International Journal of Engineering, Science and Mathematics
Vol. 9, Issue 7, July2020,
ISSN: 2320-0294 Impact Factor: 6.765
Journal Homepage: http://www.ijesm.co.in, Email: ijesmj@gmail.com Double-Blind Peer Reviewed Refereed Open Access International Journal - Included in the International Serial Directories Indexed & Listed at: Ulrich's Periodicals Directory ©, U.S.A., Open J-Gage as well as in Cabell's Directories of Publishing Opportunities, U.S.A

Mathematical Analysis of Peristaltic Transport with a Reference To Casson Fluid

Ashwini M Rao*
Sathisha A B**
K S Basavarajappa***

Abstract

The present study deals withPeristaltic transport of biofluid to compare the variations of velocity profiles using Casson fluid. The mathematical model is proposed to analyze the function of flux transported in the presence of yield stress. The axisymmetric flow is considered for contraction and expansion of peristaltic wave. The pressure rise and the velocity change are with a reference to rise in the shear when the fluid is subjected for peristaltic wave formations in the gastrointestinal tract.

Keywords:

Peristaltic;
Yield stress;
wave;
flow;
flux;
casson fluid.

Author correspondence:

Dr. Ashwini M Rao,
Assistant Professor, Department of Mathematics,
Bapuji Institute of Engineering and Technology,
Davanagere, Karnataka, India – 577004

1.INTRODUCTION

Peristalsis is the process of contraction and elongation. Peristaltic flow is a muscle controlled flow which is generated in the fluid contained in a distensible tube when a progressive wave travels along the wall of the tube. The elasticity property of the wall affects the flow through progressive wave travelling along its length. The waves can be short, local reflexes or long continuous contractions that travel the whole length of the organ, depending upon their location and what initiates their action. Peristaltic mechanisms may be involved in movement of chyme in the gastrointestinal tract, transport of urine from kidney to the bladder through the ureter, the transport of spermatozoa in the ducts efferentes of the male reproductive tract and in the cervical canal, the movement of ova in the fallopian tubes, the transport of lymph in the lymphatic vessels and in the vasomotion in small blood vessels and milk extracted from the woman's breast.

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*Assistant professor, Department of Mathematics, Bapuji Institute of Engineering and Technology, Davanagere, Karnataka, India.
**Assistant professor, Department of PG Studies in Mathematics, Government Science College, Chitradurga, Karnataka, India.
***Professor, Department of Mathematics, Bapuji Institute of Engineering and Technology, Davanagere, Karnataka, India.

Waves emerged due to peristaltic action are the progressive waves which describe the contraction and expansion. Contractions in the form of series in the tube wall enable the fluid to transport in the direction of the wave. The resulting wave is sinusoidal due to the longitudinal and transverse movements produced by muscular fibres. The case of human arterial system, aortas, carotid artery, capillaries, arterial vessels of all sizes are constituted by connective tissues followed by smooth muscular fibres which are contractile in nature. Casson fluid is considered in the present model for two layered flow analysis. Findings include the computation of Positive average flux, limitation of flux, friction force at the wall. They describe the range of amplitude ratio to enhance the positive pumping.

Over the past few years, analytical and experimental studies have been carried out to analyze the flow parameters under the peristaltic transport. Burns et. al. [1] studied the peristaltic motion through pipe and channel flow under the assumptions of small Reynolds number. Fung et. al. [2] analyzed the flow of urine associated with peristaltic action in a two-dimensional channel. Shapiro et. al. [3] described the peristaltic pumping using long wave length at low Reynolds number for dissipation and mechanical efficiency in relevance to ureter function. Michleet. al. [4] investigated inertial and stream line curvature effects on peristaltic pumping. Srivastava et. al. [6] investigated the peristaltic transport of blood using Casson model under zero Reynolds number and long wave length approximation. Liepsch [7] discussed a detailed discussion on blood circulatory system by which the human heart operates as a double working pump for the flow of blood similar to a piston in the tube network. He also described about the contraction and expansion waves produced by the pumping action using Newtonian and non-Newtonian nature of blood. Usha et. al. [8] investigated the effects of curvature and inertial on the peristaltic transport in two fluid system.Basavarajappaet. al. [9] discussed the peristaltic transport of two-layered viscous incompressible fluid to approximate the stream functions and the interface. S. Nadeem, Noreen Sher Akbar [10] discussed the trapping phenomena for Herschel- Bulkley fluid and also for Newtonian, Bingham and power law fluid. AbdelhalimEbaid et.al. [11] explained the influence of viscosity variation on peristaltic flow in an asymmetric channel in view of new exact solutions. These solutions are used to study the effects of viscosity parameter, Daray's number, porosity, amplitude ratio, Jeffrey fluid parameter and amplitudes of the waves on the pressure rise and the axial velocity. B J Gireeshaet.al. [12] investigated non linear radiative Casson – Carreau liquid models considering the aspects of homogeneous and heterogeneous reactions and have shown that the liquid velocities in case of Casson fluid is higher than the carreau fluid with varying magnetic parameter.A Tanveer et al [17] investigated the effects of slip condition and joule heating on peristaltic flow of Bingham nano fluid and presented the formulation under the assumption of long wavelength and small Reynolds number.

