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Research Article

A NON-NEWTONIAN FLUID MODEL FOR BLOOD FLOW USING POWER-LAW THROUGH AN ATHEROSCLEROTIC ARTERIAL SEGMENT HAVING SLIP VELOCITY

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ABSTRACT
A mathematical model is developed in this paper for studying blood flow through an atherosclerotic artery with slip velocity at wall. A power law fluid model of the blood has been utilized in this study to account for the presence of red cells (erythrocytes) in plasma. The geometry of the stenosis to be manifested in the arterial segment is given due consideration in the present theoretical analysis. The governing equation of power law fluid is solved analytically with slip and other appropriate boundary conditions. An extensive quantitative analysis is performed through numerical computations on the flow velocity, the volumetric flow rate, the impedance, the wall shear stress and the effective viscosity. The results for Newtonian model of blood are presented as a special case. An extensive quantitative analysis of the measurable flow variables having more physiological significance is carried out by developing computer algorithm and codes. As hemodynamic behavior of blood is influenced by the pressure of the arterial stenosis so the theoretical investigation may help in reducing the flow disorders in human artery that lead to the formation and propagation of the arterial diseases and cardiovascular disorders.

Keywords: Power law fluid, impedance, effective viscosity, atherosclerosis, slip velocity.

INTRODUCTION
Diseases of the heart and circulatory system are still a major cause of death in the industrialized world. The understanding of anatomy and physiology of an organic system depends much on the knowledge of blood flow through arteries. The cause and development of many arterial diseases are related to the flow characteristics of blood and the mechanical behavior of the blood vessel walls. The medical term 'Stenosis or Arteriosclerosis' means narrowing of body passage, tube or orifice and is a frequently occurring cardio- vascular disease in human arteries. Arteries are narrowed by abnormal and unusual deposition of cholesterol and some other substances resulting in the development of stenosis in the arteries. One of its most serious consequences is the increased resistance to the blood flow bringing about significant alterations in pressure distribution, wall stress and the flow resistance (impedance). The altered hemodynamic system may further influence the development of the disease and arterial deformity and change the regional blood rheology. Then there is significant fluid retention in the body, including the heart-muscle, leading to cardiac ischemia. Although the exact mechanisms responsible for

the initiation of this phenomena are not clearly known it is believed that the fluid dynamical parameters, particularly the wall shear stress play an important role in the genesis of the disease. There are considerable evidences that the vascular fluid dynamics play important role in the development and progression of arterial stenosis – a fatal disease caused due to local narrowing in the lumen of an artery. When the degree of narrowing becomes significant- enough to impale the flow of blood from the left ventricle to the arteries, heart problems develop. While the exact mechanism of the formation of Stenosis in a conclusive manner remains somewhat unclear from the stand point of physiology/pathology – a systematic study of the rheology and fluid dynamic property of blood and blood-flow could play a vital role in the basic understanding, diagnosis and treatment of many cardio-vascular, cerebra-vascular and arterial diseases. Therefore, the rheological complexities involved in the blood flow in the cardio-vascular system have attracted serious attention from many researchers. Physiologically blood is an aqueous liquid (plasma) having some suspended particles like white blood cells, erythrocytes, platelets and others.

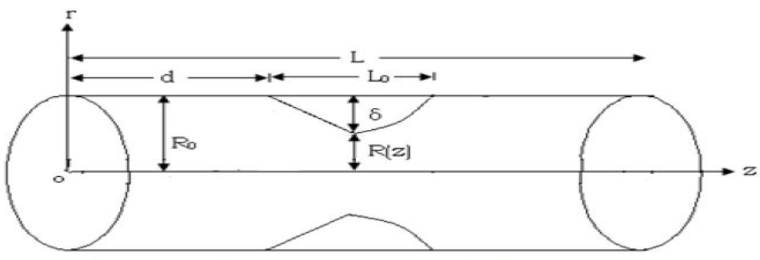
In the series of the papers, (Texon, 1957; May et al.,1963; Hershey and Cho, 1966; Young, 1968; Forrester and Young, 1970; Caro et al., 1971; Fry,1972 Young and Tsai, 1973; Lee, 1974; Richard et al., 1977) the effects on the cardiovascular system can be understood by studying the blood flow in its vicinity. In these studies the behaviour of the blood has been considered as a Newtonian fluid. However, it may be noted that the blood does not behave as a Newtonian fluid under certain conditions. It is generally accepted that the blood, being a suspension of cells, behaves as a non-Newtonian fluid at low shear rate (Charm and Kurland, 1965; Hershey et at., 1964; Whitemore, 1968; Cokelet, 1972; Lih, 1975; Shukla et al., 1990).

