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A MATHEMATICAL MODEL OF BLOOD FLOW IN A MULTI-IRREGULAR STENOSED ARTERY IN PRESENCE OF UNIFORM MAGNETIC FIELD

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ABSTRACT

This paper presents a mathematical model for fluid (blood) flow through stenosed (taken as a multi-irregular stenosis) artery under an externally applied uniform magnetic field. The blood is assumed as Newtonian and medium is assumed as porous in nature. Viscosity of blood varies depending on hematocrit, which is taken to reform analogousto the real condition. This model is compatible with Magnetohydrodynamics and Ferro-hydrodynamics. The equation describing Newtonian fluid flow under above assumption with suitable boundary conditions are solved by applying Frobenius method. The flow characteristics of fluid like axial velocity profile, shear stress at wall, pressure gradient and fluid flow rate are expressed analytically. Numerical values are computed for flow characteristics using, derived analytical expression and some specific values of distinct parameters and are depicted by graphs. The results computed on the basis of distinct considered parameters in the problem shows that the shape of artery, hematocrit and magnetic field have significant impact on the flow characteristics.

Keywords Multi-irregular stenosis, Newtonian blood, MHD, Axial velocity, Magnetic field

1. INTRODUCTION

Many cardiovascular diseases, e.g. atherosclerosis (also called stenosis), hypertension, brain stroke are responsible for the deaths of people in the world. The inception and sledding of a number of such cardiovascular diseases are depending upon fluid (blood) flow and the dynamic behavior of the blood vessel. Medical records shows that approximate 80% of the total casualties of humans are due to blood vessel diseases. Among them stenosis is a most dangerous disease. It is considered that collection of cholesterol and some other substances on the inner wall and by the prevalence of connective tissues in the interior wall of artery is main cause of stenosis. Stenosis may develop at more than one location of the circulatory system. Many researchers Chien **[2]** and Fry **[6]** studied that rheological properties of fluid (blood) and the dynamical properties of flow of fluid (blood) can play an vital role in identifying, diagnosis and treatment of many atherosclerosis diseases. Blood flow in the propinquity of a stenosis in arteries has been experimentally investigated by Young and Tsai **[17]**. In 1937, Hartmann and Lazarus **[7]** studied the effect of applied magnetic field, uniformly in transverse direction on the fluid (blood) motion between two infinite stationary parallel insulated plates. After that, this work on Magnetohydrodynamics (MHD) fluid flow has received more attention. Many authors have enhanced the solution of the problem in different directions. Cramer and Pai **[4]** obtained solutions closely for velocity fields under different physical conditions. In the blood erythrocyte is a major Bio-magnetic substance, so blood motion will be affected by magnetic field. The reason of decreasing in the fluid motion rate is caused due to either increase in blood motion resistance or decrease in blood pressure. Magnetic field effect on blood motion has been analyzed considering blood as electrically conducting fluid theoretically by Chen **[3]**. The major process of influence of a constant magnetic field on viscosity of blood depends upon the interplay between the magnetic moment induced on the erythrocytes and the stationary magnetic field, applied externally. The erythrocytes have greater magnetic susceptibility along its long axis. So, it tends to orient its long axis for more magnetic sensitivity along the magnetic field applied externally. The externally applied stationary magnetic field contributes to an increase in the resistance of flowing blood. This is due to the anisotropic orientation of the erythrocytes under the effect of applied stationary magnetic field which disturbs the rolling of the cells in the flowing fluid (blood) and thereby the viscosity of blood increases as oxygenated hemoglobin is diamagnetic and deoxygenated hemoglobin is paramagnetic. The influence of a constant magnetic field on blood erythrocytes for distinct hemoglobin states (normal, reduced hemoglobin and oxidized) has been investigated by Pauling and Coryell **[11]**. The main applications of principles of Magnetohydrodynamics in the treatment and reasonable therapy (treatment) of arterial hypertension has been explored by Vardanyan **[16]**, it has been noticed that for the steady blood flow through the artery of circular cross-section, a uniform magnetic field applied in transverse direction of fluid flow alters the fluid (blood) flow rate. Misra and Singh **[9]** prepared a model to examine the flow behavior in arteries. The model has analyzed by containing all the nonlinear terms in the equation describing situation by applying a finite difference scheme. All these studies carried out by Misra and his research companions have been considered as stratum role in the field of Bio- Mathematics.