In view of the investigation done by many researchers, our study is an attempt to understand the fluid mechanics in physiological situation with the presence of Casson fluid in the tube with lubrication approach for two layered model for the behavior of flux and friction force due to change in amplitude ratios under difference pressure rise across the wavelength. Flow characteristics such as streamline, interface, limiting flux are determined and compared with observed values. Influencing with the incomplete study of the peristaltic transport in glandular ducts as gastrointestinal fluid mechanics, we consider that Casson fluid in the core layer of the tube contains 90% of the Newtonian fluid in the case of immiscible phenomenon.

2. FORMULATION

For peristaltic transport of bio-fluid we consider the geometry of the tube wall assumed to be in cylindrical polar coordinates (r, θ, z)as,

$$H(z) = a + b\sin\left(\frac{2\pi z}{\lambda}\right) \qquad (1)$$

$$H(z) = 1 + \epsilon\sin\left(\frac{2\pi z}{\lambda}\right) \qquad (2)$$

Where$\epsilon = \frac{b}{a}$ is the amplitude ratio.

Using long wave length approximation, neglecting wall slope and inertia forces for steady flow under lubrication theory, the equations of motion

$$\frac{\partial p'}{\partial z'} = \frac{1}{r'}\frac{\partial}{\partial r'}\left\{r' m_r \frac{\partial u'}{\partial r'}\left|\frac{\partial u'}{\partial r'}\right|^{n_i - 1}\right\} \qquad (3)$$

$$\frac{\partial p'}{\partial z'} = 0$$

For a Casson fluid $$\tau^{1/2} = \begin{cases} \mu^{1/2}\ e^{1/2} + \tau_0{}^{1/2}, & \tau \geq \tau_0 \\ e = 0 & , \tau < \tau_0 \end{cases} \qquad (4)$$

Where τ is the shear rate, μ −viscosity
Defining the yield stress as,

$$\tau_0{}^{1/2} = \frac{A(H - H_m)}{100}$$

Where $H - H_m - \frac{\partial u}{\partial r} = \left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H-H_m)}{100}\right]^2$

For the present model, we consider the yield stress $\tau_0 = 0$ for which $\tau \geq \tau_0$

Let $\dot{\gamma} = \frac{\partial u}{\partial r}$ i.e reduced shear rate $\dot{\gamma}$ is remodeled as $\frac{\dot{\gamma} - \dot{\gamma}_{Poiseulle}}{\dot{\gamma}_{max} - \dot{\gamma}_{Poiseulle}}$

For a peristaltic transport the value of $e = \dot{\gamma}$ lies between 0 and 1 lakh sec^{-1}.

Non-dimensional quantities are,

$$r = \frac{r'}{a}, z = \frac{z'}{\lambda}, h_1 = \frac{H_1}{a}, u = \frac{u'}{a}, m_r = \frac{\mu_2}{\mu_1}, p = \frac{p' a^{n_i+1}}{m_1 \lambda c^{n_i}} \quad (5)$$

Then equation (3) becomes

$$\frac{\partial p}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left\{ r\, m_r \left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H - H_m)}{100}\right]^2 \left|\left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H - H_m)}{100}\right]^2\right|^{n_i - 1}\right\}$$

$\frac{\partial p}{\partial z} = P$ (constant)

$$P = \frac{1}{r}\frac{\partial}{\partial r}\left\{ r\, m_r \left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H - H_m)}{100}\right]^2 \left|\left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H - H_m)}{100}\right]^2\right|^{n_i - 1}\right\}$$

2. ANALYSIS

The solution in terms of Casson fluid with remodeled $\dot{\gamma}$ as

$$\left\{ r\, m_r \left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H-H_m)}{100}\right]^2 \left[\left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H-H_m)}{100}\right]^2\right]^{n_i-1}\right\} = \frac{pr^2}{2} + A \quad (6)$$

where A is the constant of integration,

$$\left\{ \left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H-H_m)}{100}\right]^2 \left[\left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H-H_m)}{100}\right]^2\right]^{n_i-1}\right\} = \frac{pr}{2m_r} + \frac{A}{rm_r} \quad (7)$$

$\left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H-H_m)}{100}\right]^2 = 0$ at $r = 0$, (at the axis)

$u = -1$ at $r = h$, (at the wall)

Equation (7) becomes

$$\left\{ \left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H - H_m)}{100}\right]^2 \left[\left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H - H_m)}{100}\right]^2\right]^{n_i-1}\right\} = \frac{pr}{2m_r}$$