In particular it has been painted out that the flow behavior of blood in small diameter tubes (less than 0.2 mm) at less than 20 sec^{-1} shear rate can be reasonably represented by a Power Law fluid. In this present model we have also considered the velocity slip condition at the constricted wall and also the effects of peripheral layer viscosity. The intent of the present analysis is to study the effects of the slip velocity and the peripheral layer viscosity called the effective viscosity on the flow variables (velocity profile, flow rate, wall shear stress, impedance) by assuming that the flowing blood represented by a Power Law fluid.

In all the above mentioned studies, traditional no – slip boundary condition [Schlichting and Gersten (2004)] has been employed. However, a number of studies of suspensions in general and blood flow in particular both theoretical [Vand (1948); Jones (1966); Nuber (1967); Brunn (1974); Chaturani and Biswas (1984)] and experimental [Bugliarello and Hayden (1962); Bennet (1967)], have suggested the likely presence of slip (a velocity discontinuity) at the flow boundaries (or in their immediate neighbourhood). Recently, Misra and Shit (2007), Ponalgusamy (2007), Biswas and Chakraborty (2009), Verma et al. (2011) have developed mathematical models for blood flow through stenosed arterial segment, by taking a velocity slip condition at the constricted wall. Thus, it seems that consideration of a velocity slip at the stenosed vessel wall will be quite rational, in blood flow modelling.

MATERIALS AND METHODS

Considering the axisymmetric flow of blood through an atherosclerotic artery of circular cross-section with stenosis specified at the position shown in figure below:



Geometry of a composite stenosis in an artery.

The geometry of the stenosis which is assumed to be manifested in the arterial wall segment is described as:

$$\frac{R(z)}{R_0} = 1 - \frac{\delta}{2R_0}\left[1 + \cos\frac{2\pi}{l_0}\left(z - d - \frac{l_0}{2}\right)\right];$$ When d≤z≤d+l_0
$$= 1;$$

otherwise (1)

Where R(z) is the radius of the artery with stenosis, R_0 is the radius of the artery without stenosis, δ is the maximum height of the stenosis in the artery, l_0 is the length of the stenosis, l is the length of the artery and d is the location of the stenosis in the artery.

The Governing Equations of Power Law Fluid Model are:

$$\tau = \mu e^n \quad (2)$$
$$\tau = \frac{1}{2}Pr \quad (3)$$
$$e = -\frac{du}{dr} \quad (4)$$

The Boundary Conditions:
u=u_s at r=R(z); τ is finite at r=0;$\frac{\partial u}{\partial r} = 0$ at r=0;

Where,τ is the wall shear stress, u is the blood velocity, u_s is the slip velocity, μ is the apparent viscosity of blood, P is the pressure gradient, R or R(z) is the radius of the artery with stenosis and $\frac{\partial u}{\partial r}$ is the velocity gradient.

