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Mathematical Modelling Of Blood Flow through Three Layered Stenosed Artry

Sapna Ratan Shah[1], Anuradha and Anamika[2]
[1]*Biomechanical lab, School of Computational and Integrative Sciences, Jawaharlal Nehru University, New Delhi*
[2]*Department of Mathematics, Harcourt Butler Technical University, Kanpur-208002*

Abstract: A three layer mathematical model is presented to study the blood flow characteristics using blood fluid as casson's and bingham plastic fluid model. The important characteristics of blood flow such as velocity profile, wall shear stress, and volumetric flow rate is calculated. The governing equations used to analyze such flow conditions, should include effect of curvature of blood vessels, pulsatile flow in the blood vessel. Numerical expression is calculated for finding the velocity, wall shear stress, and volumetric flow rate. Perturbation technique is used to calculate these expressions and matlab programming is used to find computational results. The computational results are presented graphically.
Key words: Stenosed Artery, Non-Newtonian Fluid, Casson's Fluid Model, Bingham Plastic Fluid Model, Flow Rate, Velocity Profile.

I. INTRODUCTION

Circulatory disorders are known to be responsible for over seventy five percent of all deaths and "Arteriosclerosis" is one of the major causes for these. A model for abnormal growth in the lumen of artery is called stenosis, which is developed due to intravascular plaques. As the disease advances, it affects severely on the coronary flow rate and perfusion.

Fig. 1. (a) Artery with multiple stenosis

Many theoretical analysis and experimental studies of the flow through stenosis have been performed by Jain et al., [6]. Blood flow in the human circulatory system is caused by pumping action of heart, and Shah [12] found an innovative solution for the problem of blood flow through stenosed artery using generalized Bingham Plastic fluid model. Pulsatile blood flow in the artery is also because of pumping action of heart. This is cause that there are so many researchers studied about the pulsatile flow in the stenosed artery. Devajyoti [4] studied the Pulsatile Blood Flow through a Catheterized Artery with an Axially Nonsymmetrical Stenosis. The flow of blood through small diameter tubes is of physiological and clinical importance, due to its complexity and anomalous behavior, it is difficult to analyze it. Pontrelli [10] found the pulsatile blood flow in small vessels, in simulations in Biomedicine. Deville [15] studied the pulsatile blood flow behavior of non-Newtonian fluids through arterial stenosis. To understand the effect of stenosis in the lumen artery Srivastava et al., [13] investigated flow of blood through an overlapping stenosis treating blood as non-Newtonian fluid. There are many researchers [2, 3, 7, 9, 11] studied the two layer model of blood flow. In this series Biswas et al.

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presented two-layered mathematical model for blood flow inside an asymmetric stenosed artery with velocity slip at interface. Gupta et al., [1] presented a three – layer semi-imperical model for flow of blood and other particulate suspensions through narrow tubes.

A. Formulation of the problem

Let us consider an axially symmetric, laminar, pulsatile and fully developed flow of blood through a circular cylindrical tube having overlapping constriction satisfied at the position as shown in (Fig. 2). The geometry of the stenosis

$$\frac{R(z)}{R_0} = 1 - \frac{3}{2}\frac{\delta}{R_0 L_0^4}\left[11(z-d)L_0^3 - 47(z-d)^2 L_0^2 + 72(z-d)^3 L_0 - 36(z-d)^4\right], d \le z \le d + L_0 \quad (1)$$

$$= 1, \qquad \text{otherwise}$$

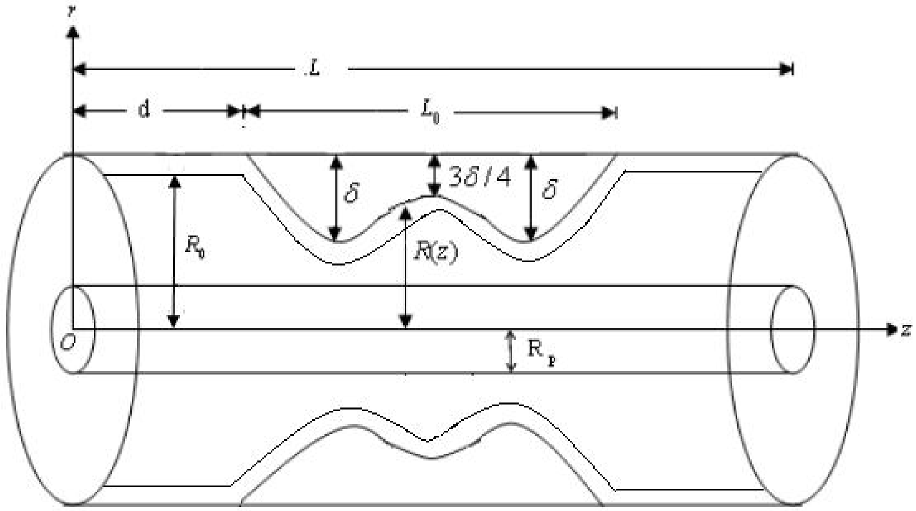

Fig. 2. The geometry of an arterial overlapping stenosis

Where R(z) and R_0 are the radius of the tube with and without stenosis, respectively R_p is the radius of the plug flow region, L_0 is the length of the stenosis and indicates its location, δ is the maximum height of the stenosis appears at two locations: $z=d+L_0/6$ and $z=d+5L_0/6$. The stenosis height at $z=d+L_0/2$ from origin, called critical height.

