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Non-Newtonian Blood Flow In A Stenosed Artery With Porous Walls In The Present Of Magnetic Field Effect

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ABSTRACT: This paper is introduced the impact of magnetic field on a Non-Newtonian biomagnetic fluid. The stenosis artery with porous media model is used for solving the magnetic field and fluid equations simultaneously. The lump in stenosis artery creates vortexes after it place which disrupt the vessel flow. The external magnetic field is applied to weaken this vortexes and produce uniform flow. Furthermore the magnetic field decreases the shear stress on the artery due to neutralizing the created vortex. Another significant effect of applying magnetic force is declining the pressure in this region such that ten times higher magnetic field intensity from 10^{11} results 8.6X and 6.5X lower maximum pressure and shear stress on artery walls respectively.

Keywords : Biomagnetic, Heat Transfer, Porosity, Stenosis Artery

1 INTRODUCTION

Nowadays, the thickness of intimal is the main reason of cardiovascular diseases and formation of atherosclerosis. Insofar as stenosis artery disease take the life of many people. In atherosclerotic, arteries are generally narrowed and the inner walls are covered by oil material. The main reason of stenosis formation is backlogging of macromolecules on arterial walls. This lump clogs the blood flow and can cause infarct. There are numerous ways for controlling the blood flow [1]. Dissolving the lump and increasing the heat transfer rate are the privilege ways for controlling the artery flow[2]. The other way is destroying the vortexes which create after the lump. Because these vortexes interfere with blood flow and restrict the main blood flow[3]. The magnetic field does this target by applying an extra force to biofluid such as Synovial Fluid[4] and Spinal Fluid. During the last decades, numerous investigations have been done in finding the characteristic of blood flow in artery. In [5] the effect of magnetic field on stereotyping the blood flow in the stenosis artery is discussed. This paper neglects the non-Newtonian effect of biofluid viscosity and porous characteristic of artery wall[6-8]. The laminar and Brinkman's model for fluid flow by Navier stokes equations in porous and free media is study in[5]. In [9] the velocity and temperature of biofluid flow in artery geometry under applying the external magnetic field is discussed. The effect of multi stenosis on the blood flow is brought up in [10, 11]. In [12] different models of macro blood flow is coupled with various area and number of stenosis. The time dependent heat transfer of two-dimensional artery model is considered in paper [13]. Our paper, introduces the effect of Lorentz and magnetization forces on the stenosis artery for uniforming biofluid flow after the lump.

2 GOVERNING EQUATIONS

Let us consider the two-dimensional flow of a non-Newtonian, steady state, viscous and incompressible flow inside a stenosis artery. The geometry of stenosis with porous walls is shown in Figure1 and assumed as below function[14]:

$$\frac{y}{R_0}=\begin{cases}1-\dfrac{h}{2R_0}[1+\cos\{\dfrac{\pi(x-x_1)}{x_0}\}] & L_s\le x\le 2x_0+L_s\\ 1 & otherwise\end{cases}$$

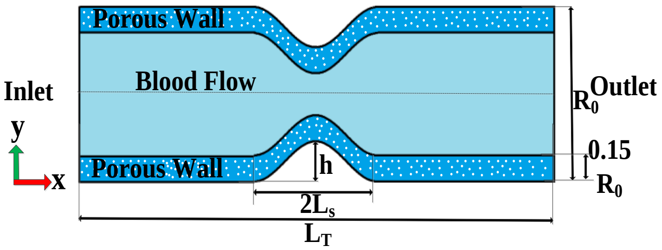

Figure 1. Modeled stenosis artery.

Where x1 is the center of stenosis, x0 is the half of the stenosis region width and R0 is the width of artery. The up and down vessel walls are modeled as porous material. This is acceptable with actual behavior of our artery blood. As depicted in Figure1, h is the maximum height of stenosis. Increasing this parameter creates critical situation for blood flow in artery. Under the action of magnetic field the governing equations on the biofluid in the free and porous regions are described by Cauchy and Brinkman equations which are explained bellow.