Combining the equations (2), (3) and (4) we get:

$$\frac{du}{dr} = -\left(\frac{1}{2}\frac{P}{\mu}\right)^{\frac{1}{n}}.r^{\frac{1}{n}}$$

Now, integrating both sides, we get:

$$\int du = -\left(\frac{1}{2}\frac{P}{\mu}\right)^{\frac{1}{n}}\int r^{\frac{1}{n}}dr$$

So, u=$-\left(\frac{1}{2}\frac{P}{\mu}\right)^{\frac{1}{n}}\frac{r^{\frac{n+1}{n}}}{n+1}n$+c where c= Constant (5)

Putting the boundary conditions, r=R at u=u_s

$$u_s = -\left(\frac{1}{2}\frac{P}{\mu}\right)^{\frac{1}{n}}R^{\frac{n+1}{n}}\frac{n+1}{n} + cm$$ Where c= Constant (6)

Combing equations (5) and (6) we get:

$$u = -\left(\frac{1}{2}\frac{P}{\mu}\right)^{\frac{1}{n}}r^{\frac{n+1}{n}}\frac{n}{n+1} + \left(\frac{1}{2}\frac{P}{\mu}\right)^{\frac{1}{n}}R^{\frac{n+1}{n}}\frac{n}{n+1} + u_s$$

So, $u = \frac{n}{n+1}\left(\frac{1}{2}\frac{P}{\mu}\right)^{\frac{1}{n}}\left[R^{\frac{n+1}{n}} - r^{\frac{n+1}{n}}\right] + u_s$ (7)

Now, $Q = \int_0^R 2\pi ur\,dr$

Putting the value of u, we get

$Q =$
$\int_0^R 2\pi\left[\frac{n}{n+1}\left(\frac{1}{2}\frac{P}{\mu}\right)^{\frac{1}{n}}\left[R^{\frac{n+1}{n}} - r^{\frac{n+1}{n}}\right] +\right.$
$\left. u_s\right] rdr$
(8)

Solving equation (8) we get,

$$Q = \frac{n}{n+1}\left(\frac{1}{2}\frac{P}{\mu}\right)^{\frac{1}{n}} \pi R^{\frac{3n+1}{n}}\left(1 - \frac{2n}{3n+1}\right) + \pi u_s R^2$$

$$\text{So,} Q = \frac{n}{3n+1}\pi R^{\frac{3n+1}{n}}\left(\frac{1}{2}\frac{P}{\mu}\right)^{\frac{1}{n}} + \pi u_s R^2 \qquad (9)$$

From equation (9) we get, $\frac{dp}{dz} = 2\mu\left[\frac{(3n+1)(Q-\pi u_s R^2)}{n\pi R^{\frac{3n+1}{n}}}\right]^n$; where $P = \frac{dp}{dz}$

$$\text{So,} \int_{p_0}^{p_1} dp = 2\mu\left(3+\frac{1}{n}\right)^n \int_0^l \left(\frac{Q}{\pi R^{\frac{3n+1}{n}}} - \frac{u_s}{R^{\frac{n+1}{n}}}\right)^n dz$$

=>

$$\int_{p_0}^{p_1} dp = 2\mu\left(3+\frac{1}{n}\right)^n\left[\int_0^d \left(\frac{Q}{\pi R_0^{\frac{3n+1}{n}}} - \frac{u_s}{R_0^{\frac{n+1}{n}}}\right)^n dz + \int_d^{d+l_0}\left(\frac{Q}{\pi R^{\frac{3n+1}{n}}} - \frac{u_s}{R^{\frac{n+1}{n}}}\right)^n dz + \int_{d+l_0}^{L}\left(\frac{Q}{\pi R_0^{\frac{3n+1}{n}}} - \frac{u_s}{R_0^{\frac{n+1}{n}}}\right)^n dz\right]$$

$$\text{So,} \Delta P = 2\mu\left(\frac{3n+1}{n}\right)^n\left[\left(l - \frac{2l_0}{3}\right)\left(\frac{Q}{\pi R_0^{\frac{3n+1}{n}}} - \frac{u_s}{R_0^{\frac{n+1}{n}}}\right)^n + \frac{2l_0}{3}\left(\frac{Q}{\pi R^{\frac{3n+1}{n}}} - \frac{u_s}{R^{\frac{n+1}{n}}}\right)^n\right] \qquad (10)$$