The momentum equation is given by

$$\rho\frac{\partial u^*}{\partial t^*} = -\frac{\partial p^*}{\partial z^*} - \frac{1}{r^*}\frac{\partial (r^*\tau^*)}{\partial r^*} \quad (2)$$

The Casson's equation describing the non-Newtonian behavior of blood may be written as

$$\tau^{*1/2} = \left(-\mu\frac{\partial u^*}{\partial r^*}\right)^{1/2} + \tau_y^{1/2}, \qquad \tau^* > \tau_y \quad (3)$$

$$-\frac{\partial u^*}{\partial r^*} = 0, \qquad \tau^* \le \tau_y \quad (4)$$

The Bingham Plastic equation describing the non-Newtonian behavior of blood may be written as

$$\tau^* = -\mu\frac{\partial u^*}{\partial r^*} + \tau_y, \qquad \tau^* > \tau_y \quad (5)$$

$$-\frac{\partial u^*}{\partial r^*} = 0, \qquad \tau^* \le \tau_y \quad (6)$$

The theoretical analysis takes care of the two-phase flow of blood, the peripheral plasma layer is considered to be Newtonian, while the core region that is supposed to contain all the erythrocytes contained in the blood inside the artery is treated as non-Newtonian. The mathematical model that is developed here is formulated by the following set of equations:

$$\tau^* = -\mu\frac{\partial u^*}{\partial r^*}, \qquad if\ R_0^*(z^*,t^*) < r^* < R^*(z^*,t^*), \quad (7)$$

$$\tau^{*1/2} = \left(-\mu\frac{\partial u^*}{\partial r^*}\right)^{1/2} + \tau_y^{1/2}, \qquad if\ R_p^*(z^*,t^*) < r^* < R_0^*(z^*,t^*), \quad (8)$$

$$\tau^* = -\mu\frac{\partial u^*}{\partial r^*} + \tau_y, \qquad if\ 0 < r^* < R_p^*(z^*,t^*) \quad (9)$$

Along with the boundary conditions

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$u^* \text{ at } r^* = R^*(z^*, t^*),$ (10)

$\tau^* \text{ is finite at } r^* = 0.$ (11)

These equations are to be supplemented by the condition of continuity of u^* and r^* at the interfaces $r^* = R_0^*(z^*, t^*)$ and $r^* = R_p^*(z^*, t^*)$.

The pressure gradient which is function of z^* and t^*, is represented as

$$\frac{\partial}{\partial z^*} p^*(z^*, t^*) = -q^*(z^*) f(t^*) \quad (12)$$

$$\text{with } q^*(z^*) = -\frac{\partial}{\partial z^*} p^*(z^*, 0), f(t^*) = 1 + A\sin(\omega t^*). \quad (13)$$

For the analysis presented in the sequel, we use the following non-dimensional variables

$$z = \frac{z^*}{a}, r = \frac{r^*}{a}, R(z,t) = \frac{R^*(z^*, t^*)}{a}, R_0(z,t) = \frac{R_0^*(z^*, t^*)}{a}, \quad R_p(z,t) = \frac{R_p^*(z^*, t^*)}{a}, \tau = \frac{2\tau^*}{q_0 a}, \quad \theta = \frac{2\tau_y}{q_0 a}, u = \frac{u^*}{\frac{q_0 a^2}{4\mu}}, t = t^*\omega, Q(z,t) = \frac{Q^*(z,t)}{\frac{\pi q_0 a^4}{8\mu}}, d = \frac{d^*}{a}, \ \delta = \frac{\delta^*}{a}, L_0 = \frac{L_0^*}{a}, L = \frac{L^*}{a}, \alpha^2 = \frac{\alpha^2 \omega}{\frac{\mu}{\rho}}, q(z) = \frac{q^*(z^*)}{q_0}$$

(14)

where q_0 is the constant pressure gradient (which is negative).

In terms of these non-dimensional variables, eq. (2) reads

$$\alpha^2 \frac{\partial u}{\partial t} = 4q(z) f(t) - 2\frac{1}{r}\frac{\partial (r\tau)}{\partial r}, \qquad 0 < r < R(z,t), \quad (15)$$

while the equations (7) to (9) take the forms

$$-\frac{\partial u}{\partial r} = 2\tau, \qquad R_0(z,t) < r < R(z,t), \quad (16)$$

$$-\frac{\partial u}{\partial r} = 2\left[\theta + \tau - 2\sqrt{\theta\tau}\right], \quad R_p(z,t) < r < R_0(z,t), \quad (17)$$

$$-\frac{\partial u}{\partial r} = 2(\tau - \theta), \qquad 0 < r < R_p(z,t), \quad (18)$$

u=0 at r=R, τ is finite at r=0. (19)

Also u and τ have to be continuous at $r = R_0(z,t)$ and $r = R_p(z,t)$. (20)

The volumetric flow rate is given by

$$Q(z,t) = 4\int_0^{R(z,t)} r u(z,r,t) dr. \quad (21)$$

B. Analytical solution of the problem

Considering the Womersley parameter to be very small, the velocity u, shear stress τ as well as R_0 and R_p can be expressed in the following form

$u(z, r, t) = u_0(z, r, t) + \alpha^2 u_1(z, r, t) + \ldots$ (22)

$r(z, r, t) = r_0(z, r, t) + \alpha^2 u_1(z, r, t) + \ldots$ (23)

$R_0(z, r, t) = R_{00}(z, r, t) + \alpha^2 R_{10}(z, r, t) + \ldots$ (24)

$R_p(z, r, t) = R_{0p}(z, r, t) + \alpha^2 R_{1p}(z, r, t) + \ldots$ (25)

