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Mathematical Modelling of Blood Flow in Multi-Stenosed Artery with MHD Effect Under Porous Medium

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Abstract: ***We consider a mathematical model that simulates the blood flow within a multi-stenoses artery under the influence of an external transverse magnetic field. The interaction between the magnetic field and electrically conducting fluid (blood) generates force, which drives the movement of blood in the arterial stenotic region. Fluid's non-Newtonian behaviour is often modelled using Power-law and Casson fluids, particularly when simulating blood flow in narrow arteries and other vascular structures where the viscosity changes. Therefore, we assume the laminar and non-Newtonian behaviour characteristics of blood flow in narrow blood vessels. The governing equations are formed by transforming coordinates for a nonlinear model of pulsatile blood flow in the circulatory system and formulate the analytical expressions for axial velocity, wall shear stress, volumetric flow rate, pressure gradient and resistive flow/impedance with numerical computations to show the effect of various parameters over analytical results by using MATLAB software. These expressions uncover the significant variations in flow characteristics due to stenosis shape and the presence of a transverse magnetic field; basically, it is capable to alter the behaviour of blood flow within the artery. This investigation may provide useful information to the researchers, mathematicians and medical practitioners, who are working to investigate the effect of magnetic field on blood flow in narrow or stenosed arteries.***

Keywords: Magnetohydrodynamics (MHD), Multi-stenosis, Wall shear stress, Volumetric flow rate, Axial velocity.

AMS Subject Classification: 76Z05

1. Introduction

Few decades ago, so many researchers have been taken attention into this field where they understood the mechanisms of flowing behavior of blood under the different influence of external conditions. According to the reports of health organizations, millions of people die annually due to cardiovascular disorders. Stenosis or blocking is one of the major common conditions that affect the normal pattern of flow of blood. The thickening of tissues of the artery's walls due to plaque buildup, as described by arterial stenosis or atherosclerosis. This condition involves the gradual accumulation of fat, cholesterol, cellular waste products, and other substances like calcium and fibrin, causing to narrow or completely block arteries that can lead to various health problems, which are responsible for occurring complications. It may bring significant change in the blood flow. That's why probes of blood flow in stenotic arteries can help scientists to understand cardiovascular conditions and allow for efficient diagnostics of these conditions. Various investigations on blood circulation, either theoretical or numerical, have been performed by the many researchers like; Kapur (1985) delved the use of mathematical models to study biological systems, including population growth and genetic processes, also employed a variety of mathematical techniques, including differential equations, probability and statistical modelling. Ku (1997) discussed the basic normal flows in arteries and the biological responses to these flows, and also saw the specific arteries exhibit flow characteristic; which are three-dimensional and developing. Pralhad and Schultz (2004) considered the blood as a couple stress fluid to study the dynamics of blood flow in narrowed blood vessels, which offer insights into various blood diseases. Molla and Paul (2012) investigated non-Newtonian blood flow of arterial stenosis using large eddy simulation, and they have focused on how different blood viscosity models affect shear stress and pressure on the arterial walls. Salahuddin et al. (2025) studied the blood flows in stenotic arteries under porous media with heat generation.

The most of the works done in the literature are mainly focused on the single symmetric and non-symmetric blockage/stenoses. However, the stenosis can appear either single or multiple stenoses in series; which are not always symmetrical; it can be found in various irregular shapes, including overlapping or bell-shaped configurations. Chakravarty and Mandal (1994) constructed the mathematical modelling to study the effect on blood flow under overlapped arterial stenosis. They focused on how an overlapping stenosis impacts on pressure distribution, wall shear stress, and overall flow resistance including axial velocity and volumetric flow rate. Misra and Shit (2006) analyzed Blood, a complex fluid, can be modelled as Herschel-Bulkley fluid to account for its non-Newtonian behavior, especially in narrow blood vessels or at low shear rates. Srivastava et al. (2010) considered the blood as a double layered with a core region where erythrocytes and peripheral layer in plasma model, which used to understand the stuff of this overlying condensation on blood flow characteristics. Ha and Lee (2014) computed the numerical simulation techniques to model blood flow in the curved artery with different stenosis conditions. This allows them to study the effects of stenosis on various hemodynamic parameters, which can be used to improve blood flow dynamics in the presence of stenosis. Pokhrel et al. (2020) investigated the parameters like pressure drop and shear stress rates within the stenotic region, blood as Newtonian fluid to model the flow dynamics in the narrow artery through the Navier Stokes equations.