$$\text{Now, } \lambda_0 = \frac{\Delta P}{Q} = \frac{2\mu}{Q}\left(\frac{3n+1}{n}\right)^n\left[\left(l - \frac{2l_0}{3}\right)\left(\frac{Q}{\pi R_0^{\frac{3n+1}{n}}} - \frac{u_s}{R_0^{\frac{n+1}{n}}}\right)^n + \frac{2l_0}{3}\left(\frac{Q}{\pi R^{\frac{3n+1}{n}}} - \frac{u_s}{R^{\frac{n+1}{n}}}\right)^n\right]$$

$$\text{And, } \lambda_N = \frac{2\mu}{Q}\left[\left(\frac{3n+1}{n}\right)\left(\frac{Q}{\pi R_0^{\frac{3n+1}{n}}} - \frac{u_s}{R_0^{\frac{n+1}{n}}}\right)\right]^n . l$$

$$\text{So,} \lambda = \frac{\lambda_0}{\lambda_N} = \left[1 - \frac{2l_0}{3l} + \frac{2l_0}{3l}\frac{\left(\frac{Q}{\pi R^{\frac{3n+1}{n}}} - \frac{u_s}{R^{\frac{n+1}{n}}}\right)^n}{\left(\frac{Q}{\pi R_0^{\frac{3n+1}{n}}} - \frac{u_s}{R_0^{\frac{n+1}{n}}}\right)^n}\right] \qquad (11)$$

$$\text{Now, } \tau_R = -\frac{R}{2}\frac{dp}{dz} = -\frac{R}{2}2\mu\left[\frac{(3n+1)(Q-\pi u_s R^2)}{n\pi R_0^{\frac{3n+1}{n}}}\right]^n$$

$$\text{And, } \tau_N = -\frac{R_0}{2}2\mu\left[\frac{(3n+1)(Q-\pi u_s R_0^2)}{n\pi R_0^{\frac{3n+1}{n}}}\right]^n$$

$$\text{So, } \tau = \frac{\tau_R}{\tau_N} = \left(\frac{Q-\pi u_s R^2}{Q-\pi u_s R_0^2}\right)^n\left(\frac{R_0}{R}\right)^{3n} \qquad (12)$$

Now, $\mu_e = \frac{\pi P R^4}{8Q}$

$$= \frac{\pi R^4}{8Q}\left[2\mu\left(\frac{(3n+1)(Q-\pi\mu_s R^2)}{n\pi R^{\frac{3n+1}{n}}}\right)^n\right] = \frac{1}{8Q}\left[2\mu\left(\frac{(3n+1)(Q-\pi\mu_s R^2)}{nR^{\frac{3n-3}{n}}\pi^{\frac{n-1}{n}}}\right)^n\right]$$

So, $\mu_e = \frac{\mu}{4Q}\left(\frac{3n+1}{n}\right)^n\left[\frac{(Q-\pi u_s R^2)^n}{R^{(3n-3)}\pi^{(n-1)}}\right]$ (13)

