlet velocity described by [$u_x = u_{max}(1 - (x/h)^2)$], u_{max} is the maximum velocity, h is the tube height, the density of blood=1060 Kg/m^3 and the dynamic viscosity is η and it is constant for Newtonian fluid and for non-Newtonian fluid changes and depend on shear rate $\gamma^{\bullet}$ as shown in Eq.(7).

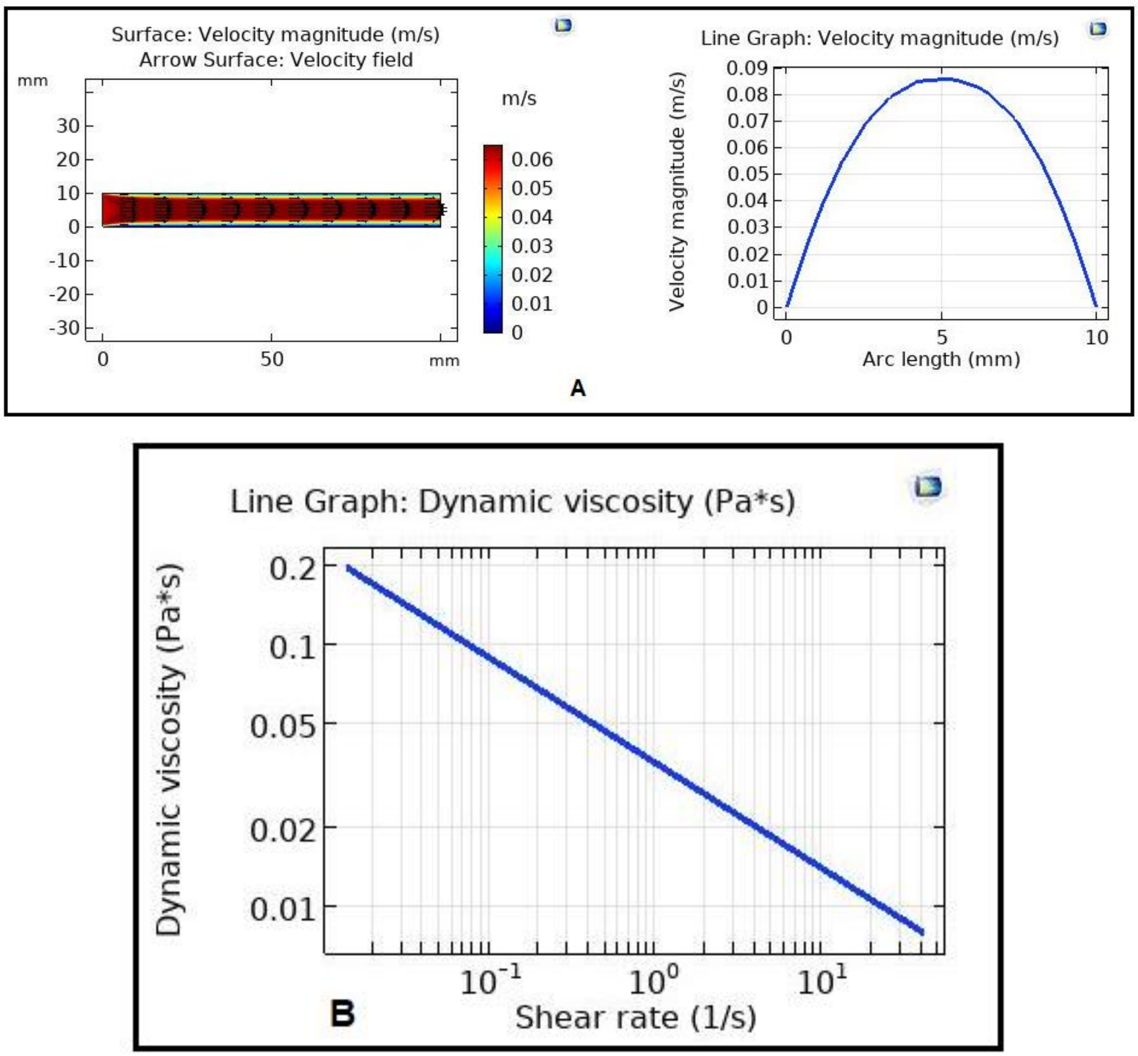

Figure2: Results of simulation: surface of velocity magnitude for Newtonian blood flow in the tube; line graph velocity profile for Newtonian blood flow inside the tube (A); log scale Dynamic viscosity for non-Newtonian blood