Bali and Awasthi **[1]** analyzed the influence of magnetic field applied externally in transverse direction on flow of blood in stenotic artery by considering the viscosity of fluid (blood) as dependence upon radial co-ordinate. Mekheimer *et al*. **[8]** analyzed influence of magnetic field, wall properties and porosity for anisotropically elastic multi-stenosis arteries on the characteristics of blood flow. Misra *et al*. **[10]** prepared a mathematical model for analyzing blood flow in a porous blood vessel with multi stenoses in the existence of externally applied magnetic field. Blood flowing through the artery is considered to be Newtonian. Shit *et al*. **[14]** prepared a model to analyze influence of magnetic field on fluid (blood) flow characteristics through an overlapping tapered stenosed artery with externally applied magnetic field theoretically. Shah **[12]** prepared a model to describe blood movement in a radially symmetric but axially non-symmetric stenosed artery when blood is considered as power-law fluid and in the existence of applied uniform magnetic field on the flow. Recently Siddiqui *et al*. **[15]** studied magnetic field effect on fluid (blood) flow characteristics of fluid flow through stenosed artery. Sharma *et al*. **[13]** studied the effect of, Jeffrey fluid parameter, Hartmann number, shape and size of the stenosis on inner wall of blood vessels, on the velocity, volume flow rate and shear stress at wall.

In this research paper, the effect of magnetic field applied externally on blood flow in a porous medium with multi-irregular stenosed artery, has been analyzed, assuming the blood to be Newtonian. The analysis is carried with applying suitable analytical methods and few important predictions have been made using the model. This can play a vital role in determination of systolic and diastolic pressures in human body in particular situations. The study shows that a rise in the hematocrit percentage level leads to a rise in systolic pressure or fall in diastolic pressure, both of which are harmful for the heart. Since this analysis has been implemented for situation under which the human body is subjected to applied external magnetic field, it includes the swear of suitable application in magnetic/ electromagnetic therapy, which has achieved enough popularity today.

2. Mathematical Formulation

Geometry of multi- irregular stenosis is shown in **Figure 1** and shape may be represented by

$$R(z)=\begin{cases} R_0-\frac{2\delta}{L_0}(z-d), & d\le z\le d+\frac{L_0}{2}\\ R_0-\frac{2\delta}{L_0}(z-d-L_0), & d+\frac{L_0}{2}\le d+L_0\\ R_0-\delta+\frac{4\delta}{L_0^2}\left(z-d-\frac{3L_0}{2}\right)^2, & d+L_0\le z\le d+2L_0 \end{cases}. \quad (1)$$