RESULTS AND DISCUSSION

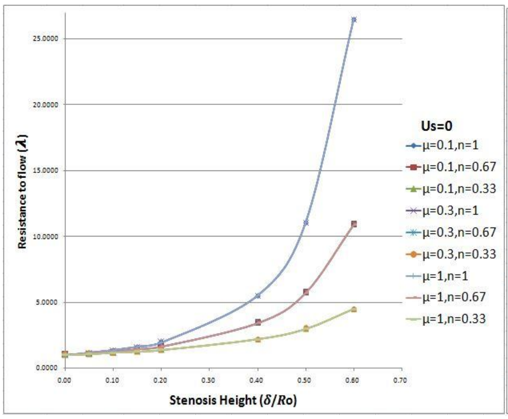


Fig. 1

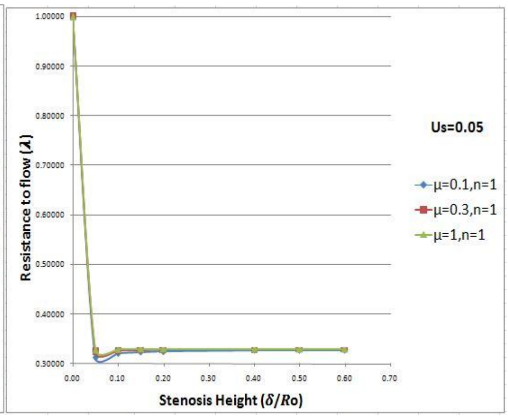


Fig. 2

Fig. 1 and 2: illustrate the variation of resistance to flow (λ) with the stenosis height (δ/Ro) for the given values of the flow behavior index (n) and apparent viscosity(μ). When slip velocity (u_s) is 0, λ increases with the increase in stenosis height, but when u_s is 0.05 unit, λ steeply decreases upto a certain extent and remain more or less constant after that.

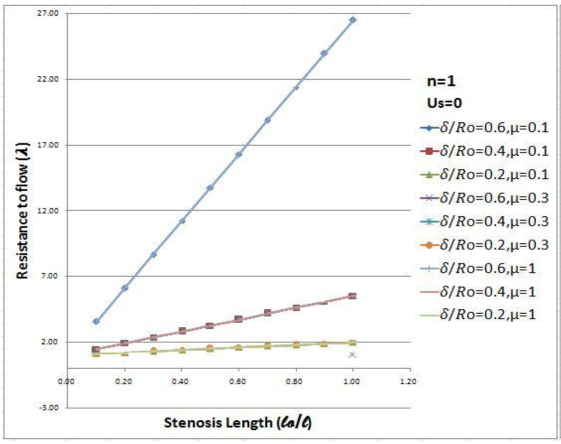


Fig. 3

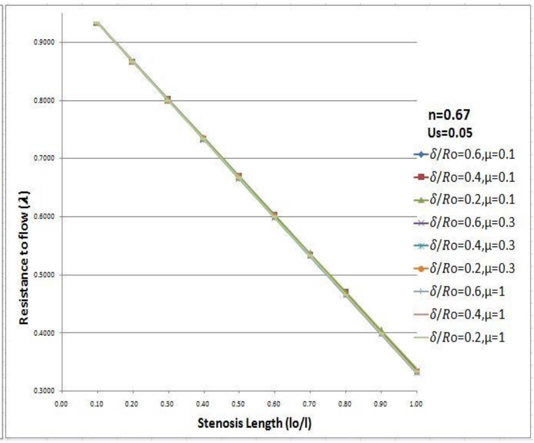
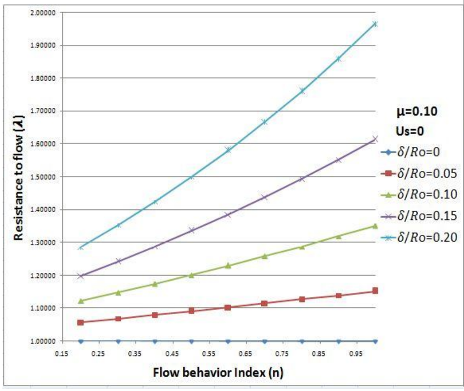


Fig. 4

Fig. 3 and 4: Illustrate the variation of resistance to flow (λ) with the stenosis length (l/l_0) for the given values of the stenosis height (δ/Ro) and apparent viscosity(μ). When slip velocity (u_s) is 0, λ is directly proportional to the stenosis length (l/l_0), but when u_s is 0.05 unit, λ proportionally decreases with the increase in stenosis length. The overlapping nature of the

graph states that the change in values of apparent viscosity(μ) doesn't or very negligibly affects the results, while considering u_s.



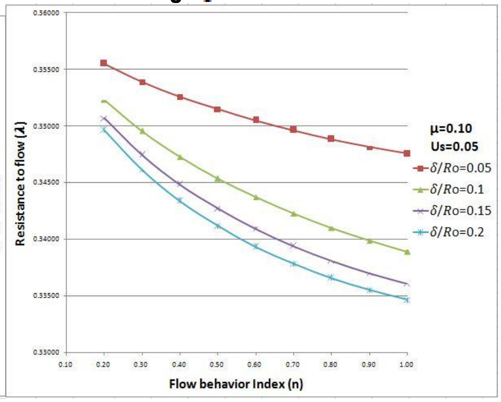


Fig. 5 **Fig. 6**

Fig. 5 and 6: Illustrate the variation of resistance to flow (λ) with the flow behavior index (n) for the given values of the stenosis height (δ/Ro). When slip velocity (u_s) is 0, λ increases with the increase in n, but when u_s is 0.05 unit, λ proportionally decreases with the increase in n.