Using (22) and (23) in (15). We have

$$\frac{\partial}{\partial r}(r\tau_0) = 2rq(z)f(t) \quad (26)$$

$$\frac{\partial u_0}{\partial t} = -\frac{2}{r}\frac{\partial}{\partial r}(r\tau_1) \quad (27)$$

integrating (26) and using the boundary condition (19), we have

$$\tau_0 = q(z)f(t)R_p, \qquad 0 \le r \le R_p. \quad (28)$$

In the regions $R_p \le r \le R_0$ and $R_0 \le r \le R$, the continuity of τ_0 at R_{0p} and R_{00} yield

$$\tau_0 = q(z)f(t)r. \quad (29)$$

Introducing (22) and (23) into equations (16) to (18) and equating like powers of α we obtain

$$-\frac{\partial u_0}{\partial r} = 2\tau_0, \quad -\frac{\partial u_1}{\partial r} = 2\tau_1, \qquad \text{if } R_0 \le r \le R. \quad (30)$$

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$$-\frac{\partial u_0}{\partial r} = 2\left[\theta + \tau_0 + 2\sqrt{\tau_0\theta}\right], -\frac{\partial u_1}{\partial r} = 2\tau_1\left[1 - 2\sqrt{\frac{\theta}{\tau_0}}\right], \quad \text{if } R_p \le r \le R_0. \qquad (31)$$

$$\frac{\partial u_0}{\partial r} = 2(\tau_0 - \theta), \quad \frac{\partial u_1}{\partial r} = 2\tau_1, \qquad \text{if } 0 \le r \le R_p \qquad (32)$$

The boundary condition for u_0 and u_1 are:

$u_0 = 0$, $u_1 = 0$ at $r = R$ (33)

u_0, u_1 are continuous at R_{00} and R_{0p}.

From (29), (30) and (32) we have

$u_0 = q(z)f(t)(R^2 - r^2)$ $R_0 \le r \le R$ (34)

Using (3.12) in (3.8) and (3.10), one can find

$$u_0 = [q(z)f(t)(R_{00}^2 - r^2) + 2\theta(R_{00} - r)] + q(z)f(t)(R^2 - R_{00}^2) - \frac{8}{3}\sqrt{\theta q(z)f(t)}\left(R_{00}^{3/2} - r^{3/2}\right) \qquad R_p \le r \le R_0 \qquad (35)$$

Now from (29), (32), (33) and (35)

$$u_0 = \left[q(z)f(t)\left(R_{0p}^2 - r^2\right) - 2\theta(R_{0p} - r)\right] + 2\theta\left(R_{0p} - R_{00}\right) + q(z)f(t)\left(R_{0p}^2 - R_{00}^2\right) - \frac{8}{3}\sqrt{\theta q(z)f(t)}\left(R_{0p}^{3/2} - R_{00}^{3/2}\right) + q(z)f(t)(R_{00}^2 - R^2) \qquad 0 \le r \le R_p \qquad (36)$$

Neglecting the squares and higher power of α in (25) and using (28), one obtains

$$r|_{\tau_0=\theta} = R_{0p} = \frac{\theta}{q(z)f(t)}. \qquad (37)$$

Again, making use of the regularity condition that τ_1 is finite at $r = 0$, equation (35) and (27) as

$$\tau_1 = \left[-q(z)f'(t)\frac{R_{0p}^2}{4} - \frac{q(z)f'(t)}{2}\left(R_{0p}^2 - R_{00}^2\right) + \theta\frac{R_{0p}}{3} - \theta\left(R_{0p} - R_{00}\right) - \frac{q(z)f'(t)}{2}(R_{00}^2 - R^2) - \frac{4}{3}\sqrt{\frac{\theta q(z)}{f(t)}}f'(t)\left(R_{0p}^{3/2} - R_{00}^{3/2}\right)\right]R_{0p} \qquad 0 \le r \le R_p \qquad (38)$$

The continuity of τ_1 at $r = R_{0p}$ yields

$$\tau_1 = -\left[\frac{q(z)f'(t)}{2}\left(R_{00}^2\frac{r}{2} - \frac{r^3}{4}\right) + \theta\left(R_{00}\frac{r}{2} - \frac{r^2}{3}\right) - \frac{2}{3}\sqrt{\frac{\theta q(z)}{f(t)}}f'(R_{00}^{3/2}\frac{r}{2} - \frac{2}{7}r^{5/2})\right] - q(z)f(t)(R^2 - R_{00}^2)\frac{r}{4} + \frac{A_2}{r} \qquad R_p \le r \le R_0 \qquad (39)$$

Where,

$$A_2 = -\left[\theta\left(R_{00}\frac{R_{0p}}{2} - \frac{R_{0p}^2}{3}\right) + \frac{q(z)f'(t)}{2}R_{0p}\left(\frac{R_{00}^2}{2} - \frac{R_{0p}^3}{4}\right) - \frac{4}{3}\sqrt{\frac{\theta q(z)}{f(t)}}f'(t)\left(R_{00}^{3/2}\frac{R_{0p}}{2} - \frac{2}{7}R_{0p}^{5/2}\right)\right] - q(z)f'(t)(R^2 - R_{00}^2)\frac{R_{0p}}{4} \qquad (40)$$

Similarly, since τ_1 is continuous at R_0, we have

$$\tau_1 = -\frac{1}{2}q(z)f'(t)\left(R^2\frac{r}{2} - \frac{r^3}{4}\right) + \frac{A_3}{r} \qquad R_0 \le r \le R, \qquad (41)$$

Where,

$$A_3 = -\left[\theta\left(\frac{R_{00}^2}{6}\right) + q(z)f'(t)\frac{R_{00}^3}{8} - \frac{6}{21}\sqrt{\frac{\theta q(z)}{f(t)}}f'(t)R_{00}^{5/2}\right]R_{00} + A_2 \qquad (42)$$