2.1 Heat transfer and fluid flow

In this paper the non-dimensional variables are defined at first.

$$x=\frac{\bar{x}}{R_0} \quad y=\frac{\bar{y}}{R_0} \quad u=\frac{\bar{u}}{v_0} \quad v=\frac{\bar{v}}{v_0} \quad p=\frac{\bar{p}}{\rho {v_0}^2} \quad H=\frac{\bar{H}}{H_0}$$

$$T=\frac{\bar{T}}{T^*} \tag{1}$$

Where $\alpha = k/\rho cp$ and $v_0=\alpha/R_0$ are the thermal diffusivity and characteristic velocity of the fluid. The non-dimensional Cauchy equations are expressed as below functions:

- Continuity:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{2}$$

- x-momentum:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{\partial p}{\partial x}+\Pr\times|\dot{\gamma}|(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2})+(Fx)_M+(Fx)_L \tag{3}$$

- y-momentum:

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{\partial p}{\partial y}+\Pr\times|\dot{\gamma}|(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2})+(Fy)_M+(Fy)_L \tag{4}$$

The Energy equation for the biofluid explained by:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2})+Ec\times\Pr\times|\dot{\gamma}|\times\phi-Mn_F\times Q_M+\frac{Mn_M}{\mathrm{Re}}\times Q_L \tag{5}$$

The Brinkman equations for momentum formula inside the porous region are:

- x momentum:

$$0=-\frac{\partial p}{\partial x}+\Pr\times|\dot{\gamma}|(\frac{\partial^2 u_p}{\partial x^2}+\frac{\partial^2 u_p}{\partial y^2})+\Pr\times Da\times u_p+(Fx)_M+(Fx)_L \tag{6}$$

- y momentum:

$$0=-\frac{\partial p}{\partial y}+\Pr\times|\dot{\gamma}|(\frac{\partial^2 v_p}{\partial x^2}+\frac{\partial^2 v_p}{\partial y^2})+\Pr\times Da\times v_p+(Fy)_M+(Fy)_L \tag{7}$$

$\vec{V}=(u,v)$ and $\vec{V}_p=(u_p,v_p)$ are the two dimensional velocity field inside the free and porous regions. The third and fourth terms in the momentum and energy equations are appeared due to Magneto Hydro Dynamic (MHD) and Ferro Hydro Dynamic (FHD) impression and they are equal to:

$$(Fx)_M=Mn_F\chi_m H\frac{\partial H}{\partial x} \quad (Fx)_L=\frac{Mn_M}{\mathrm{Re}}(\chi_m+1)^2(vH_xH_y-u{H_y}^2) \tag{8}$$

$$(Fy)_M=Mn_F\chi_m H\frac{\partial H}{\partial y} \quad (Fx)_L=\frac{Mn_M}{\mathrm{Re}}(\chi_m+1)^2(uH_xH_y-vHx^2) \tag{9}$$

$$Q_M=-Mn_F\times Ec\times\frac{\partial\chi}{\partial T}T\times H(u\frac{\partial H}{\partial x}+v\frac{\partial H}{\partial y})$$
$$Q_L=\frac{Mn_M}{\mathrm{Re}}\times Ec\times(\chi_m+1)^2\times(uH_y-vH_x)^2 \tag{10}$$

the non-Newtonian behavior of biofluid, in this paper is modeled by power law formula [15]:

$$\eta=\eta_0|\dot{\gamma}|^n \tag{11}$$

The value of η_0 and n are cited in Table 1.