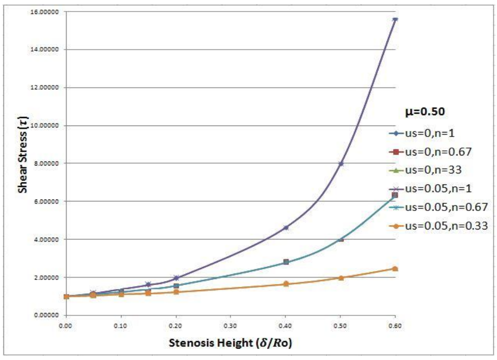
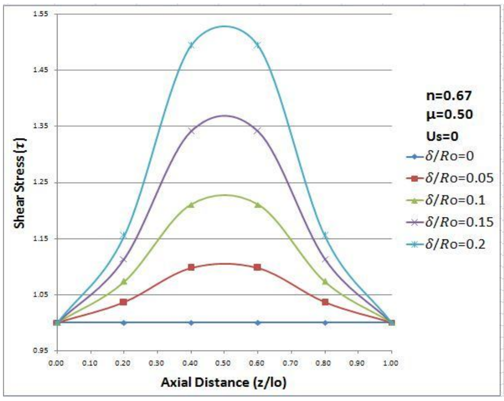


Fig. 7

Fig. 7: Illustrates the variation of shear stress (τ) with the stenosis height (δ/Ro) for the given values of the flow behavior index (n) and slip velocity (u_s). τ increases with the increase in stenosis height. The change in slip velocity (u_s) from 0 to 0.05 has no effect on the values of wall shear stress (τ).



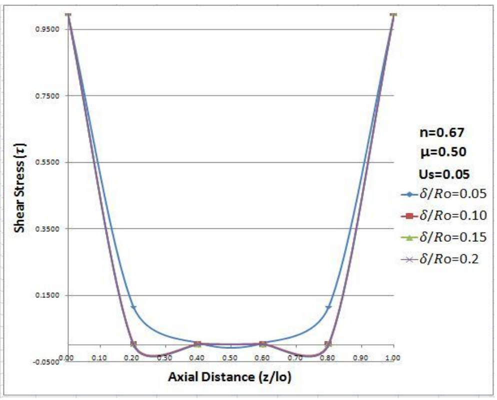


Fig. 8 **Fig. 9**

Fig. 8 and 9: illustrate the variation of shear stress (τ) with the axial distance (z/l_0) for the given values of the stenosis height (δ/Ro). When slip velocity (u_s) is 0, τ increases upto a certain

limit and then decreases with the axial distance, but when u_s is 0.05 unit, λ τ decreases upto a certain limit and then increases with the axial distance.

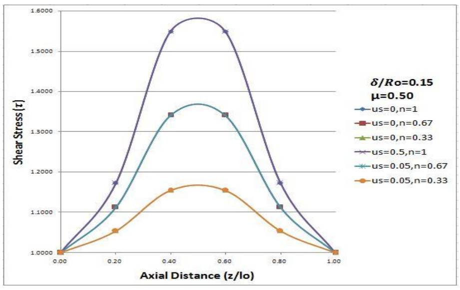
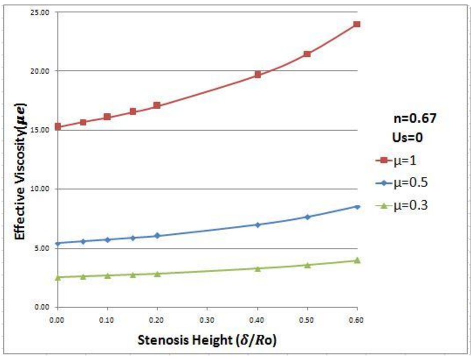


Fig. 10

Fig. 10 illustrates the variation of shear stress (τ) with the axial distance (z/l_0) for the given values of the flow behavior index (n) and slip velocity (u_s). τ increases upto a certain limit and then decreases with the axial distance. The change in slip velocity (u_s) from 0 to 0.05 has no effect on the values of wall shear stress (τ).



