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Performance Modeling and Analysis of Magnetic Field on Nutritional Transport Capillary Tissues System Using Modified Herschel-Bulkley Fluid

Sapna Ratan Shah
Department of Mathematics
Harcourt Butler Technological Institute, Kanpur, India
sapna1980jan@rediffmail.com

Abstract: *The effects of magnetic field on capillary-tissue exchange system where the rheology of flowing blood in the capillary is characterized by the modified Herschel-Bulkley fluid. Blood is the suspension of cells in plasma blood can be regarded as a suspension of magnetic particles (red cells) in non-magnetic plasma. An axially non-symmetric but radially symmetric stenosis is considered when an externally uniform magnetic field is applied on the flow. The effect of magnetic field is considered in the transverse direction of blood flow and viscosity of blood is taken as radial co-ordinate dependent. Assessment of the severity of the disease could be made possible through the variation of a parameter named as retention parameter. The concentration profile and associated physiological diffusion variable involved in the study for normal and diseased state have been analyzed. The model is also employed to study the effect of shape of stenosis on flow characteristics. Finally the significance of the present model over the existing published literature has been pointed out by comparing the results with other theories.*

Keywords: *Herschek-Bulkley fluid, Nutrition transport, Rheology, Magnetic field, Stenosis shape parameter.*

1. INTRODUCTION

The study of blood flow through mammalian circulatory system has been the subject of scientific research for about a couple of centuries. Like most of the problems of nature and life science, it is complex one due to the complicated structure of blood, the circulatory system and their constituent materials. The experimental studies and the theoretical treatment of blood flow phenomena are very useful for the diagnosis of a number of cardiovascular diseases and development of pathological patterns in human or animal physiology and for other clinical purposes and practical applications. It is known that blood is electrically conducting fluid. Thus by Lenz's law, the Lorentz's force will oppose the motion of conducting fluid which will alter the haemodynamic indicators of the blood flow, in grneral. Hence by the application of magnetic field the blood flow can be deaccelerated and so it may help in treatment of certain cardiovascular diseases and in the dieases with accelerated blood circulations such as hypertension, hemorrhages [4, 5]. This idea of electromagnetic fields in medical research was firstly given by [8] and later [2] discussed the possibility of regulating the movement of blood in human system by applying magnetic field. Flow and diffusion through capillary-tissue exchange system has also been identified as one of the thrust areas of research. In narrow capillaries, at times, the arterial transport become much larger as compared to axial transport and it contributes to the development of atherosclerotic plaques, greatly reducing the capillary diameter. The problem of flow and diffusion become much more difficult through a capillary with stenosis at some region when an externally uniform magnetic field is applied on the flow. The response of blood flow through an artery under stenotic conditions has been attempted by [1, 6]. Accordingly, considerable effort has been expended studying the fluid mechanics of flow through a stenosis [7, 3, 16]. Several workers [10, 12, 15] proposed various representative models for blood in narrow capillaries. Viscosity depending on the local variation of the concentration of the suspended cells has been introduced by [11]. In 1997 [14] studied the effect of concentration on viscosity and the effect of the concentration on blood flow through a vessel with stenosis and found it an important aspect from physiological point of view. [13] have also discussed the effect of the variation of concentration of the suspended cells of blood. The theoretical study of [9] pointed out that blood obeys the

Casson's equation only in the limited range, except at very high and very low shear rate and that there is no difference between the Casson's plots and the Herschel-Bulkley plots of experimental data over the rang where the Casson's plot is valid. Also he suggested that the assumptions include in the Casson's equation are unsuitable for cow's blood and that the Herschel-Bulkley equation represents fairly closely what is occurring in the blood. Since the Herschel-Bulkley equation contains one more parameter than as compared to Casson's equation, it would be expected that more detailed information about blood properties could be obtained by the use of the Herschel-Bulkley equation. Herschel-Bulkley equation is reduced to the mathematical models, which describes the behavior of Newtonian fluid, Bingham fluid and power law fluid by taking appropriate value of the parameters. Presented herein is the study of diffusion phenomenon in modeled normal and stenosed capillary-tissue exchange system. This model incorporates modified Herschel-Bulkley fluid representation for the blood flow through an axially non-symmetrical but radially symmetric stenosis when a uniform magnetic field is externally applied on the flow.