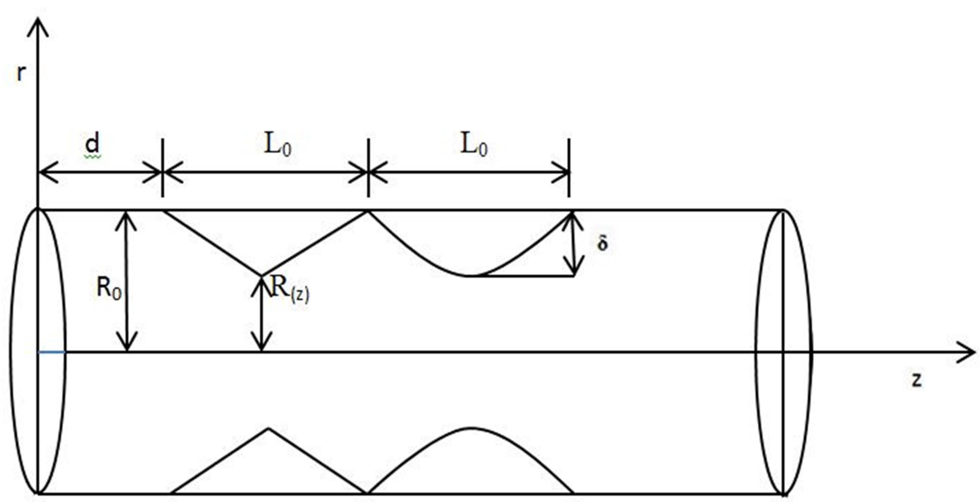

Figure 1: Multi irregular stenosed artery

Where

R(z) = Radius of stenosed portion of artery.

R_0 = Radius of artery without stenosis.

$2L_0$ = Total length of stenosed arterial segment.

δ = highest height of the stenosis

d = indicates stenosis location

Let the fluid (blood) flow be considered steady, laminar axially symmetric, unidirectional flow through a porous medium in an artery consisting multi-irregular stenoses in the presence of applied external magnetic field considering blood as a protrusion of erythrocytes in plasma. Fluid is considered uniformly dense throughout. But the viscosity varies in the radial direction. As per our consideration the governing equation of flow may be given as

$$\frac{dp}{dz}+\frac{1}{r}\frac{d(r\tau)}{dr}+\sigma B_0^2\,u+\frac{\mu(r)}{\bar{k}}=0. \qquad (2)$$

Where u is the blood velocity component in z direction, ρ is blood pressure, σ represents electrical conductivity, B_0 denotes strength of applied and magnetic field and the permeability of the porous medium is $\bar{k}$.

The shear stress τ is given by

$$\tau=-\,\mu(r)\frac{du}{dr}. \qquad (3)$$

whereμ(r) is the coefficient of viscosity of blood. μ(r) is defined by use of Einstein's formula for viscosity coefficient, which is given as

$$\mu(r)=\mu_0[1+\beta h(r)]. \qquad (4)$$

whereμ_0 represents the coefficient of plasma viscosity, β represents a constant has value 2.5 for blood and h(r) represents the hematocrit. The analysis will be enacted by using the following empirical formula

$$h(r)=H\left[1-\left(\frac{r}{R_0}\right)^m\right]. \qquad (5)$$

The boundary condition for the present problem may be put mathematically in the form

u = 0 at r = R(z). no slip condition (6)

Since there is no radial flow along the axis of the artery so the axial velocity gradient of the blood flow may be assumed to be equal to zero i.e.

$\frac{du}{dr}=0$at r = 0. symmetry about the axis. (7)

Let us take a transformation

$$x=\frac{r}{R_0},$$

Then the governing equation (4) takes the form

$$\frac{1}{x}\frac{d}{dx}\left[x(a_1 - a_2x^m)\frac{du}{dx}\right] - M^2u - \frac{1}{k}x(a_1 - a_2x^m)u = \frac{R_0}{\mu_0}\frac{dp}{dz}, \quad (8)$$

With $a_1 = 1 + a_2, a_2 = \beta H, \ \ k = \frac{\bar{k}}{R_0^2}, M^2 = \frac{\sigma(B_0R_0)^2}{\mu_0}$.