according to the formula of viscosity in Eq. (7),(B) input velocity according to [ux = umax (1 - (x/h)2)] and the maximum velocity value 0.06m/s.

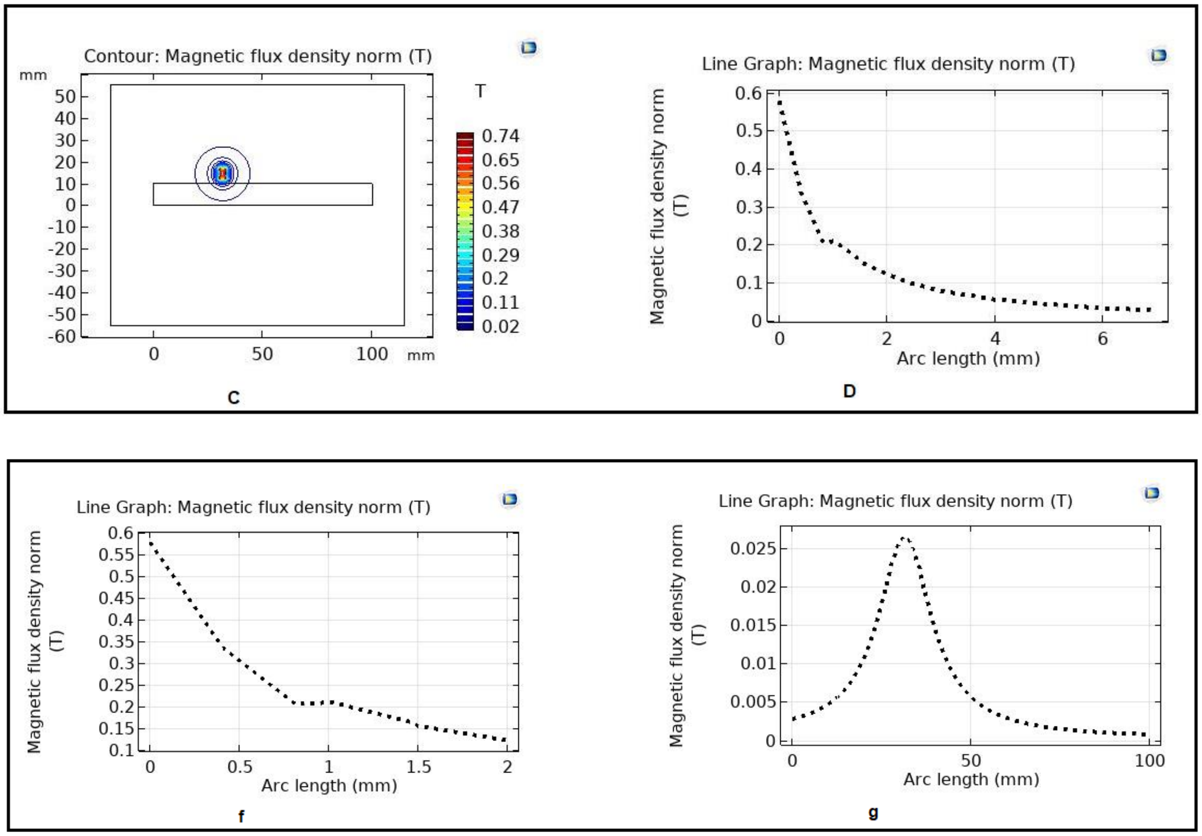

Figure3: Results of simulation: contour of magnetic flux density for permanent magnet at a limit distance x=30mm (C); magnetic flux density along the distance between the surface of magnet and the tube center as line graph (D); magnetic flux density along the distance between the surface of magnet and the tube surface as line graph (f); magnetic flux density along the tube center as line graph (g).