Using (33), the equations (30)-(32) give rise to

$$u_1 = -q(z)f'(t)\left[\frac{R^2}{4}(r^2 - R^2) - \frac{(r^4 - R^4)}{16}\right] - 2A_3\log\left(\frac{r}{R}\right) \qquad R_0 \le r \le R \qquad (43)$$

$$u_1 = X(r) \qquad R_p \le r \le R_0 \qquad (44)$$

$$u_1 = -2\left[-q(z)f'(t)\frac{R_{0p}^2}{4} + \theta\frac{R_{0p}}{3} - \theta\left(R_{0p} - R_{00}\right) - q(z)f'(t)\frac{(R_{0p}^2 - R_{00}^2)}{2} + \frac{4}{3}\sqrt{\frac{\theta q(z)}{f(t)}}f'(t)\left(R_{0p}^{3/2} - R_{00}^{3/2}\right) - \frac{q(z)f'(t)}{2}(R_{00}^2 - R^2)\right]R_{0p}\left(R_{0p} - r\right) + X\left(R_{0p}\right) \qquad 0 \le r \le R_p \qquad (45)$$

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Where,

$$X(r) = \Bigg[2\theta\left(R_{00}\frac{(R_{00}^2 - r^2)}{4} - \frac{(R_{00}^4 - r^4)}{12}\right) + 2q(z)f'(t)\left(R_{00}^2\frac{(R_{00}^2 - r^2)}{4} - \frac{(R_{00}^4 - r^4)}{16}\right) - \frac{4}{3}\sqrt{\frac{q(z)}{f(t)}}f'(t)\left(R_{00}^{3/2}\frac{(R_{00}^2 - R^2)}{4} - \frac{4}{49}(R_{00}^{7/2} - r^{7/2})\right) + q(z)f(t)(R^2 - R_{00}^2)\frac{(R_{00}^2 - r^2)}{4} - 2A_2 log\left(\frac{r}{R_{00}}\right)\Bigg]$$

$$-2\sqrt{\frac{\theta}{q(z)f(t)}}\Bigg[\theta\left(\frac{R_{00}}{3}(R_{00}^{3/2} - r^{3/2}) - \frac{2}{21}(R_{00}^{7/2} - r^{7/2})\right) + q(z)f'(t)\left(\frac{R_{00}^3}{3}(R_{00}^{3/2} - r^{3/2}) - \frac{1}{14}(R_{00}^{7/2} - r^{7/2})\right) - \frac{2}{3}\sqrt{\frac{q(z)}{f(t)}}f'(t)\left(\frac{R_{00}^{3/2}}{3}(R_{00}^{3/2} - r^{3/2}) - \frac{2}{21}(R_{00}^3 - r^3)\right) + q(z)f(t)\left(\frac{R^2 - R_{00}^2}{6}\right)(R_{00}^{3/2} - r^{3/2}) + 2A_2(R_{00}^{1/2} - r^{1/2})\Bigg]$$

$$+q(z)f'(t)\left(\frac{R^2}{4}(R_{00}^2 - R^2) - \left(\frac{R_{00}^4 - R^4}{16}\right)\right) - 2A_3 log\left(\frac{R_{00}}{R}\right) \quad (46)$$

The expression for velocity in the peripheral and core layers can now be calculated by using the equations (22), (34)-(35) and (43)-(45).

The volumetric flow rate can be computed from (21) by re-writing it in the form

$$Q(z,t) = 4\left(\int_0^{R_p} ru(z,r,t)\,dr + \int_{R_p}^{R_0} ru(z,r,t)dr + \int_{R_0}^{R} ru(z,r,t)dr\right). \quad (47)$$

Different expression for u(z, r, t) can to be used for the different regions.

The value of R_{00} in (24) is found by using the continuity of u_0 at R_{00}. In doing so, we have used the Newton-Raphson method, by taking the non-dimensional velocity in the peripheral layer at R_{00} as its value in the steady case, i.e. 0.03.

It may be noted that if we write $u = u_0 + \alpha^2 u_1$ and use (34)-(36) and (43)-(45). We find that the right hand side of (47) involves the unknown quantity q(z). The quantities Q(z, t) and q(z) in (47) are both unknown. In order to determine q(z) one may choose the value of Q(z, t) as its value in the steady state. By considering $\theta/q(z)f(t) \ll 1$ and using (47), we find

$$q(z) = \frac{Q_s}{R^4} + \frac{16}{7}\left(\frac{\theta Q_s}{R^5}\right)^{\frac{1}{2}} + \frac{64\theta}{49R}, \text{ Where } R = R(z, t). \quad (48)$$

While computing q(z), one may take $Q_s = 1.0$. After q(z) is determined, Q(z, t) can be calculated from (47).

II. RESULTS AND DISCUSSION

The volumetric flow rate and the wall shear stress are the two important characteristics in the study of fluid flow through a stenosed artery. Using appropriate boundary conditions, analytical expressions for the velocity profile, volumetric flow rate and shear stress have been obtained. Where,

$L = 30$, $L_0 = 10$, $d = 10$, $\theta = 0.05$, $A = 0.7$, $\delta = 0.1$, $\alpha^2 = 0.049$, $T = 1.0$.

Fig. 3 to Fig. 4 shows the variation of velocity with radius for different values of time t and amplitude A. It is found that when time t is increases then the velocity will also increases. And velocity decreases with the increasing value amplitude.