The boundary coditions are given below

$$u = 0 \text{ at } x = \frac{R(z)}{R_0} \quad (9)$$

and

$$\frac{du}{dx} = 0 \text{ at} x = 0. \quad (10)$$

3. Solution of problem

Equation (4) with boundary condition are solved by the Frobenius method. For applying Frobenius method u has to bounded at x = 0. The series solution of equation (8) is given by

$$u = C\sum_{n=0}^{\infty} A_n x^n + \frac{R_0^2}{4a_1\mu_0}\frac{dp}{dz}\sum_{n=0}^{\infty} B_n x^{n+2}, \quad (11)$$

Where C, $A_n$and$B_n$are arbitrary constant and given as

$$A_{n+1} = \frac{a_2(1+n)(n+1-m)A_{n+1-m}+\left(m^2+\frac{a_1}{k}\right)A_{n-1}-\frac{a_2}{k}A_{n-1-m}}{a_1(1+n)^2}, \quad (12)$$

$$B_{n+1} = \frac{a_2(3+n)(n+3-m)B_{n+1-m}+\left(m^2+\frac{a_1}{k}\right)B_{n-1}-\frac{a_2}{k}B_{n-1-m}}{a_1(3+n)^2} \quad (13)$$

and $A_0 = B_0 = 0$.

The constant C involved in equation (11) is obtained with the help of boundary condition (9)

$$C = -\frac{R_0^2\frac{dp}{dz}\sum_{n=0}^{\infty} B_n\left(\frac{R}{R_0}\right)^{n+2}}{4a_1\mu_0\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^{n}} \quad (14)$$

Using equations (12), (13) and (14) in equation (11)

$$u = \frac{-\frac{R_0}{4a_1\mu_0}\frac{dp}{dz}\left[\sum_{n=0}^{\infty} B_n\left(\frac{R}{R_0}\right)^{n+2}\sum_{n=0}^{\infty} A_n x^n - \sum_{n=0}^{\infty} B_n x^{n+2}\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^{n}\right]}{\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^{n}}, \quad (15)$$

If u_0 is average velocity

$$u_0 = -\frac{R_0^2}{8\mu_0}\left(\frac{dp}{dz}\right)_0, \tag{16}$$

Then

$$\bar{u} = \frac{u}{u_0} = \frac{\frac{2}{a_1}\frac{dp}{dz}/\left(\frac{dp}{dz}\right)_0\left[\sum_{n=0}^{\infty} B_n\left(\frac{R}{R_0}\right)^{n+2}\sum_{n=0}^{\infty} A_n x^n - \sum_{n=0}^{\infty} B_n x^{n+2}\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^n\right]}{\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^n}. \tag{17}$$

Volumetric flow rate is given by

$$Q = \int_0^{\frac{R}{R_0}} 2\pi R_0 x u(x) dx,$$

$$Q = -\frac{\pi R_0^3}{2a_1/\mu_0}\left(\frac{dp}{dz}\right)\frac{\left[\sum_{n=0}^{\infty} B_n\left(\frac{R}{R_0}\right)^{n+2}\sum_{n=0}^{\infty}\left\{\frac{A_n\left(\frac{R}{R_0}\right)^{n+2}}{n+2}\right\} - \sum_{n=0}^{\infty}\left\{\frac{B_n\left(\frac{R}{R_0}\right)^{n+4}}{n+4}\right\}\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^n\right]}{\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^n}. \tag{18}$$

In the absence of magnetic field it yields

$$Q_0 = -\frac{\pi R_0^3}{8\mu_0}\left(\frac{dp}{dz}\right)_0, \tag{19}$$

$$\bar{Q} = \frac{Q}{Q_0} = \frac{4}{a_1}\frac{dp}{dz}/\left(\frac{dp}{dz}\right)_0 \times \frac{\left[\sum_{n=0}^{\infty} B_n\left(\frac{R}{R_0}\right)^{n+2}\sum_{n=0}^{\infty}\left\{\frac{A_n\left(\frac{R}{R_0}\right)^{n+2}}{n+2}\right\} - \sum_{n=0}^{\infty}\left\{\frac{B_n\left(\frac{R}{R_0}\right)^{n+4}}{n+4}\right\}\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^n\right]}{\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^n}. \tag{20}$$