2. FORMULATION OF THE PROBLEM

Herschel-Bulkley fluid model- The stress-strain relation of Herschel-Bulkley fluid is given as;

$$f(\tau') = \left(-\frac{du'}{dr}\right) = \frac{1}{\mu'}\left(\tau' - \tau'_0\right)^n, \qquad \tau' \geq \tau'_0 \tag{1}$$

$$f(\tau') = \left(-\frac{du'}{dr'}\right) = 0, \qquad \tau' \leq \tau'_0$$

$$\text{where } \tau' = \left(-\frac{dp'}{dz'}\frac{r'}{2}\right), \qquad \tau'_0 = \left(-\frac{dp'}{dz'}\frac{R'_c}{2}\right),$$

and μ' denotes Herschel-Bulkley viscosity coefficient, τ'_0 is yield stress, τ' is shear stress, R'_c is the radius of the plug-flow region, u' is the axial velocity along the z' direction and n is the flow behavior index. The relation correspond to the vanishing of the velocity gradients in regions, in which the shear stress τ is less than the yield stress τ_0 this implies a plug flow wherever $\tau' \leq \tau_0'$ when the shear rates in the fluid are very high, $\tau' \geq \tau_0'$, the Power-law fluid behavior is indicated.

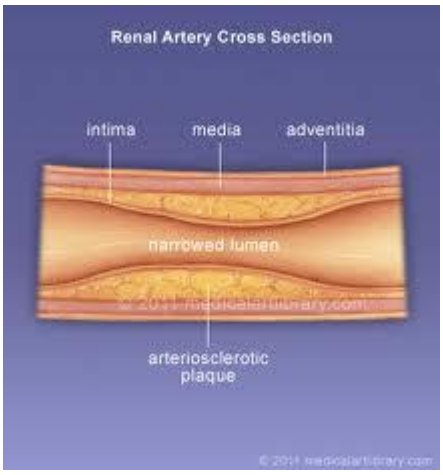

Fig 1. *Stenosis*

In the present analysis, it is assumed that the stenosis develops in the arterial wall in an axially non-symmetric but radially symmetric manner and depends upon the axial distance z and the height of its growth. The geometry of the stenosis, which is assumed to be manifested in the capillary segment, is described as [Fig (1)];

$$R'(z) = R_0[1 - A[L_0'^{(m-1)}(z' - d') - (z' - d')^m], \qquad d' \leq z' \leq d' + L_0' \tag{2}$$

$$= R_0, \qquad \text{otherwise,}$$

Where the parameter $A = \frac{\delta_S}{R_0(L_0^{'})^m}\frac{m^{m/(m-1)}}{(m-1)}$

where δ_s denotes the maximum height of stenosis at $z^{'} = (d^{'} + L^{'}_0 / m^{m/(m-1)})$. The ratio of the stenosis height to the radius of the normal artery is much less than unity. $R^{'}(z)$ and R_0 are the radius of the artery with and without stenosis respectively. $L^{'}_0$ is the stenosis length, $d^{'}$ represents the location of stenosis and m is stenosis shape parameter. In the case of $m \geq 2$, stenosis shape parameter indicates an axially symmetric stenosis. The ratio of the stenosis height to the radius of the normal artery is much less than unity.

2.1 Governing Equations

Governing equation can be written as:

$$\left(-\frac{\partial P^{'}}{\partial Z^{'}}\right)+\frac{1}{r^{'}}\frac{\partial}{\partial r^{'}}\left(\mu^{'} r^{'}\frac{\partial u^{'}}{\partial r^{'}}\right)+ J^{'}\times B^{'} = 0 \tag{3}$$

where, $J^{'} = \sigma(E^{'} + u^{'}\times B^{'})$

$$\mu^{'} = \mu_0\left(\frac{r^{'}}{R_0}\right)^{(-M)}$$

$E^{'}$ - Electric field

$B^{'}$ - Magnetic field

σ - Electric conductivity

$J^{'}$ - Magnetic flux

M - Parameter depending upon the hematocrit value of the blood.