2.2 The magnetic field intensity

The magnetization property (M) is determined the impression of magnetic field on the ferrofluid. Among numerous formula, the linear equation which depends on the magnetic field intensity and temperature is used in this paper[16].

$$M=\chi_m H \tag{12}$$

χ_m is the magnetic susceptibility that varies with temperature:

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$$\chi_m = \frac{\chi_0}{1+(\beta T^*)(T - \frac{T_0}{T^*})} \quad (13)$$

χ_0, β and T0 are constant parameters and electrical current through two wires is generated the magnetic field. The wires are parallel and its magnetic field intensity is express by:

$$H_x = H_0 \frac{(x-a_1)}{((x-a\ )^2+(y-b_1)^2)},$$

$$H_y = -H_0 \frac{(y-b_1)}{[illegible]} \quad (14)$$

H0 is the magnetic field strength which depends on the applied magnetics induction (B=μ0 (H+M)) and a, b are the location of wires. The non-dimensional parameters which appear in the above equations are:

- Reynolds number:

$$\mathrm{Re} = \frac{R_0 \rho v_0}{\eta_0 \times (\frac{\alpha}{R_0^2})^{-0.4}} = \frac{\rho \alpha}{\eta_0 \times (\frac{\alpha}{R_0^2})^{-0.4}} \quad (15)$$

- Eckert number:

$$Ec = \frac{v_0^2}{c_p T^*} = \frac{\alpha^2}{c_p T^* R_0^2} \quad (16)$$

- Prandtl number:

$$\mathrm{Pr} = \frac{\eta_0 \times (\frac{\alpha}{R_0^2})^{-0.4}}{\rho \alpha} \quad (17)$$

- Darcy number:

$$Da = \frac{R_0^2}{k_{br}} \quad (18)$$

- Magnetic number of FHD:

$$Mn_F = \frac{\mu_0 H_0^2}{\rho v_0^2} = \frac{\mu_0 H_0^2 R_0^2}{\rho \alpha^2} \quad (19)$$

- Magnetic number of MHD:

$$Mn_M = \frac{\mu_0^2 H_0^2 R_0^2 \sigma}{\eta} \quad (20)$$

2.3 Bondary conditions

The systems of equations 1-11 are elliptic and require boundary condition: On the upper and lower arterial walls:

$$T = T_1, u = v = 0 \quad (21)$$

$$x = 7 \quad 0 < y < 1 \quad \frac{\partial T}{\partial x} = 0, p = 0 \quad (22)$$

$$x = 0 \quad 0 < y < 1 \quad T = T_1, u = 1500(y - y^2) \quad (23)$$

For obtaining a continuous velocity field between the free and porous interface, the velocity is equal. All the constant parameters are given in Table **1**.

Table 1. Numerical values of parameters.

Parameters	Numerical value	Parameters	Numerical value
Pr_{blood}	4.56	Ec_{blood}	7.378×10^{-6}
Pr_{wall}	4.04	Da	100-400-800
β	5.6×10-3 K^{-1}	Mn_M	150
Re_{wall}	0.247	Mn_F	[105:5×105]
Re_{blood}	0.23	χ_0	0.06
T_1	300 ^0K	b_1	-0.1
n	0.6	a_1	3.5
η_0	35×10^{-3} $kg.m^{-1}.s^{-1}$	b_2	1.1
Ec_{wall}	1.05×10^{-5}	a_2	3.5

The velocity and temperature contours in the stenosis region are depicted in Figure2. Around this region the velocity becomes significantly high corresponds to lower cross sectional area. As the streamlines show after the stenosis region two vortexes are created near the up and down walls. These vortexes can disrupt the blood flow. The temperature contour shows that the temperature is high in the middle of vessel due to linear dependency of temperature to velocity. As the velocity is maximized in stenosis region the temperature becomes high in this region too. The figure shows the temperature is high in the communal interface of porous and free region. This is result of higher Eckert number of porous walls versus free space.