The research on narrowed arteries has been particularly active, and magnetic fields are being explored for their potential to improve blood flow in constricted arteries. The influence of magnetohydrodynamics (MHD) on blood flow in stenotic arteries is a crucial area of study, as it affects the hemodynamic behavior and can alter the flow characteristics under porous medium; it can also change the velocity profile and viscosity of blood, which is crucial for understanding various cardiovascular diseases linked to abnormal flow patterns. Some of that work has been reported as Chaturani and Saxena (2001) proposed a double layered fluid flow between parallel plates under the influence of a magnetic field. Bali and Awasthi (2007) studied the blood flow in stenotic arteries in presence of magnetic effect and found, it reduces the overall resistance to blood flow to make easier blood flow in the narrowed region. Ramakrishnan and Shailendhra (2013) aimed to understand the behavior of blood flow under hydromagnetic medium, where the thickness of the porous layer is finite; they also compared their findings with previous work using the boundary conditions and thick porous layer. Rashidi et al. (2017) discussed a comprehensive mathematical study on magnetohydrodynamic effect on the biological systems, and they found the accumulation of fluid particles that are moved to specific regions increases by increasing the magnetic effect; which may be useful in medication procedures where targeted delivery is key to treatment effectiveness. Cherkaoui et al. (2022) investigated the effect at high magnetic field on blood flow in the steno's artery, and gave numerical illustration on it. Shankar et al. (2025) focused on methods for simulating and evaluating blood flow characteristics in arteries, which are used to understand the effects of factors like stenosis, blood viscosity and the mechanical properties of arterial walls on blood flow.

The proposed work of this study is organized the mathematical model on blood flow in multi-stenosed artery and problem statement as; this section presents the descriptive introduction of the paper and related review literature of earlier work. Section 2, contains the necessary notation and assumptions to formulate the model. Section 3, gave the governing equations in cylindrical coordinates system (r, θ, z) that describe mathematical relationship on the magneto hydrodynamic effects in porous media, especially within stenoses arteries experiencing oscillating flow. The analytical expressions for different flow characteristics are obtained in section 4. Numerical and graphical illustration are explored in section 5. And finally, the last section 6 of the paper presents the necessary concluding remarks and arranged related references alphabetically, which makes it easier for the reader.

2. Formulation of the Problem

This mathematical model is proposed and analyzed by studying the non-Newtonian axisymmetric flow of blood with a multi-constricted arterial segment under the effect of magnetic field transversely. The magnetic field may be effective to control the blood flow in a significant amount. The artery is considered to be an overall fixed diameter over the symmetrically stenosis and the arterial wall segment is assumed to be inflexible as well as deformable. We assume the different radii of arteries according to their position, for normal artery R_0 and in cosine shaped multi stenotic artery R.

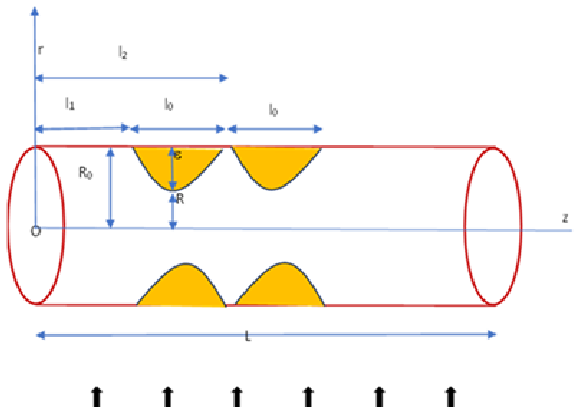


Figure 1. The model geometry of stenosis in an arterial segment

In cylindrical polar coordinate system (r, θ, z), with the z−axis aligned with the stenotic arterial axis of blood flow; where r be the radial and θ be the circumferential directions. Let, no excess charge density and neglect induced magnetic field, then ∇·E = 0 and ∇ × E=0. The external magnetic field does not affect the electrical and hydrodynamic property of fluid so, Lorentz force is given by (J × B), where J be the current density, and J can be obtained from Ohm's law i.e. J = σ (q x B), when relative effects are negligible. The geometry of multi constriction in non-dimensional form; symmetrical about the axis of artery and nonsymmetric with radial direction can be given by the following relation:

$$\frac{R}{R_0} = 1 - \frac{\varepsilon}{2R_0}\left[1 + \cos\frac{2\pi}{l_0}\left(z - l_i - \frac{l_0}{2}\right)\right];\ i = 1,2,\ldots, for \quad l_i \le z \le l_i + l_0$$
$$= 1, \text{otherwise}$$

We make some necessary notation and assumptions to formulate the model

R : Radius of a stenosed artery
R_0: Radius of a normal artery
ε : Maximum height of the stenosis; (ε << R_0)
l_0 : length of stenosis arteries
l_i : location of stenosis; i=1, 2, ...
B_0: Transverse magnetic field
E : Electrical field
σ : Conductivity of fluid
u : Radial velocity
w : Axial velocity
ρ : Density of the fluid
μ : Viscosity parameter

P : Pressure of the fluid
K : Porosity index
Q : Volumetric flow rate
λ : Resistance to flow
τ_w : Wall Shear stress parameter

- The incompressible, laminar blood flow allow along z-direction only or axisymmetric. The velocity component taken to be constant along the flowing direction into the circulatory system at the inflow point and outflow point remains relatively constant over time.
- The Blood flow is considering typically laminar for smooth characterization, incompressible having constant density during flow; it also exhibits the viscous behavior, to resists flow due to internal friction.
- The blood is under transverse magnetic effect zone; it will introduce a circular motion to generate the magnetic properties on fluid particles.
- The magnetic field generated by the walls themselves is considered weak compared to the applied magnetic field by taking the dimensionless parameter, Reynolds number is very low i.e. only external magnetic field dominates.

3. Governing equations and Mathematical Analysis

The governing equations of magnetohydrodynamics can be achieved by a combination of the incompressible, laminar flow in cylindrical coordinates (r, θ, z) system accompanied by Initial and boundary conditions to refer the system's state at the beginning and limitations or conditions that affect the system's behavior respectively. Dimensionless parameters like Reynolds number are ratios of physical quantities that help characterize the flow and determine the nature of the flow regime. The proposed mathematical model is obtained through Navier-Stokes equations and equation of continuity, which can describe the motion of viscous fluids, accounting for pressure, velocity, and viscosity in the following form:

$$\frac{\partial w}{\partial z} = 0 \tag{1}$$

$$\frac{\partial p}{\partial r} = 0 \tag{2}$$

$$\frac{1}{r}\frac{\partial p}{\partial \theta} = 0 \tag{3}$$

$$\rho\frac{\partial w}{\partial t} = -\frac{\partial p}{\partial z} + \mu\left(1+\lambda\frac{\partial}{\partial t}\right)\left(\frac{\partial^2 w}{\partial r^2}+\frac{1}{r}\frac{\partial w}{\partial r}\right) - \left(\sigma B_0^2 - \frac{\mu}{k}\right)w \tag{4}$$

For no slippiness in artery's wall; the axisymmetric boundary conditions are

$$\frac{\partial w}{\partial r} = 0 \quad \text{at } r = 0$$
$$P = P_0 \quad \text{at } z = 0$$
$$w = 0 \quad \text{at } r = R$$
$$P = P_L \quad \text{at } z = L$$

For the convenience, we introduce a transformation to solve these equations of the problems as by substituting above transformation in the motion equation from the above, partial differential equations, here p does not depend on r and q so make the substitutions:

$$y = \frac{r}{R_0}$$

By substituting above transformation in the motion equation (1)-(4) and the coefficient of blood $\mu(r) = \mu_0[1+\beta.h(r)]$, where, β = 2.5; Haematocrit $h(r) = H\left[1-\left(\frac{r}{R_0}\right)^K\right]\mu_0$,