The concentration equation for the solute is expressed by

$$u^{'}\left(\frac{\partial C^{'}}{\partial z^{'}}\right) = D^{'}\left(\frac{\partial^2 C^{'}}{\partial r^{'2}}+\frac{1}{r^{'}}\frac{\partial C^{'}}{\partial r^{'}}\right) \tag{4}$$

Where C represents the concentration of the solute, u is the axial velocity and D the diffusion coefficient for the solute under consideration in the blood.

2.2 Boundary Conditions

Following boundary conditions are introduced to solve the above equations:

$$\left(\frac{\partial u^{'}}{\partial r^{'}}\right) = 0 \quad \text{at} \quad r^{'} = 0$$

$$u^{'} = 0 \quad \text{at} \quad r^{'} = R(z)$$

$$\tau^{'} \text{ is finite} \quad \text{at} \quad r^{'} = 0$$

$$P^{'} = P_0 \quad \text{at} \quad z^{'} = 0 \tag{5}$$

$$P^{'} = P_L \quad \text{at} \quad z^{'} = L$$

$$\frac{\partial C^{'}}{\partial r^{'}} = 0 \quad \text{at} \quad r^{'} = 0,$$

$$D^{'}\frac{\partial C^{'}}{\partial r^{'}} = V^{'}N^{'}C^{'} \quad \text{at} \quad r^{'} = R,$$

where $N^{'}$ is retention parameter, $C^{'}$ is concentration; $u^{'}$ is the axial velocity and $D^{'}$ the diffusion coefficient.

2.3 Non Dimensional Scheme

$$R=\left(\frac{R^{'}}{R_0}\right),\mu=\left(\frac{\mu^{'}}{\mu_0}\right),r=\left(\frac{r^{'}}{R_0}\right),L_0=\left(\frac{L_0^{'}}{L}\right),\sigma=\left(\frac{\sigma^{'}}{R_0}\right),$$

$$\mathrm{Re}=\left(\frac{\rho U_0 R_0}{\mu_0}\right),d=\left(\frac{d^{'}}{L}\right),z=\left(\frac{z^{'}}{L}\right),P=\left(\frac{P^{'}}{\rho U_0^2}\right),u=\left(\frac{u^{'}}{U_0}\right) \tag{6}$$

The governing equations and boundary conditions are transformed to:

$$\begin{aligned} R(z) &= 1-A[L_0^{(m-1)}(z-d)-(z-d)^m], && d\le z\le d+L_0 \\ &= 1, && \text{otherwise,} \end{aligned} \tag{7}$$

where, $A=\dfrac{\delta}{R_0 L_0^m}\dfrac{m^{m/(m-1)}}{(m-1)}$

$$r^{-M}\left(\frac{\partial^2 u}{\partial r^2}\right)+(1-M)r^{-(1+M)}\left(\frac{\partial u}{\partial r}\right)-H^2 u=\mathrm{Re}\,\varepsilon\left(\frac{\partial p}{\partial z}\right) \tag{8}$$

where, $J=\sigma(E+u\times B)$

$$\mu=r^{-M}$$

$$H^2=\left(\frac{B_0^2 R_0^2 \sigma}{\mu_0}\right)$$

$$\begin{aligned} \left(-\frac{du}{dr}\right) &= \frac{r^{-(1+M)}}{\mu\varepsilon H^2}\left(\tau-\tau_0\right)^n, && \tau\ge\tau_0 \\ \left(-\frac{du}{dr}\right) &= 0, && \tau\le\tau_0 \end{aligned} \tag{9}$$

$$u\left(\frac{\partial C}{\partial z}\right)=D\left(\frac{\partial^2 C}{\partial r^2}+\frac{1}{r}\frac{\partial C}{\partial r}\right) \tag{10}$$

$$\begin{aligned} &\left(\frac{\partial u}{\partial r}\right)=0 && \text{at} && r=0 \\ &u=0 && \text{at} && r=R(z) \\ &\tau \text{ is finite} && \text{at} && r=0 \\ &P=P_0 && \text{at} && z=0 \\ &P=P_L && \text{at} && z=L \\ &\frac{\partial C}{\partial r}=0 && \text{at} && r=0, \\ &D\frac{\partial C}{\partial r}=\mathrm{VNC} && \text{at} && r=R, \end{aligned} \tag{11}$$