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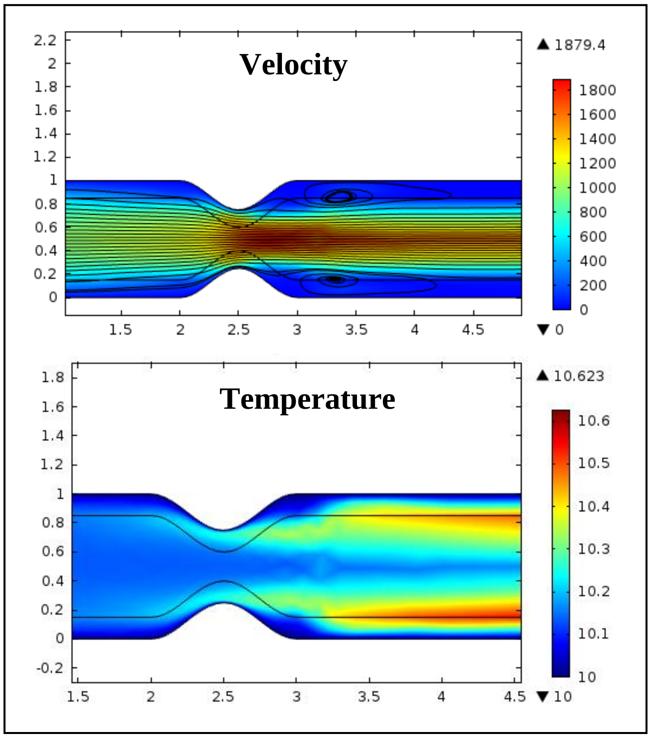

Figure2. The velocity and temperature contours of stenosis artery without magnetic effect.

3 SIMULATION RESULTS

The velocity streamline and temperature contours in present of three different value of magnetic field intensity, are demonstrated in Figure3. The primary effect of exerting magnetic field to the biomagnetic fluid is destroying the formed vortex approximately after the stenosis region.

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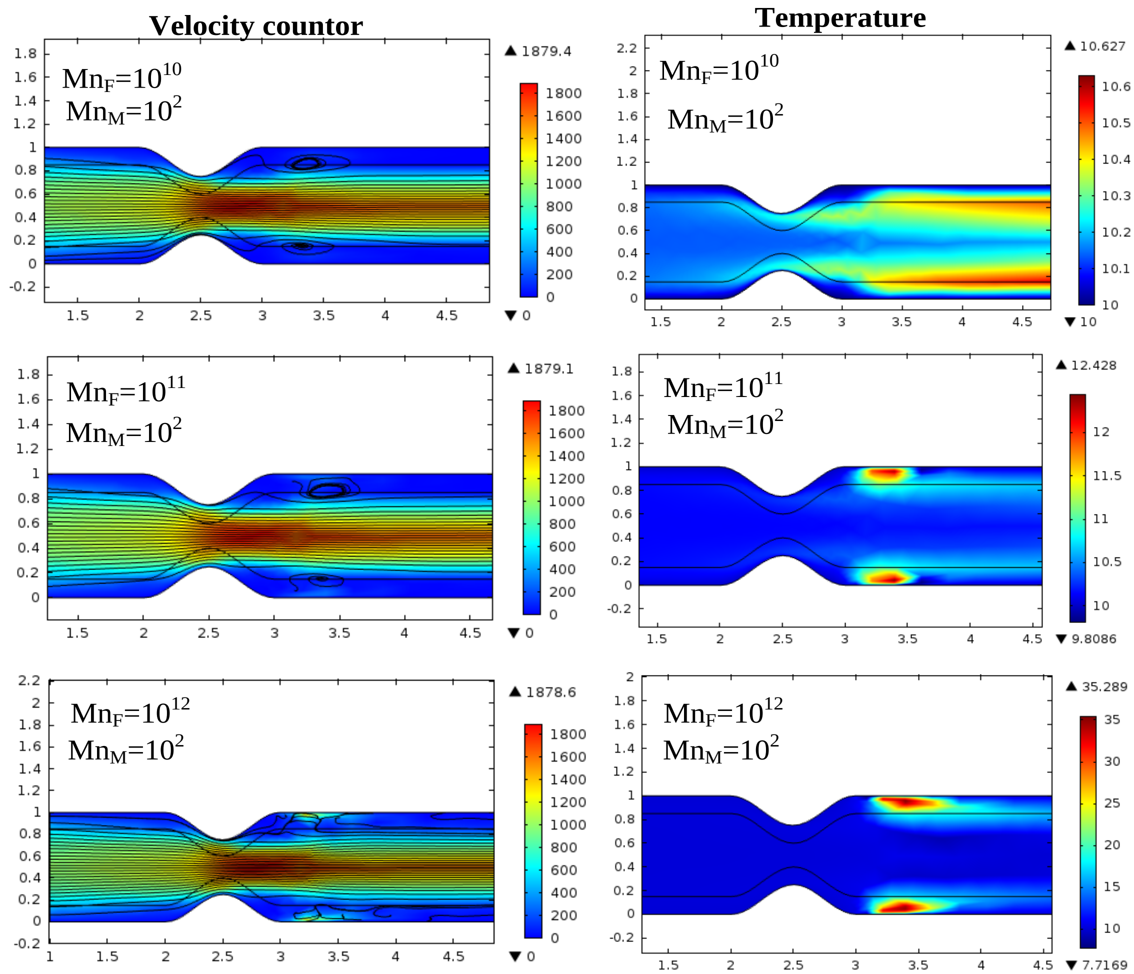