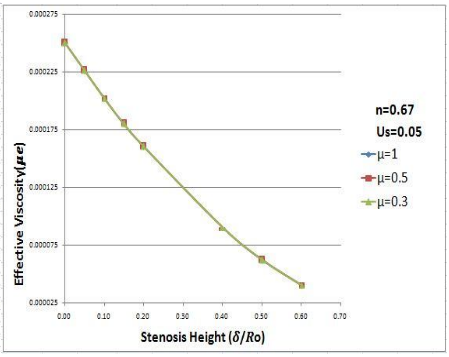
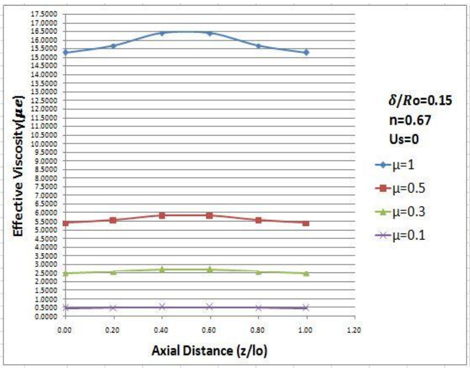


Fig. 11 **Fig. 12**

Fig. 11 and 12: Illustrate the variation of effective viscosity (μ_e) with the stenosis height (δ/Ro) for the given values of apparent viscosity(μ). When slip velocity (u_s) is 0, μ_e is directly proportional to the stenosis height, but when u_s is 0.05 unit, μ_e proportionally decreases with the increase in stenosis length. The overlapping nature of the graph states that the change in values of apparent viscosity(μ) doesn't or very negligibly affects the results while considering u_s.



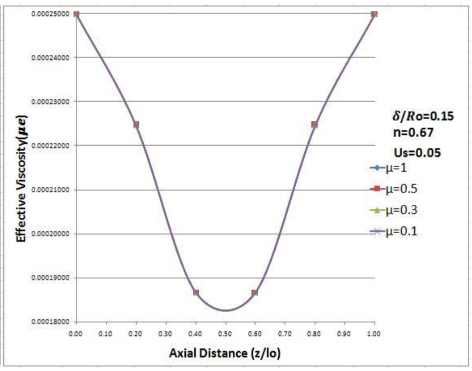


Fig. 13 **Fig. 14**

Fig. 13 and 14: Illustrate the variation of effective viscosity (μ_e) with the axial distance (z/l_0) for the given values of the apparent viscosity(μ). When slip velocity (u_s) is 0, μ_e increases upto a certain limit and then decreases with the axial distance, but when u_s is 0.05 unit, μ_e decreases upto a certain limit and then increases with the axial distance. The overlapping nature of the

graph states that the change in values of apparent viscosity(μ) doesn't or very negligibly affects the results while considering u_s.

CONCLUSION

The theoretical analysis provides a scope in bringing out many interesting results on rheological properties of blood flow through narrow, circular, stenosed arteries considering power law fluid model of blood. It is interesting to note that the rheological parameters, the radius, height and length of the stenosis influence the flow characteristics qualitatively and quantitatively. The effect of inclusion of slip velocity at the wall of the stenosis is given due consideration in the study which was neglected by the previous researchers. The investigation provides a scope for ascertaining the dominating role of slip velocity in different conditions of arteriosclerosis. It is to conclude that the results will help the physicians in predicting the stenotic range, the critical location and severity of the disease so that they may take crucial decision for treatment through medicine or through surgery. Further careful investigations are suggested to address the problem more realistically and to overcome the restrictions imposed on the present work.

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