3. SOLUTION OF THE PROBLEM

By equation (8) and (9) we get,

$$u = \frac{-R_e\varepsilon\left[1+\frac{8\beta+H^2}{4^2\ 1+\beta}+\frac{8\beta+H^2\ \ 15\beta+H^2}{4^2 6^2\ 1+\beta^{\ 2}}+.....\right]}{2^2\ 1+\beta\ \left[1+\frac{H^2}{2^2\ 1+\beta}+\frac{8\beta+H^2\ \ H^2}{2^2 4^2\ 1+\beta^{\ 2}}+.....\right]}$$

$$\left[1+\frac{H^2 r^2}{2^2\ 1+\beta}+\frac{8\beta+H^2\ \ r^4}{2^2 4^2\ 1+\beta^{\ 2}}+.....\right]\frac{\partial P}{\partial Z}+$$

$$\frac{R_e\varepsilon\frac{\partial P}{\partial Z}}{2^2\ 1+\beta}\left[r^2+\frac{8\beta+H^2\ \ r^4}{4^2\ 1+\beta}+\frac{8\beta+H^2\ \ 15\beta+H^2\ \ r^6}{4^2 6^2\ 1+\beta^{\ 2}}+.....\right] \quad (12)$$

Using equation (9) we have,

$$P=\left(-\frac{dp}{dz}\right)=\frac{2\mu}{R^{(1+3n)}}\left[1+\frac{8\beta+H^2}{4^2\ 1+\beta}+\frac{8\beta+H^2\ \ 15\beta+H^2}{4^2 6^2\ 1+\beta^{\ 2}}+.....\right]^n \quad (13)$$

to determine λ, we integrate equation (13) for the pressure P_L and P_o are the pressure at z = 0 and z = L, respectively, where L is the length of the tube.

$$\Delta P = P_L - P_0 = \frac{2\mu}{\pi\ R_0^{1+3n}}\left[1+\frac{8\beta+H^2}{4^2\ 1+\beta}+\frac{8\beta+H^2\ \ 15\beta+H^2}{4^2 6^2\ 1+\beta^{\ 2}}+.....\right]^n \int_0^L \frac{dz}{\left(\frac{R(z)}{R_0}\right)^{(1+3n)}\ f(\bar{y})^{\ n}} \quad (14)$$

The resistance to flow is given by the coefficient λ is define as follows [18]:

$$\lambda = L/2R_0\pi \frac{-R_e\varepsilon\left[1+\frac{8\beta+H^2}{4^2\ 1+\beta}+\frac{8\beta+H^2\ \ 15\beta+H^2}{4^2 6^2\ 1+\beta^{\ 2}}+.....\right]}{2^2\ 1+\beta\ \left[1+\frac{H^2}{2^2\ 1+\beta}+\frac{8\beta+H^2\ \ H^2}{2^2 4^2\ 1+\beta^{\ 2}}+.....\right]}$$

$$\left[1+\frac{H^2}{2^2 3\ 1+\beta}+\frac{8\beta+H^2}{2^2 4^2\ 1+\beta^{\ 2}}+.....\right]+$$

$$\frac{R_e\varepsilon}{2^2\ 1+\beta}\left[\frac{1}{3}+\frac{8\beta+H^2}{4^2 5\ 1+\beta}+\frac{8\beta+H^2\ \ 15\beta+H^2}{4^2 6^2 7\ 1+\beta^{\ 2}}+.....\right] \quad (15)$$

The apparent viscosity (μ_0/μ) is defined as follow:

$$\mu_{app} = \frac{1}{\left(\frac{R(z)}{R_0}\right)^{1+3\ n}\ f(\bar{y})} \quad (16)$$