Figure3. The velocity and temperature contours of stenosis artery in different magnetic field intensity.

This magnetic field creates two vortexes in opposite direct, and neutralize the formed vortexes after the lump. With increasing the magnetic field intensity, formed vortexes by magnetic this field expand, till they overcome the flow vortexes and two vortexes in opposite direction are created. So, the magnetic intensity is important and should be optimum for reaching the target goal. In this paper, the best option for magnetic intensity is 1012. Figure3 shows by increasing magnetic field intensity, the flow vortexes are destroyed almost which can result better and smooth blood flow in vessel. Temperature contours for different magnetic field intensity are also depicted in figure. This shows that the powerful magnetic field can focus the temperature near the wire place due to heat effect of wire in blood. The temperature with ten times higher magnetic field intensity from 1010 and 1011 becomes 1.2X and 3.5X respectively. Shear stress on the low wall is demonstrated in Figure4. By strengthening the magnetic field, the bigger vortexes which can influence wider area are created , therefore main vortex is destroyed completely and the velocity gradient decreases and lower shear stress value is applied to the wall. By applying magnetic field with ten times stronger than 10^{11}, the shear stress will become 6.6X lower in vortex created region. The magnetic forces significantly affect the biofluid pressure. Increasing the magnetic field intensity causes the pressure after the lump declines due to neutralizing the vortex and calm current creation. This fact is shown in Figure5 that by increasing the magnetic field from 10^{11} to 10^{12}, the maximum pressure becomes 8.6X lower. Maximum temperature and pressure versus changing in porosity of walls and the magnetic field are archived in Table 2. The Darcy number indicates the porosity of walls which higher value of it results lower porous characteristic of walls and nearing it to rigid walls. As mentioned before, the magnetic field acts as a heat source around the wire current. This field has more effect on porous media than solid walls due to lower heat transfer of high porosity media. The table shows that increasing the magnetic field intensity produces higher pressure and temperature in artery such that with applying 10^{12} the magnetic field (Mnf), the temperature and pressure increase 2.7X and 4.1X respect with neglecting magnetic effect.