For steady flow $\bar{Q} = 1$,

Pressure gradient in non dimensional form is given as

$$\overline{\frac{dp}{dz}} = \frac{dp}{dz}/\left(\frac{dp}{dz}\right)_0,$$

$$\overline{\frac{dp}{dz}} = \frac{a_1}{4}\frac{\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^n}{\left[\sum_{n=0}^{\infty} B_n\left(\frac{R}{R_0}\right)^{n+2}\sum_{n=0}^{\infty}\left\{\frac{A_n\left(\frac{R}{R_0}\right)^{n+2}}{n+2}\right\} - \sum_{n=0}^{\infty}\left\{\frac{B_n\left(\frac{R}{R_0}\right)^{n+4}}{n+4}\right\}\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^n\right]}. \tag{21}$$

Shear stress at wall is given as

$$\tau_R = \left[-\mu(r)\frac{du}{dz}\right]_{r=R(z)},$$

$$\tau_R = \frac{R_0}{4a_1}\left[1 + \beta H\left[1 - \left(\frac{R}{R_0}\right)^m\right]\left(\frac{dp}{dz}\right)\left[\frac{\sum_{n=0}^{\infty} B_n\left(\frac{R}{R_0}\right)^{n+2}\sum_{n=0}^{\infty} nA_n\left(\frac{R}{R_0}\right)^{n-1} - \sum_{n=0}^{\infty}(n+2)B_n\left(\frac{R}{R_0}\right)^{n+1}\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^n}{\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^n}\right], \tag{22}$$

$$\tau_N = -\frac{R_0}{2}\left(\frac{dp}{dz}\right)_0,$$

In the absence of magnetic field , shear stress at wall is given as

$$\tau = \frac{\tau_R}{\tau_N},$$

$$\tau = \frac{1}{2a_1}\left(\frac{\overline{dp}}{dz}\right)\left[1+\beta H\left\{1-\left(\frac{R}{R_0}\right)^m\right\}\right]\left[\frac{\sum_{n=0}^{\infty} B_n\left(\frac{R}{R_0}\right)^{n+2}\sum_{n=0}^{\infty} nA_n\left(\frac{R}{R_0}\right)^{n-1} - \sum_{n=0}^{\infty}(n+2)B_n\left(\frac{R}{R_0}\right)^{n+1}\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^{n}}{\sum_{n=0}^{\infty} A_n\left(\frac{R}{R_0}\right)^{n}}\right] \quad 23$$

4. RESULT AND DISCUSSION

In the above section analytical expressions for different flow characteristics of blood are obtained. In this section we are discussing the blood flow characteristics by depicting graphs, using following valid numerical data which is applicable to blood. The values of parameters are taken as for computation L_0 = 1, d = 1, H = 0, 0.1, 0.2, 0.3, M = 0, 2.5, 4.0, 6.0

Figure 2 gives the velocity in axial direction for distinct values of the hematocrit H i.e. H = 0, 0.1, 0.2, 0.3. It reveals that the axial velocity decreases at the central region of the artery corresponding increase value of hematocrit level H. This fact lies within the hematocrit as the viscosity of blood is high in the core region due to the concentricity of blood cells rather than low viscosity in the plasma near the wall of artery.

Figure 3 describe change in axial velocity at z = 2.2 onset of the second stenosis for a set of values of Hartmann Number M = 0, 2.5, 4, 6. It is obvious from graph that the velocity in axial direction significantly decreases corresponding increase of the intensity of magnetic field. It is quite known that when a magnetic field is applied in electrically conducting fluid (here for blood) there generates Lorentz force, which has a tendency to slow the movement of fluid. **Figures 4 and 5** give the variation of the shear stress at wall for distinct values of the hematocrit H = 0, 0.1, 0.2, 0.3 and Hartmann number M = 0, 2.5, 4, 6. It is clear from fig. 4 that shear stress at wall reduces as the hematocrit H increases. **Figure 5** shows that the shear stress at wall increases significantly corresponding to increasing values of Hartmann number M. **Figures 6-7** illustrate the change in pressure gradient along the length of stenosis for distinct values of the physical parameters of interest.