On using Eq. (15) the solution for apparent viscosity subject to the boundary conditions (11) is given as:

$$\mu_{app} = -\left\{ b\left[\frac{2H^2}{2\ 1+\beta} + \frac{4\ 8\beta+H^2}{2^2 4^2\ 1+\beta^{\ 2}} + ... \right]\frac{\partial P}{\partial Z} + \frac{R_e \varepsilon \frac{\partial P}{\partial Z}}{2^2\ 1+\beta}\left[2 + \frac{4\ 8\beta+H^2}{4^2\ 1+\beta} + \frac{6\ 8\beta+H^2\ \ 15\beta+H^2}{4^2 6^2\ 1+\beta^{\ 2}} + ... \right] \right\} \tag{17}$$

$$\tau = -R_e \varepsilon \left\{ \frac{L}{R_0}\left[1 - \frac{3\delta_S}{2R_0} + \frac{9\delta_S^2}{8R_0^2} + A_1\left(\frac{5\delta_S}{2R_0} - 1 \right) \right] + \frac{L_0}{2\pi R_0}\left[\frac{3\delta_S}{2R_0} - \frac{6\delta_S^2}{4R_0^2} + A_1\left(\frac{20\delta_S^2}{4R_0^2} - \frac{5\delta_S}{2R_0} \right) \right] \sin\frac{2\pi}{L_0}\left(L - d - \frac{L_0}{2} \right) + \frac{L_0}{4\pi R_0}\frac{7\delta_S^2}{8R_0^2}\sin\frac{4\pi}{L_0}\left(L - d - \frac{L_0}{2} \right) + \frac{L_0}{2\pi R_0}\left[\frac{3\delta_S}{2R_0} + \frac{6\delta_S^2}{4R_0^2} + A_1\left(\frac{20\delta_S^2}{4R_0^2} - \frac{5\delta_S^2}{2R_0} \right) \right] + \frac{L_0}{4\pi R_0}\left[\frac{40\delta_S^2}{8R_0^2}A_1 - \frac{3\delta_S^2}{8R_0^2} \right] \right\} \tag{18}$$

To solve the eq. (10) takes the form:

$$\frac{\nu R_0^2}{D_1 L}\frac{\partial C_1}{\partial x} = \frac{\partial^2 C_1}{\partial \eta^2} + \frac{1}{\eta}\frac{\partial C_1}{\partial \eta} \tag{19}$$

The boundary conditions are:

$$\begin{aligned} &\frac{\partial C_1}{\partial \eta} = 0 \qquad \text{at} \quad \eta = 0, \\ &D_1 \frac{\partial C_1}{\partial \eta} = VNC_1 \qquad \text{at} \quad \eta = \frac{R}{R_0} \end{aligned} \tag{20}$$

$$\bar{u} = \frac{R_0^2}{4\mu L}\left(\frac{dp}{dx} \right)(R'^2 a\left[1 + \frac{H^2 r^2}{2^2\ 1+\beta R^2} + \frac{8\beta+H^2\ \ H^2}{2^2 4^2\ 1+\beta R^{2\ 2}} + ... \right]\frac{\partial P}{\partial Z} + \left(\frac{R'\eta^3}{(n+1)} \right) - \left(\frac{\eta^4(2n+1)}{(1+1/n)}\left(\frac{R^{5n/3+1}\eta^2}{n} - \frac{54\,\eta^{n+5/2}}{(2n+1)} \right) \right) \tag{21}$$

$$+2\eta_c^2\left(\frac{R'\eta_c^2}{(3n+1)} - \frac{R_c^2\eta^2}{1/n} \right)\frac{R_e \varepsilon \frac{\partial P}{\partial Z}}{2^2\ 1+\beta R^2}(r^2 + \frac{8\beta+H^2}{4^2\left(1+\beta R^2\right)}r^4 + \frac{\left(15\beta+H^2\right)\left(8\beta+H^2\right)}{4^2 6^2\left(1+\beta R^2\right)^2} + ...))$$