So,

$$\frac{1}{y}\frac{d}{dy}\left[y(c_1 - c_2\, y^n)\frac{du}{dy}\right] = \frac{R_0^2}{\mu}\frac{\partial p}{\partial z} \tag{5}$$

where $\quad c_1 = 1 + c_2, \; c_2 = \beta H$

boundary condition after reduction as:

$$\left.\begin{aligned} \frac{du}{dy} = \frac{dw}{dy} = 0 \; at \; y = 0 \\ u = w = 0 \quad at \quad y = \frac{r}{R_0} \end{aligned}\right\} \tag{6}$$

From the above (1)-(3), partial differential equations, p is independent of r and θ so make the substitutions:

$$w(y,t) = \bar{w}(y)e^{i\omega t}$$
$$\frac{\partial p}{\partial z} = -Pe^{i\omega t}$$

By putting these values in equation (5), also use complex substitution (or real and imaginary parts); i.e. w(r) = u(r) + i v(r)

$$\frac{d^2\bar{w}}{dy^2} + \frac{1}{y}\frac{\partial\bar{w}}{\partial y} - \left(\frac{\sigma B_0^2 R_0^2}{\mu} - \frac{R_0^2}{k} + \frac{i\omega\rho R_0^2}{\mu}\right)\bar{w} - \frac{R_0^2}{\mu}P = 0 \tag{7}$$

and the solution using boundary conditions by equation (6), is given as

$$\bar{w}(y) = \frac{P}{i\mu\left(\frac{\sigma B_0^2}{\mu} - \frac{1}{k} + \frac{i\omega\rho}{\mu}\right)} \times \left\{1 - \frac{J_0\left(\delta^2\frac{y}{R_0}i^{3/2}\right)}{J_0\left(\delta^2\frac{R}{R_0}i^{3/2}\right)}\right\}e^{i\omega t}$$

$$\text{Or } \; \bar{w}(y) = \frac{c_1}{2c_2}\left[\frac{1}{\left(\frac{R}{R_0}\right)^2} - \frac{1}{y^2}\right] + \frac{R_0^2}{2\mu.c_2}\frac{dp}{dz}\left[\frac{1}{y} - \frac{1}{\frac{R}{R_0}}\right] \tag{8}$$

where $\delta^2 = \frac{\sigma B_0^2 R_0^2}{\mu} - \frac{R_0^2}{k} + \frac{i\omega\rho R_0^2}{\mu}$, and J_0 = complex argument; zero order Bessel's function.

4. The Analytical Expressions

- Volumetric flow rate Q is given by

$$Q = 2\pi\int_0^R wrdr,$$

$$Q = \frac{R\,R_0^2\,P}{i\mu\left(\frac{\sigma B_0^2}{\mu} - \frac{1}{k} + \frac{i\omega\rho}{\mu}\right)} \times \left\{\frac{R}{R_0} - \frac{2\,J_1\left(\delta^2\frac{r}{R_0}i^{3/2}\right)}{J_0\, i^{3/2}\delta^2\left(\delta^2\frac{R}{R_0}i^{3/2}\right)}\right\}e^{i\omega t} \tag{9}$$

where J_1 = complex argument; first order Bessel function.

- Axial velocity is given by the following analytical expression

$$w(r,t) = \frac{P}{i\mu\left(\frac{\sigma B_0^2}{\mu} - \frac{1}{k} + \frac{i\omega\rho}{\mu}\right)} \times \left\{1 - \frac{J_0\left(\delta^2\frac{r}{R_0}i^{3/2}\right)}{J_0\left(\delta^2\frac{R}{R_0}i^{3/2}\right)}\right\}e^{i\omega t} \tag{10}$$

- The expression for Pressure Gradient

$$\frac{\partial p}{\partial z} = \left[\frac{R_0 i\mu\left(\frac{\sigma B_0^2}{\mu} - \frac{1}{k} + \frac{i\omega\rho}{\mu}\right) \; J_0\left(\delta^2 \frac{R}{R_0} i^{3/2}\right)}{R\, J_0\left(\delta^2 \frac{R}{R_0} i^{3/2}\right) - 2\, J_1\left(\delta^2 \frac{r}{R_0} i^{3/2}\right)} \right] Q e^{i\omega t} \qquad (11)$$