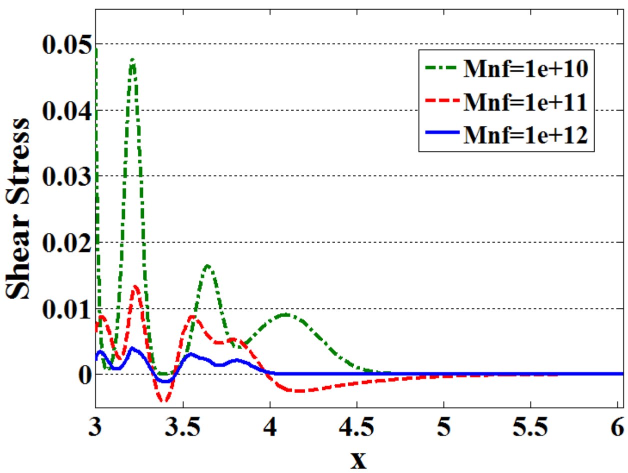

Figure4. Shear stress in the vortex place with different magnetic field intensity and MnM=10^2.

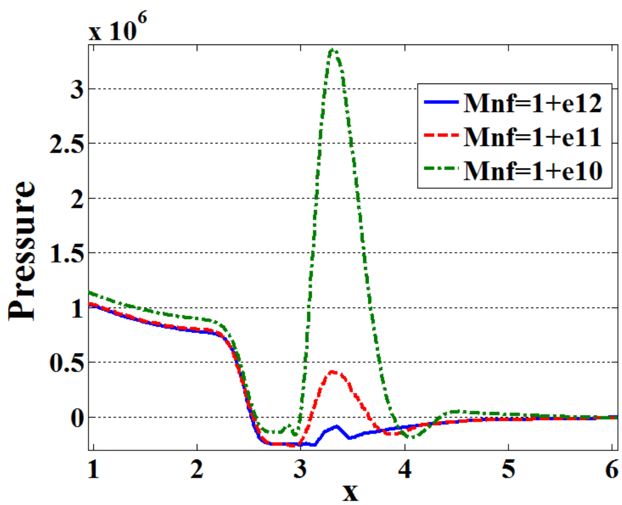

Figure5. Pressure distribution in stenosis artery with different magnetic field intensity and $Mn_M=10^2$.

Table 2. Maximum temperature and pressure in different porosity and $Mn_M=10^2$.

Da	40		400		4000	
Mn_f	T	$P\times10^{-6}$	T	$P\times10^{-6}$	T	$P\times10^{-6}$
0	10.47	0.470	10.55	1.070	10.62	3.70
10^{10}	10.80	0.761	10.73	1.85	10.66	3.72
10^{11}	12.59	0.997	12.40	1.98	12.31	3.84
10^{12}	31.71	4.37	29.11	4.40	27.75	4.52

4 CONCLUSION

This paper introduce the impact of magnetic field on a Non-Newtonian biomagnetic fluid in stenosis artery. The magnetic field is used for destroying the created vortex after the stenosis region corresponds to non-uniforming of flow in this region. As results shows the magnetic field can neutralize this vortexes by producing opposite vortexes in this region. Furthermore the magnetic field decrease the pressure and shear stress in this region due to creating the calm flow. The results shows that changing in temperature and pressure reduction is significant related to the value of magnetic field intensity.

Table 3. Nomenclature

p Pressure	Da Darcy number
T Temperature	Re Reynolds number
T_a Arterial temperature	Ec Eckert number
R0 Vessel diameter	k_{br} Permeability of porous media
h Height of stenosis	$\vec{V}(u,v)$ Fluid velocity in free region
Ls Half-length of stenosis	$\vec{V}_p(u_p,v_p)$ Fluid velocity in porous region
LT Length of artery	(x,y) Component of Cartesian system
H Magnetic field strength	**Greek Letters**
B Magnetic field induction	χ_m Magnetic susceptibility
M Magnetization of fluid	σ Electrical conductivity
J Density of electrical current	ε_p Porosity of porous media
Mn_F Magnetic number (FHD)	μ_0 Magnetic permeability of vacuum
Mn_M Magnetic number (MHD)	α Thermal diffusivity
Pr Prandtl number	η Dynamic viscosity

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