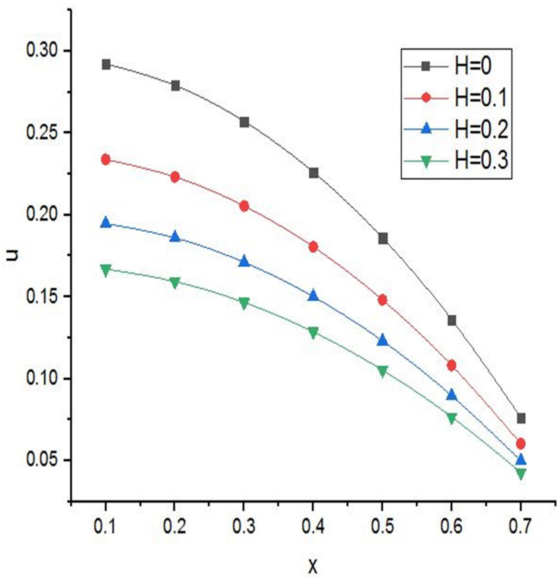

Figure 2: u and x for distinct H = 0, 0.1, 0.2, 0.3

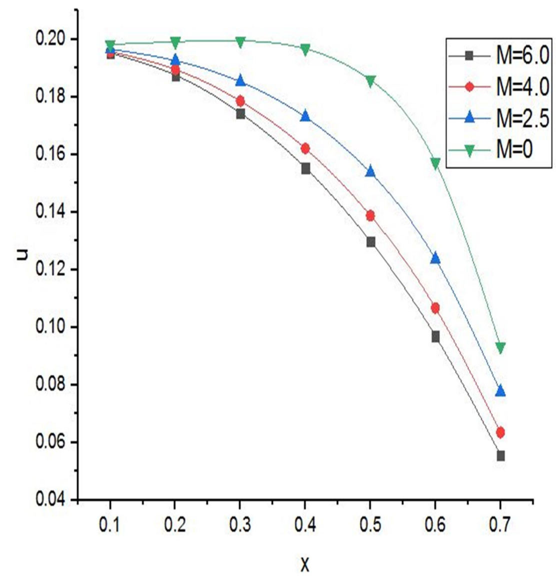

Figure 3: u and x for distinct M = 0, 2.5, 4, 6

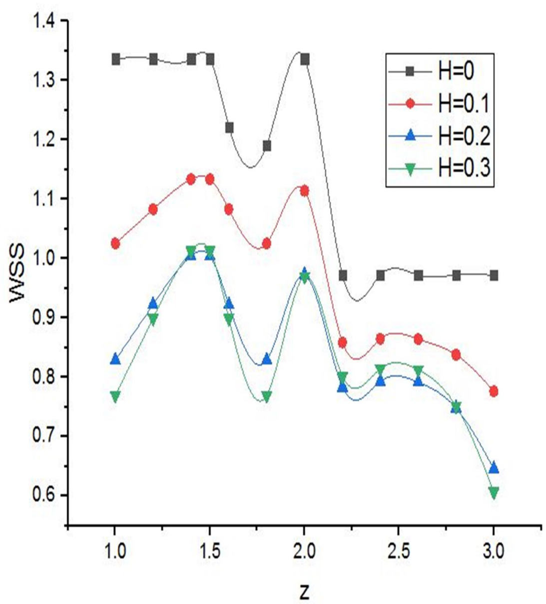

Figure 4: WSS and z for distinct H = 0, 0.1, 0.2, 0.3.