Comparision of velocities on the three different region with respect to z is shown in Fig. 5. Where u_1 is velocity in the region $R_0 \leq r \leq R$. u_2 is velocity in the region $R_p \leq r \leq R_0$. u_1 is velocity in the region $0 \leq r \leq R_p$. Fig. 6 depicts the variation of wall shear stress with axis z for different values of time t. Wall shear stress increases for the increasing values of time t. It is found that wall shear stress first increases for some values of z and then decreases. Fig. 7 shows the variation of wall shear stress with time for different values of θ. It is shown that the wall shear stress increases when time t increases and decreases when yield stress θ increases. Fig. 8 depicts the variation of wall shear stress with the height of stenosis for different values of time r. wall shear stress increases with increasing value of time and also increases for the increasing values of height of stenosis. Fig. 9 depicts the variation of volumetric flow rate with time t for different values of amplitude A. Volumetric flow rate is increases for the increasing values of tine t and also increases for the increasing values of amplitude A. Fig. 10 shows that variation of volumetric flow rate with axis z for different values of time. It is found that

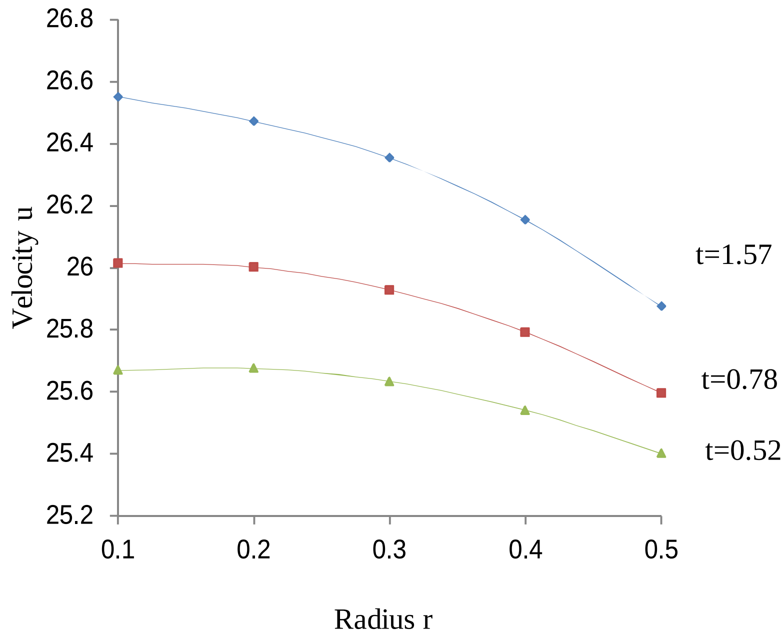

Fig. 3 Variation or velocity with radius for different values of time

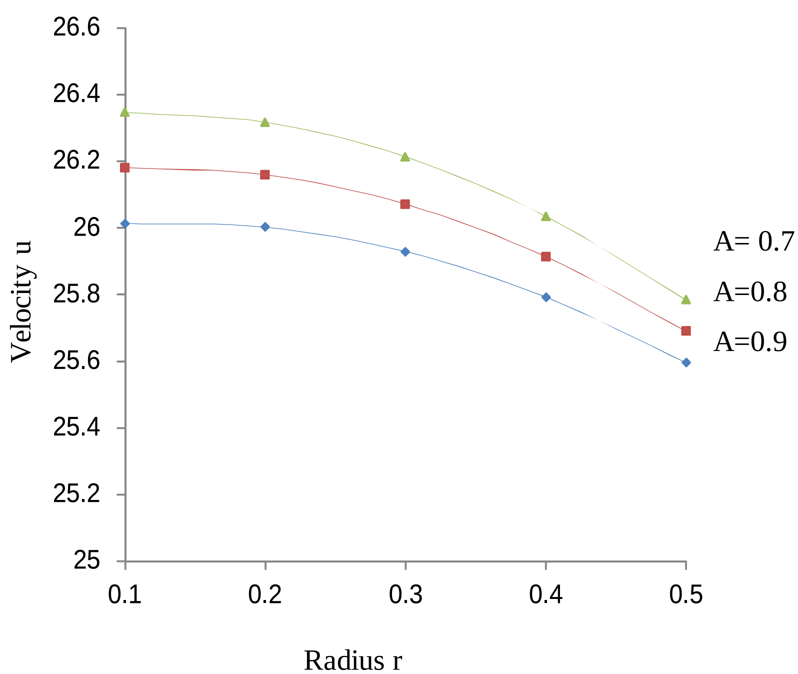

Fig. 4 Variation of velocity with radius for different values of A

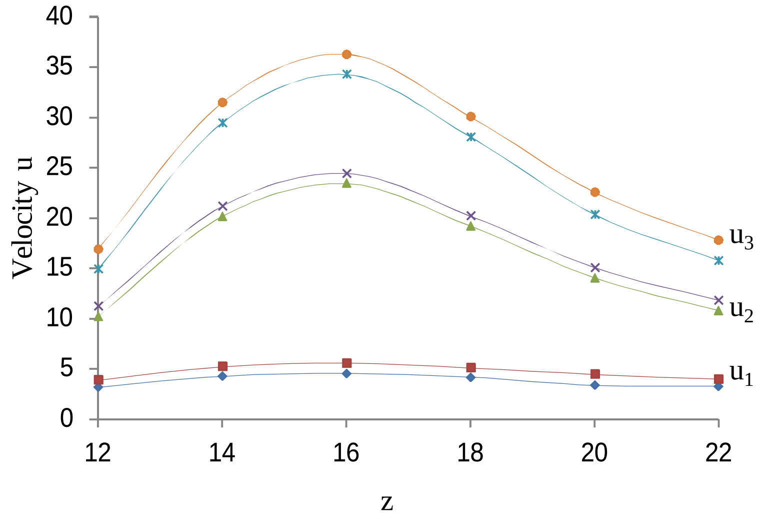

Fig. 5 Comparision of velocities in different region for different A=0.4 and A=0.8

volumetric flow rate first increases for some values of z and then decreases. It is also shown in the fig. that the volumetric flow rate increases with the increasing values of time t. Fig. 11 depicts the variation of volumetric flow rate with axis z for different values of yield stress θ. It