on using equation (20) and (21) gives,

$$C_1 = -\mu\left[\frac{2RH^2}{2^2\ 1+\beta R^2} + \frac{4R^3\ 8\beta + H^2\ H^2}{2^2 4^2\ 1+\beta R^2\ ^2} + ...\right]\frac{\partial P}{\partial Z} + \frac{R_e \varepsilon \frac{\partial P}{\partial Z}}{2^2\ 1+\beta R^2}\left[2R + \frac{4R^3\ 8\beta + H^2}{4^2\ 1+\beta R^2} + \frac{6R^5\ 8\beta + H^2\ \ 15\beta + H^2}{4^2 6^2\ 1+\beta R^2\ ^2} + ...\right] \quad (22)$$

4. RESULTS DISCUSSION

In order to have estimate of the quantitative effects of various parameters involved in the analysis computer codes were developed and to evaluate the analytical results obtained for resistance to blood flow, concentration profile and associated physiological diffusion variables for normal and diseased system associated with stenosis due to the local deposition of lipids have been determine. The results are shown in Fig 2-5 by using the values of parameter based on experimental data in capillary.

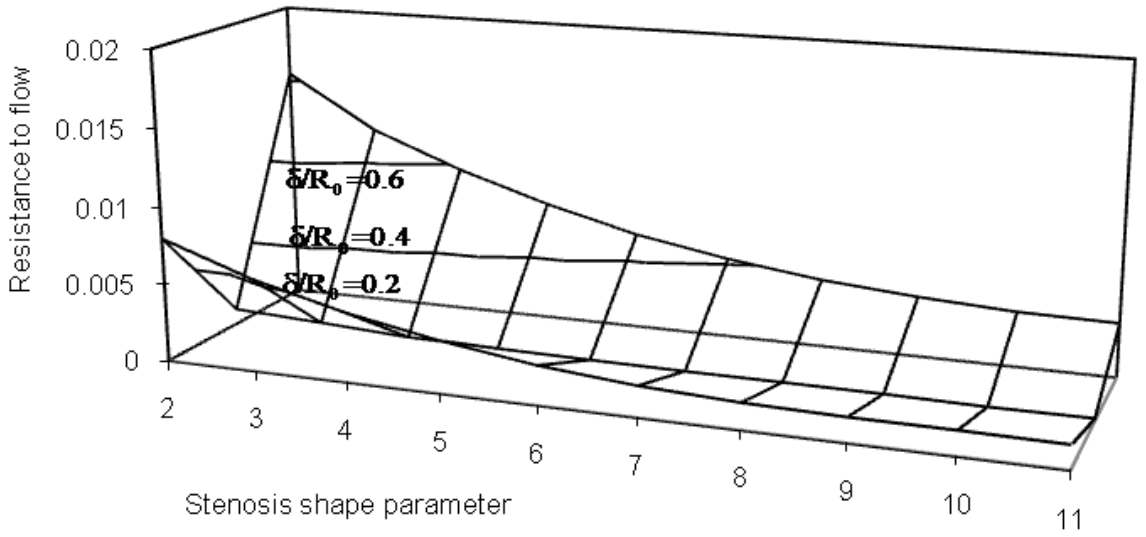

Fig 2. *Variation of resistance to flow with stenosis shape parameter*

Fig. (2) shows the results for resistance to flow for different values of stenosis shape parameter, stenosis length, stenosis size and yield stress. Resistance to flow decreases as stenosis shape parameter increases and increases as stenosis size, stenosis length and yield stress increases. Resistance to flow increase as stenosis grows or radius of artery decreases. This referred to as Fahraeus-Lindquist effect in very thin tubes. The present results are therefore consistent with the observation of Haldar [5, 4, 15]. Fig. (3) shows the results for apparent viscosity for different values of stenosis shape parameter, stenosis length, stenosis size and yield stress. Apprent viscosity increases as stenosis size, stenosis length increases and yield stress increases and decreases as stenosis shape parameter increases and results are compared with [17]. It is clear that apparent viscosity increases as stenosis grows. But the same is not true in the absence of stenosis. In capillary flow, the viscosity of blood flow found to vary with the radius of the capillary. The development of stenosis accelerates the velocity of plasma between the cells. This in turn increases the concentration of red cell and viscosity of blood in stenotic region, therefore increases. Fig (4) shows the variation of wall shear stress (τ) with stenosis size for different values of stenosis length (L_0/L). It is clear from the figure that the wall shear stress (τ) increases as stenosis size and stenosis length increases.