4. Discussions for results

The permanent magnet with magnetic field was applied to the tube in this work, with the results shown in Fig. 3. It follows from simulations that the greatest strength of the magnetic field is created in the vicinity of the magnet surface and decreases far from the magnet surface as line graph (f).

For Newtonian blood flow through the tube, surface distribution of blood velocity along the tube, parabolic flow behavior for velocity profile for laminar flow i.e. velocity magnitude is minimal near the tube wall and maximum in the center is shown in (Fig.2, A). For non-Newtonian blood flow with dynamic viscosity depending on shear rate as Eq. (7).The apparent viscosity decreases by increasing shear rate as (Fig.2, B).

Conclusion

In this study, numerical results were explained of the magnetic field created by a permanent magnet placed outside the tube. The blood in this model was considered a Newtonian and non-Newtonian fluid. Using COMSOL Multiphysics ® software, the Navier-Stokes equation for fluid (blood) and magnetostatic equation for permanent magnet are solved numerically.

References

1. D. K. Wagh,, S. D. Wagh, ‘’Blood flow considered as magnetic flow’’. Proceeding of Physiology of Fluid Dynamics III, 311–315(1992).
2. A. K. Gupta, ‘’Finite element Galerkin’s scheme for flow in blood vessels with magnetic effects’’. Int. J.Applied Systemtic Studies 3(2), 283–293(2009).
3. Y. Haik, V. Pai, C.J. Chen, ‘’Biomagnetic fluid dynamics at interfaces’’, Cambridge University Press, Cambridge, 439-452 (1999).
4. B. Berkovski, V. Bashtovoy, ‘’Magnetic fluids and applications handbook’’. Begell house inc., New York (1996).
5. E. E. Tzirtzilakis., V. D. Sakalis., N. G. Kafoussias., P. M. Hatzikonstantinou., ‘’Biomagnetic fluid flow in a 3D rectangular duct.’’ International Journal for Numerical Methods in Fluids, 44(12), 1279–1298 (2004).
6. E.E. Tzirtzilakis, “Biomagnetic fluid flow in a channel with stenosis”, Physica D, 237, 66-81 (2008).

7. K. Tzirakis, Y. Papaharilaou, D. Giordano, J. Ekaterinaris, ‘’Numerical investigation of biomagnetic fluids in circular ducts.’’ International Journal for Numerical Methods in Biomedical Engineering, 30(3), 297–317 (2014).
8. M. Alexandru, and M. Mihaela, "Magnetic field–flow interactions in drug delivery through an arterial system." Rev. Roumaine Sci. Techn. Electrotech. et Energ 56.2, 199-208(2011).
9. E. P. Furlani, ‘’Permanent Magnet and Electromechanical Device: Materials, Analysis and Applications’’. Academic, New York. (2001).
10. R. B. Bird, R. C. Armstrong., and O. Hassager, ‘’Dynamics of Polymeric Fluids’’. Fluid Mechanics. Wiley: NY, 1,(1987).
11. N. Ku David, ‘’Blood flow in arteries’’. Annual review of fluid mechanics, 29(1), 399-434 (1997).
12. J. Ferziger, M. Peric, Chap. 1- Basic Concepts of Fluid Flow, Computational Methods for Fluid Dynamics, 1-12 (2002).
13. Y. I. Cho, K. R. Kensey, “Effects of Non-Newtonian Viscosity of Blood on Flows in a Diseased Arterial Vessel, Part 1: Steady Flows,’’ Biorheology, 28(3), 241-262 (1991).