- The Resistive flow expression obtained by integrating equation (11) with using equations (1)-(4);

$$\Delta p = p_0 - p_l$$

$$\Delta p = \left[\frac{R_0 i\mu\left(\frac{\sigma B_0^2}{\mu} - \frac{1}{k} + \frac{i\omega\rho}{\mu}\right) \; J_0\left(\delta^2 \frac{R}{R_0} i^{3/2}\right)}{R\, J_0\left(\delta^2 \frac{R}{R_0} i^{3/2}\right) - 2\, J_1\left(\delta^2 \frac{r}{R_0} i^{3/2}\right)} \right] (L - 2l_0) Q e^{i\omega t} \qquad (12)$$

by using the relation, for the flow impedance;

$$\lambda = \frac{p_0 - p_l}{Q}$$

Now equations (11) and (12) yield

$$\lambda = \left[\frac{R_0 i\mu\left(\frac{\sigma B_0^2}{\mu} - \frac{1}{k} + \frac{i\omega\rho}{\mu}\right) \; J_0\left(\delta^2 \frac{R}{R_0} i^{3/2}\right)}{R\, J_0\left(\delta^2 \frac{R}{R_0} i^{3/2}\right) - 2\, J_1\left(\delta^2 \frac{r}{R_0} i^{3/2}\right)} \right] (L - 2l_0) e^{-i\omega t} \qquad (13)$$

- The Wall shear stress of artery is given by this analytical expression:

$$\tau_w = \mu \left(\frac{\partial w}{\partial r}\right)_{r=R}$$

$$\tau_w = \frac{(-i)\, P}{\mu\left(\frac{\sigma B_0^2}{\mu} - \frac{1}{k} + \frac{i\omega\rho}{\mu}\right)} \left[1 - \frac{J_1\left(\delta^2 \frac{1}{R_0} i^{3/2}\right)}{J_0\left(\delta^2 \frac{R}{R_0} i^{3/2}\right)} \right] e^{i\omega t} \qquad (14)$$

5. Numerical Results

We also performed the numerical illustration to see the effect of various parameters such as porosity parameter, height of stenosis, stenotic shape and viscosity parameter over the analytical expressions; volumetric flow rate, wall shear rate, resistance to flow, axial velocity as well as magnetic field and the effect shown in the form of graphs in MATLAB software, we coded the program to depict effect of various values of default parameters with their usual units as: $M = \frac{\sigma B_0^2 R_0^2}{\mu}$, l_0=0.004, Q=1.5, ε=0.5 , K=0.8, μ=0.04, λ =0.5, P=0.5, R=0.08 and R_0=0.5. Figure 2, explore the magnetic effect over the axial velocity and radial, by increasing the magnetic field M leads to a decrease in axial velocity. This results in a more flattened velocity profile across the radial distance and this change in the flow pattern as the magnetic field strength increases. Figure 3, describes how axial velocity changes with radial distance, is significantly influenced by the porosity parameter. From this graph, we noticed that the blood flow increased initially as the porosity parameter increased. This is because as more volume of spaces is added, fluid particles are able to move about in the artery more easily. Figure 4, portraying the relationship between flow resistance and stenosis height by varying stenosis length l_0, shows the flow resistance increases with stenosis height as well as increasing stenotic length l_0. Figure 5, shows the behavior of blood flow on different stenotic height by varying porosity parameter K; it shows an inverse relationship, as the stenosis height increases, the axial velocity decreases and this effect is more pronounced with higher porosity values. In figure 6, we notice that the wall shear stress increases with stenotic height for different stenotic lengths, the curve rises steeply with increasing stenosis height and the curve would shift upwards with increasing stenosis length; indicating higher shear stress values for longer stenotic regions. Figure 7, shows the relationship between wall shear stress and stenotic height for fixing different viscosity parameters. The wall shear rate decreases with increasing of viscosity parameter μ and increases with stenosis height. In figure 8, we observe the opposite pattern between the variation of flow rate (Q) against ε/R_0 for different values of μ; if one decreases then other parameter increases. The relationship between resistance to flow and stenosis height, with changing values of viscosity parameter μ, is displayed from figure 9 and tells that resistance to flow increases as stenosis height increases, and this effect is amplified with higher values of μ.