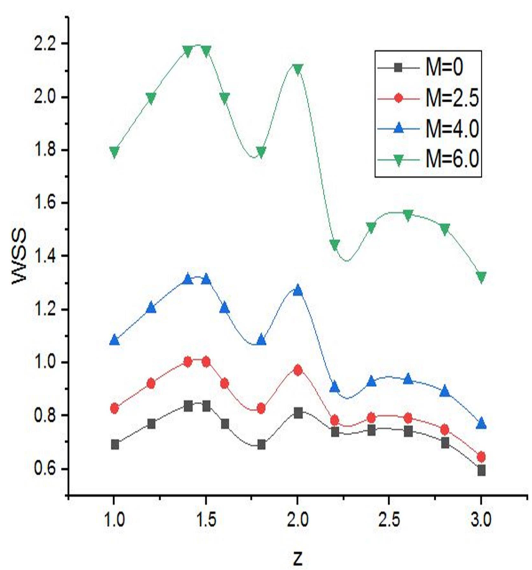

Figure 5: WSS and z for distinct M = 0, 2.5, 4, 6.

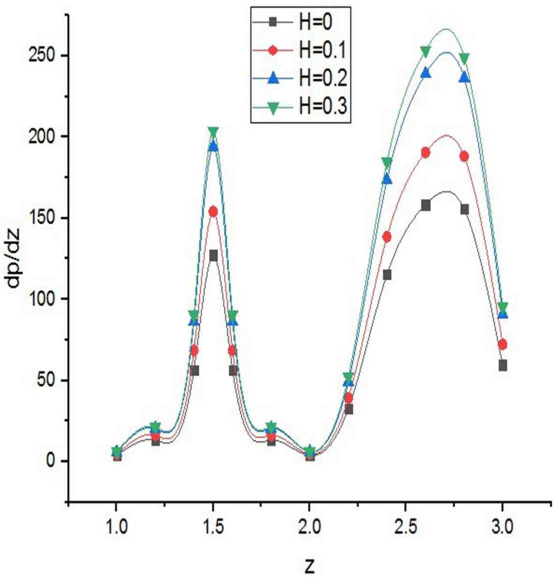

Figure 6: dp/dz and z for distinct H=0, 0.1, 0.2, 0.3

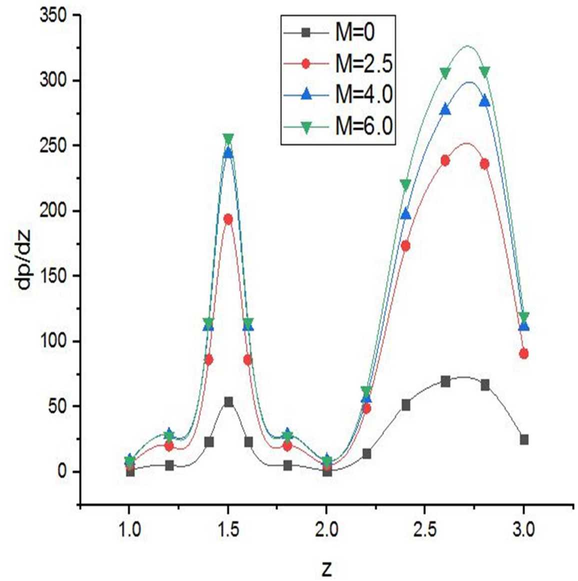

Figure 7: dp/dz and z for distinct M=0, 2.5, 4, 6

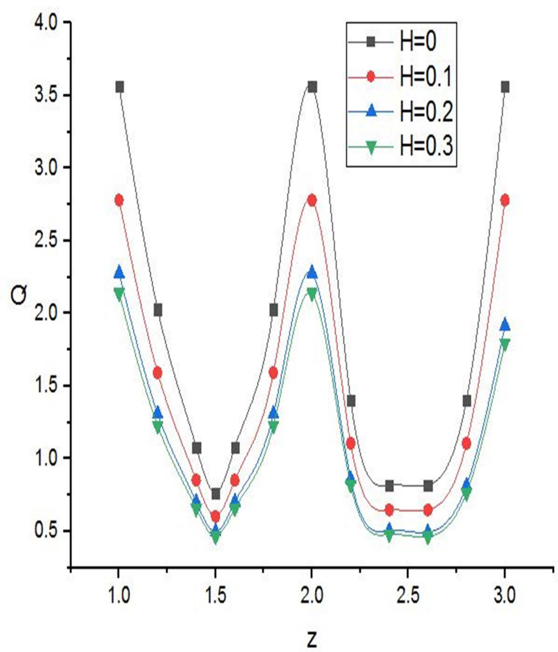

Figure 8: Q and z for distinct H = 0, 0.1, 0.2, 0.3

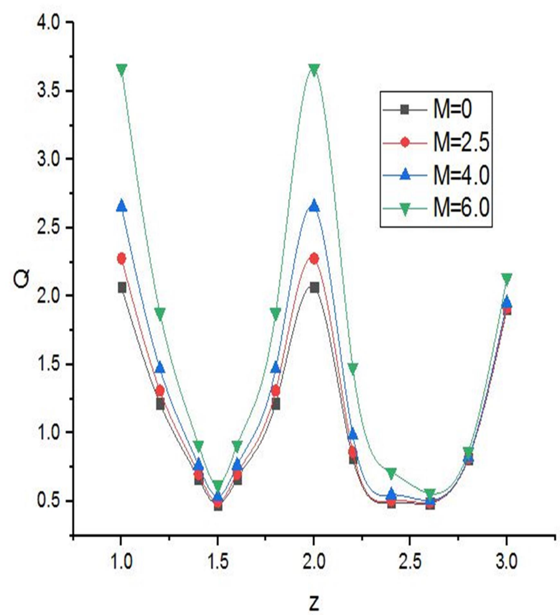

Figure 9: Q and z for distinct M = 0, 2.5, 4, 6

It has been observed from **Figure 6** that the pressure gradient grows up with the increase of the hematocrit H = 0, 0.1, 0.2, 0.3. It is clear from this figure that when the concentricity of blood cells increase at the core region that is hematocrit H is high, more pressure gradient is needed to pass the same amount of fluid through the stenoticregion. These results are coherent with those reported by Cirillo **[5]**, where in they mentioned that the greater blood viscosity caused by higher hematocrit and the consequent increased resistance to blood flow appears the most reasonable causes underlying the association between hematocrit and blood pressure (B.P.). **Figure 7** shows that the pressure gradient in axial direction increases with the increase of magnetic field intensity. It is interesting to note from these figures that the value of the pressure gradient is very low at the larynx of the first stenosis compare to the second stenosis. **Figure 8 and Figure 9** shows that the variations of fluid flow rate of the blood with the increase of Hematocrit concentration and Hartmann number. **Figure 8** reveals that the fluid flow rate decreases with the increasing of Hematocrit concentration. **Figure 9** indicates that the fluid flow rate increases corresponding to increase of the Hartmann number.

5. CONCLUSION

A mathematical model of fluid (blood) flow through multi-irregular stenosis when a uniform magnetic field applied in transverse direction has been prepared. In this model the blood viscosity varies depending on hematocrit and the blood has been treated as the porous medium. The problem is solved analytically by using the Frobenius method. The influence of various key parameters including, hematocrit H concentration the magnetic field applied uniformly and shape parameter constriction are examined. The following points of the present model may be listed as follows:

- The flow velocity in axial direction at the central region decreases gradually with the increase of magnetic field intensity and hematocrit concentration.
- Shear stress at wall and flow rate decreases with the increasing of hematocrit concentration while opposite trend seen in case of increasing magnetic field intensity.
- Pressure gradient increases with the increasing of hematocrit concentration and magnetic field intensity.
- Hematocrit play role to the regulation of blood pressure.

Thus it can be clearly conclude that the hematocrit and magnetic field affects blood flow characteristics significantly.

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