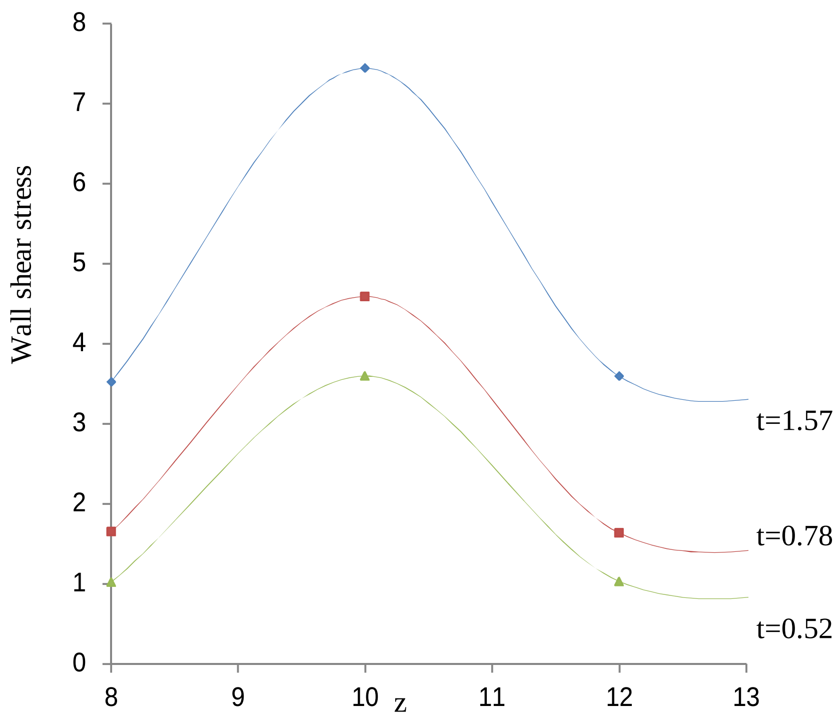

Fig. 6 Variation of wall shear stress with z for different values of t

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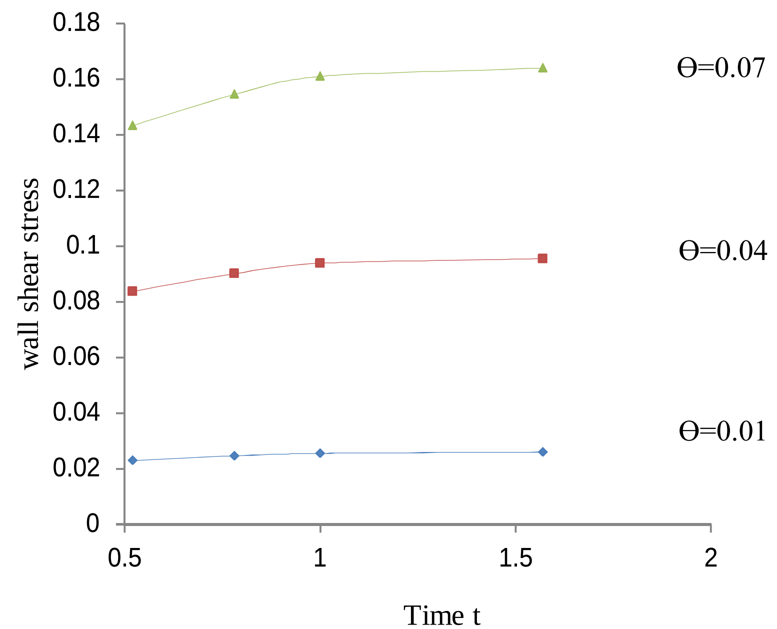

Fig. 7 Variation of wall shearstress with time for different values of Θ

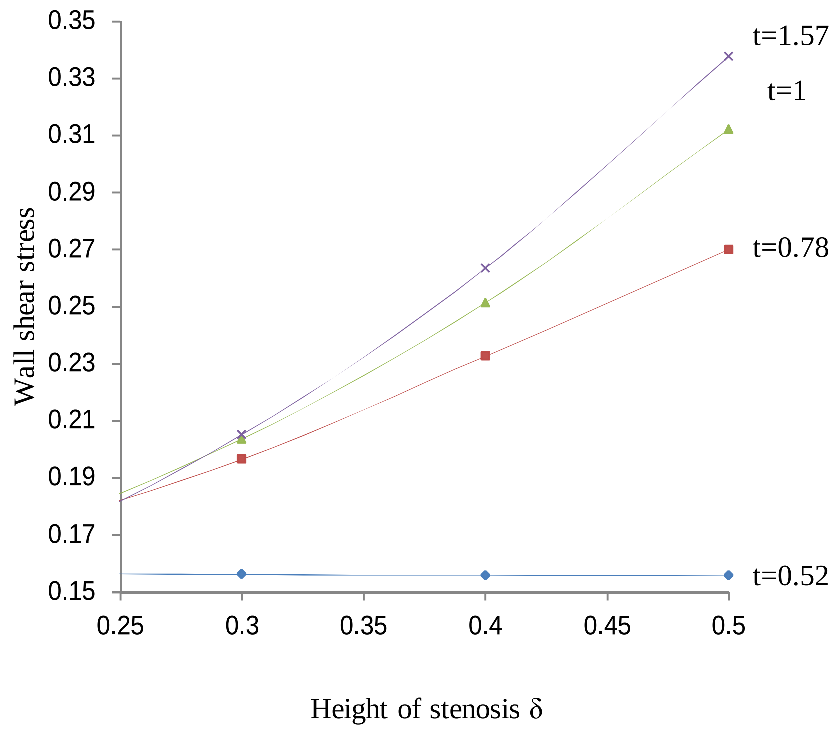

Fig. 8 Variation of wall shear stress with height of stenosis for different values of time t