6. Conclusion

This study examined the mathematical modelling of blood flow in multi-constricted artery with magnetic effect transversely; which can alter the flowing behavior in stenosed artery under porous medium. We have analyzed the characteristics of blood flow through analytical expressions like axial velocity, volumetric flow rate, resistance to flow, pressure gradient and wall shear stress in an artery numerically under the magnetic field. We have explored the graphical representation with associative numerical results obtained by MATLAB software, which plays significant role to understand the flow dynamics as well as in the field of medical science or cardiac diseases to regulate the blood inflow movement.

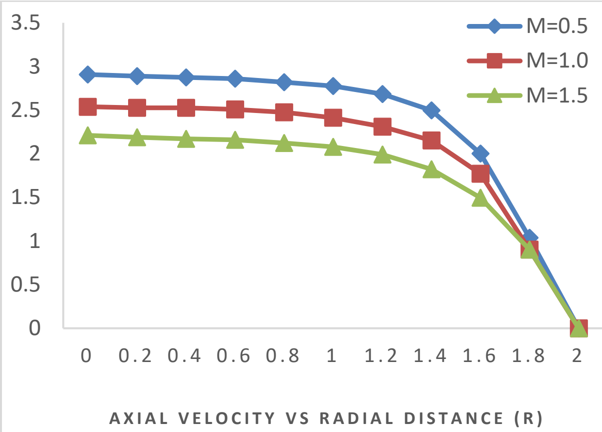


Figure 2

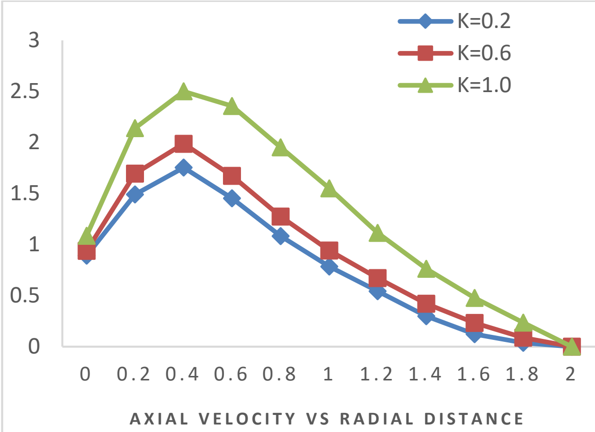


Figure 3

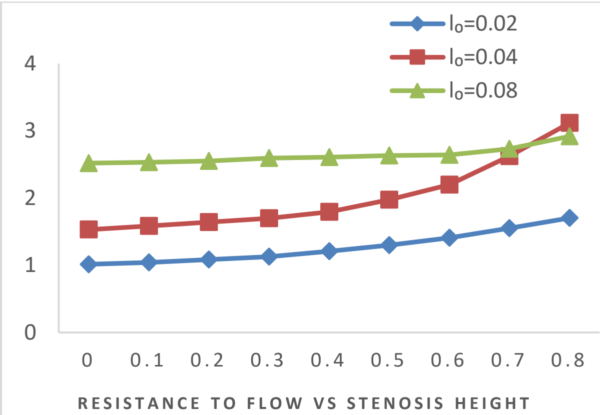


Figure 4

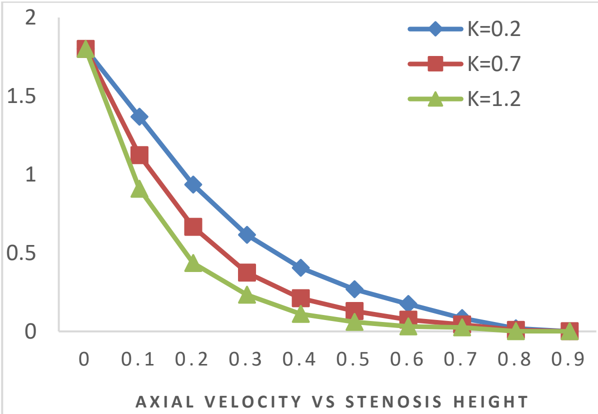
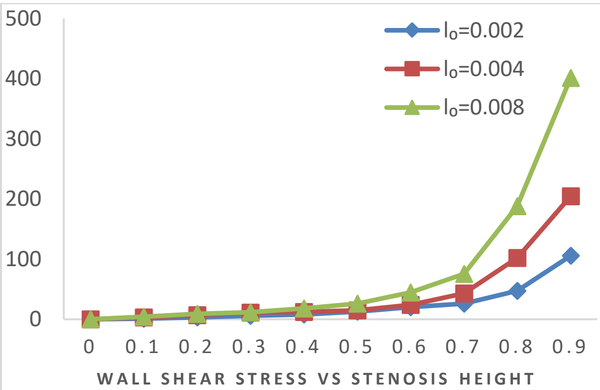


Figure 5



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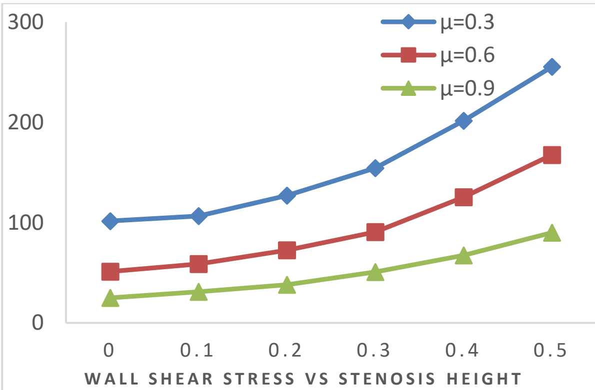