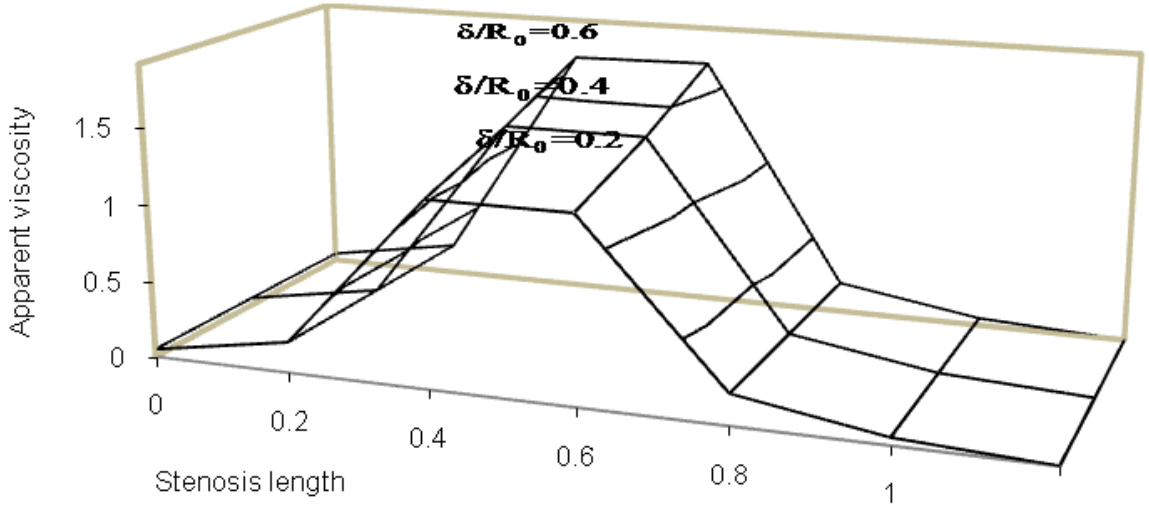

Fig 3. *Variation of apparent viscosity with stenosis length.*

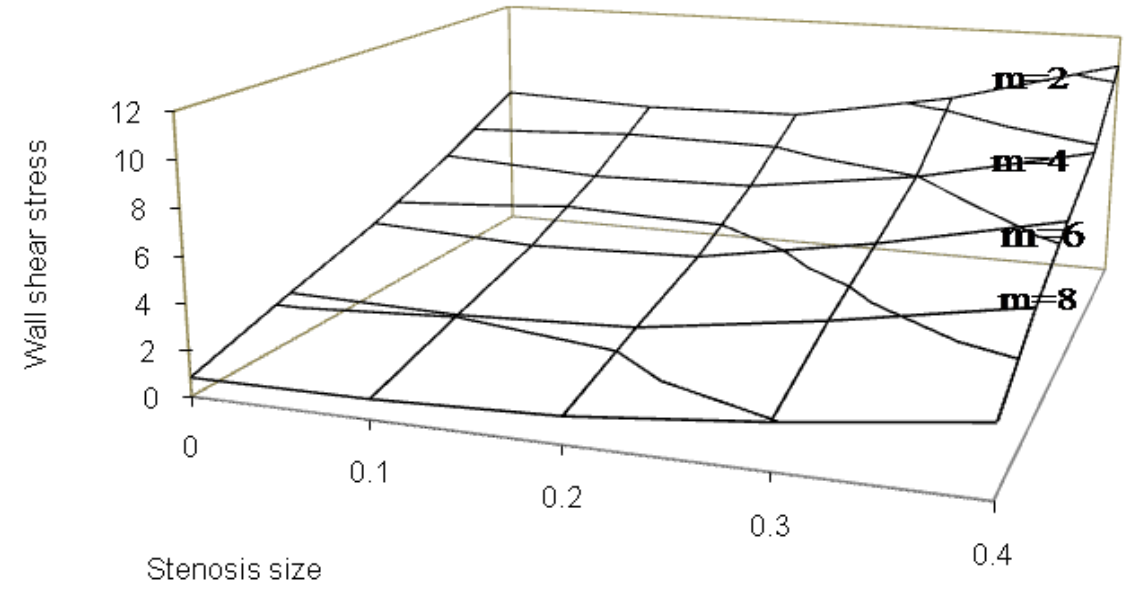

Fig 4. *Variation of wall shear stress with stenosis size for different values of stenosis shape parameter*

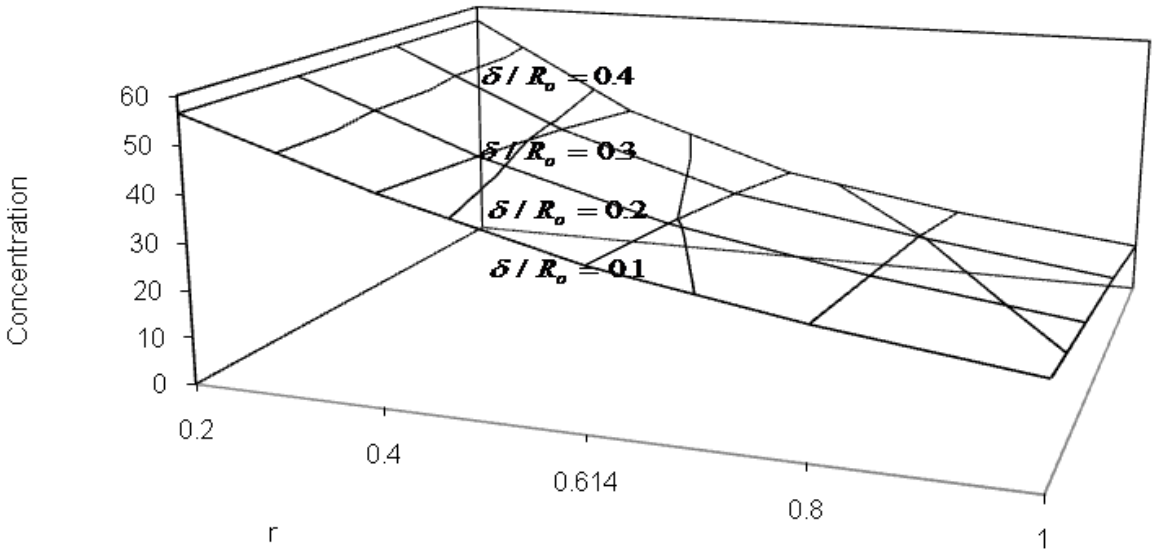

Fig 5. *Concentration profile for different values of stenosos size*

This result is consistent with result of Tandon et al. [15]. Fig (5) represents the effects of retention parameter (N) on concentration in blood flow capillary region. Increasing values of retention

parameter described the increase in retention of solute within the blood flow in the capillary region. The value of retention parameter (N=1) implies the complete retention. No solute or fluid diffuses and as retention parameter decreases from 1 to 0.4 more solute diffuses, which in turns, decreases the solute concentration in the capillary region. The variation of the values of retention parameter in the stenotic region may also be associated with the type of plaques deposited on the walls: calcified, fibrous or fatty plaque.

5. CONCLUDING REMARKS

The present study incorporates the more realistic representation for blood in small diameter blood vessels and simultaneous dispersion of solute in capillary in normal and stenotic depending on various parameters including retention parameter. Herschel-Bulkely model appears to be realistic in the sense that the equations are fairly closely to the blood flow and the central core region is easily represented and one more parameter index behavior (non-Newtonian nature of this fluid) is given in the model. The results are more encouraging and correlating well with the experimental observation that deeper region cells are deprived of the nutrients in the stenotic region. More experimental results are required for further development from clinical point of view.

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