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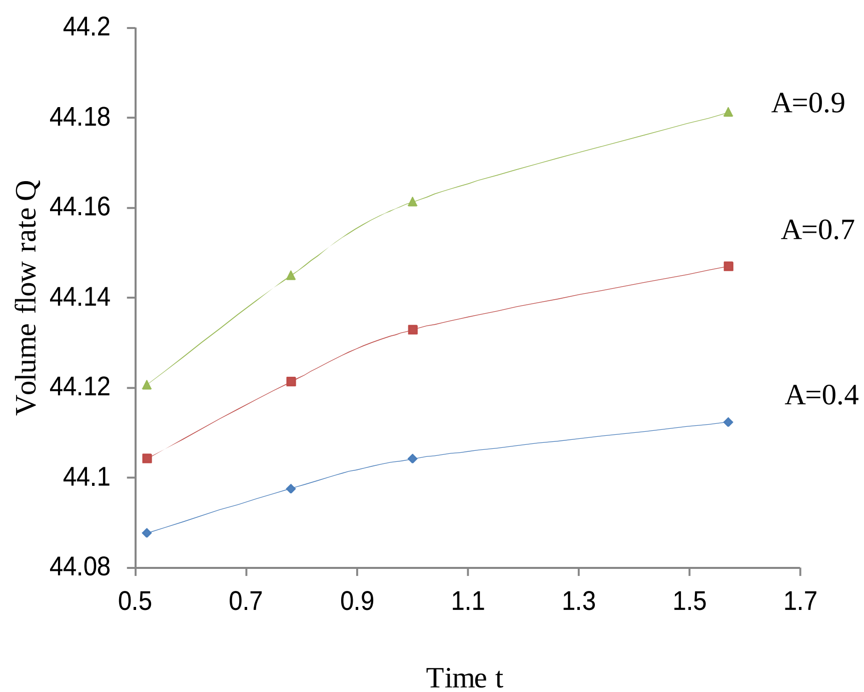

Fig. 9 Variation of volumetric flow rate with time for different values of A

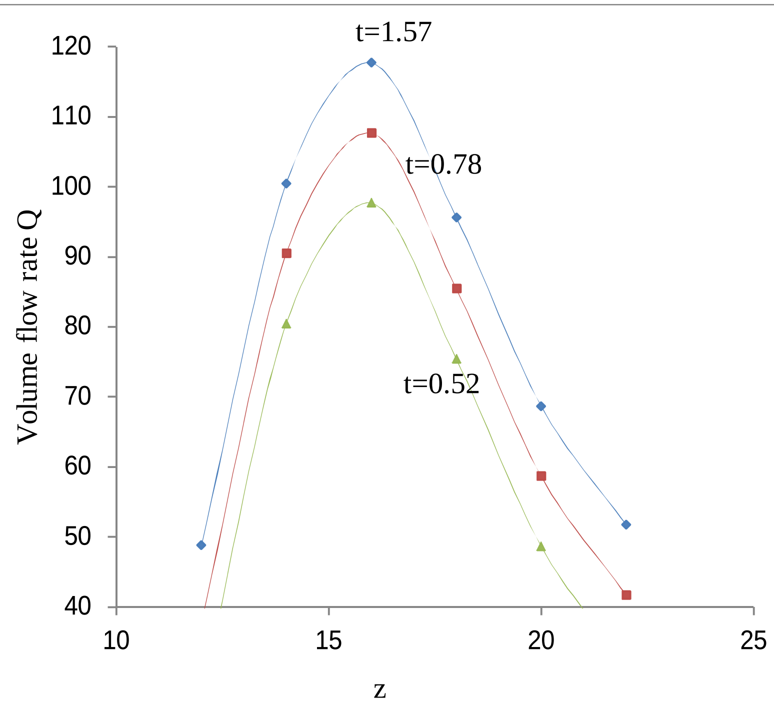

Fig. 10 Variationof volumetric flow rate with z for different values of t

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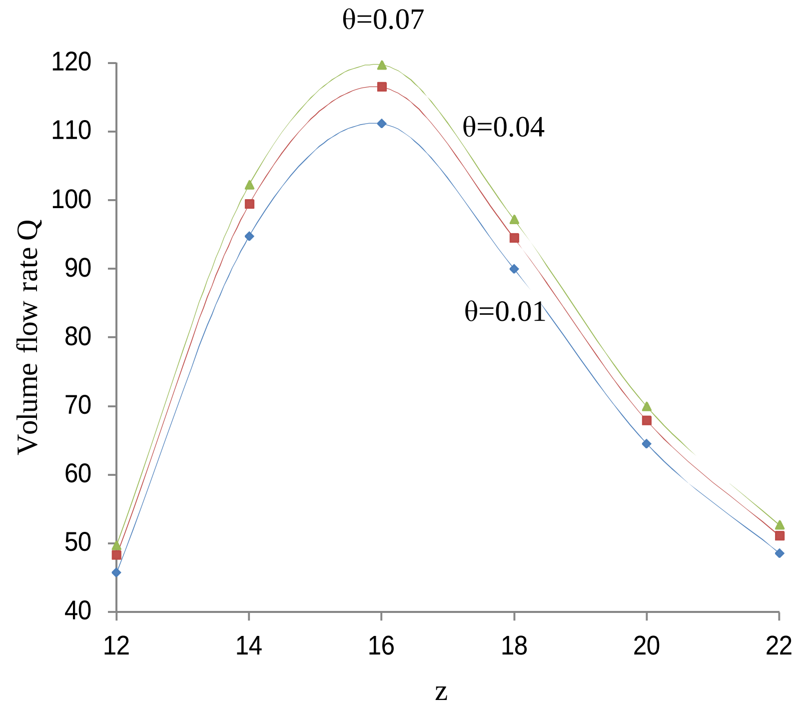