Figure 7

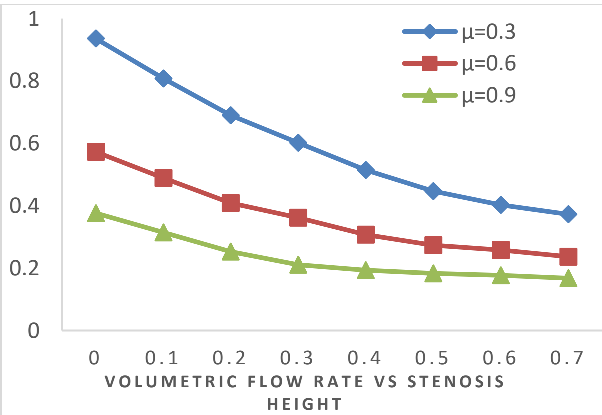

Figure 8

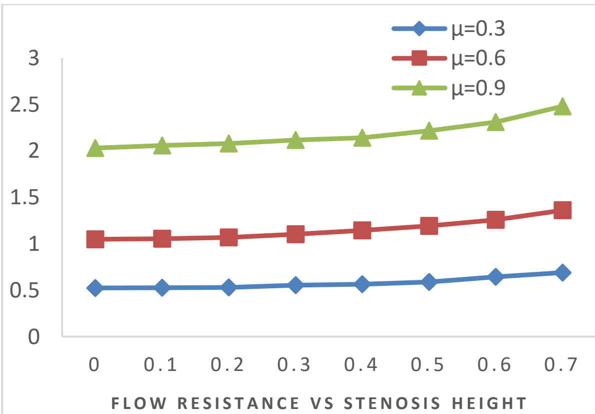

Figure 9

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Author Profile

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Krishna Rawat[1], Rishabh Painuly[2] and Mayank Negi[3] are the students of SVMKV Dehradun, which is a school having collaboration with Planetskool Research Centre. They are interested in research and mathematics, and have potential for doing mathematical research work. Planetskool provided them with research opportunity, and they took it up sincerely. They have undertaken multiple research topics, specially; creating mathematical models and understanding the relation between science and mathematical expressions of it. They frequently work towards improving their skills, imbibing research culture, learning effective communication via high-performance learning methods, made available by Planetskool. They have been selected to continue to work in various fields of mathematical application and research under Planetskool.