Fig. 11 Variation of volumetric flow rate with z for different values of θ

is shown in the fig. that the volumetric flow rate first increases for some values of z and then decreases. It is also found that the volumetric flow rate increases with the increasing values of yield stress.

III. CONCLUSION

In the above discussion, velocity in the three different regions is calculated treating blood as non-Newtonian fluid. It is also found that the plug flow velocity and velocity distribution of the two-fluid non- Newtonian model are considerably higher than those of the two fluid Newtonian fluid models. In this study it is obtained that the blood velocity decreases with the radial distribution for any regions. Wall shear stress and resistance to flow is important characteristics of blood flow calculated in the present study. It is also observed that the wall shear stress and the resistance to flow are significantly very low for the two-fluid non- Newtonian model than those of the two-fluid Newtonian fluid model. Comparison of the all these characteristic would be more useful for the further study. Hence from all the above discussions we can conclude that a three layer fluid model will affect the flow characteristics and can be utilized for medical and engineering applications.

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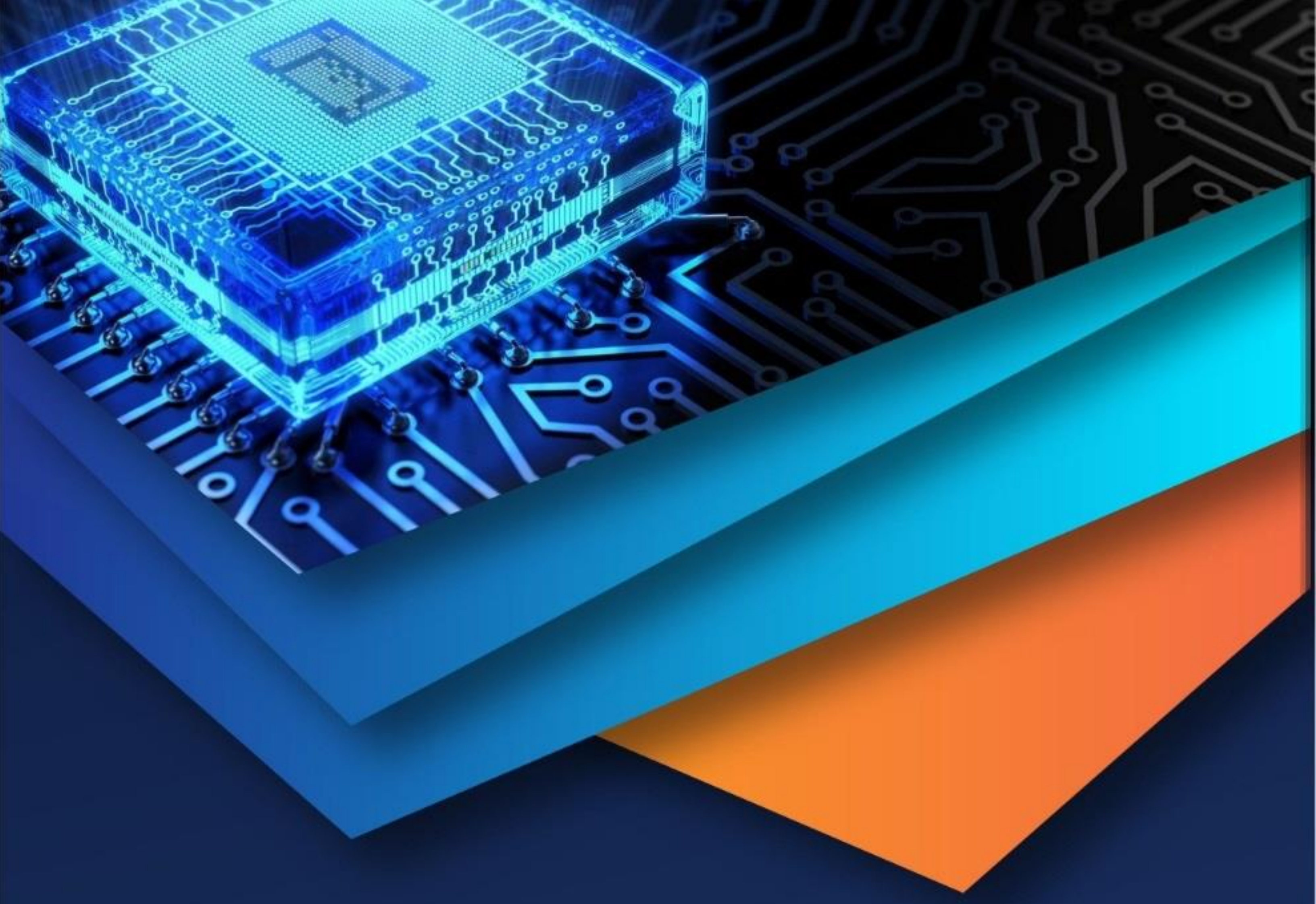

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