At the fluid interface, the conditions are the continuity of the velocity and the stress across it. Then,

$$\left|\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H-H_m)}{100}\right|^2 = \left|\frac{pr}{2m_r}\right|^{\frac{1}{n_i}} \quad (8)$$

Let v^cbe the velocity for core layer and v^P the velocity for peripheral layer, the frictional interactions between the core and peripheral layer are negligible. Then denoting the velocity u byv^f, where$v^f = v^c - v^P$, the flow can be modeled as a continuous binary mixture of two layers (chyme and core) where each point in the flow is occupied simultaneously by bothv^c and v^P. The flow medium is assumed that no body forces are acting, both the flows are incompressible. Then each phase in the two layered model is given by$\rho^\beta = \rho T^\beta \varphi^\beta$

WhereρT^β are the intrinsic density and φ^β the volume fraction of componentβ.

For the binary system we consider,

$\varphi^c + \varphi^P = 1$.

The conservation of mass for individual phase can be taken to be as,

$$\frac{\partial \varphi^c}{\partial t} + \nabla.\left(\varphi^\beta v^\beta\right) = 0$$

Where the velocity$v^c = \frac{\partial u}{\partial t}$

The overall continuity equation is obtained by the addition of equations for both phase as,

$\nabla.(\varphi^c v^c + \varphi^P v^P) = 0$ (9)

or

$\nabla.v^f = 0$ (10)

we define $v^f = (\varphi^c v^c + \varphi^P v^P)$ as a macroscopic fluid vector. For each phase the momentum equation can be modeled as,

$\rho^\beta \left(\frac{\partial v^\beta}{\partial t} + (v^\beta.\nabla)v^\beta\right) = \nabla.T^\beta + \rho^\beta b^\beta + \pi^\beta$ (11)

Where T^β - stress tensor for the β phase, b^β - resultant external body force (neglected here) and π^β - drag force between the constituents that represents inertial forces due to frictional interaction between the two layers.

For small velocities and deformation rates, the inertia terms can be assumed to be negligible. With this, equation (11) becomes,

$\nabla.T^\beta = -\pi^\beta$ (12)

Newton's third law implies $\pi^c = -\pi^P$. Then the stress tensor can be modeled as

$T^\beta = -\varphi^\beta PI + \sigma^\beta$ (13)

$-\pi^c = \pi^P = K(v^c - v^P) - P\nabla\varphi$ (14)

Where σ^P - stress, 'K' - drag coefficient of relative motion; 'P' - pressure and 'I' - identity tensor. Stress tensors are split by these stress equations into contributions due to hydrostatic pressure and those due to viscous stress. The linear drag between the constituents is represented by the interaction term. The viscous fluid stress σ^c is assumed negligible with respect to the fluid interaction terms.

The stress of viscous fluid is negligible when compared with frictional interaction between the core and peripheral layers, here $\sigma^c = 0$ and $\sigma^P = \sigma$.

Substituting the interaction terms of equation (14) in to the equation (12) and using

$\sigma^P = 1 - \varphi^c$ leads to $\nabla.\sigma = \frac{k}{\varphi^f}(v^c - v^P)$

$\nabla.\sigma = \frac{k}{\varphi^f} v^f$ (15)

where $u = (v^c - v^p) = v^f =$ velocity

where $w_i = (v^c - v^p) = v^f =$ velocity

Using equation (15) in equation (8)

$$\left|\left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H-H_m)}{100}\right]^2\right| = \left|\frac{\partial v^f}{\partial r}\right| = \left|\frac{\partial}{\partial r}\left\{\frac{\varphi^f}{k}(\nabla\cdot\sigma)\right\}\right| = \left|\frac{\partial}{\partial r}(C_1 v^f)\right|$$

Where $\nabla.\sigma = \frac{k}{\varphi^f}(v^c - v^P)$

$$\left|\left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H-H_m)}{100}\right]^2\right| = \frac{pr}{2m_r}$$

Comparing this with $\left|\left[\left(\frac{\tau}{\mu}\right)^{1/2} - \frac{A(H-H_m)}{100}\right]^2\right| = \frac{\partial}{\partial r}(C_1 v^f)$

$\frac{pr}{2m_r} = \frac{C_1 pr^m}{2m_r} = C_2 r^m$ (16)

Using equation (16), into (8) we obtain

$$\frac{\partial v^f}{\partial r} = C_2^{k_i} r^{mk_i}$$

Integrating, we get,

$B = -1 - C_2^{k_2}\frac{h^{mk_2+1}}{mk_2+1}$ (17)

Put i = 2 when $v_2^f = -1$, at $r = h$, we get,

Equation (17) becomes,

$v^f = -1 - |C_2|^{k_2}\frac{h^{mk_2+1}}{mk_2+1} + |C_2|^{k_i}\frac{r^{mk_i+1}}{mk_i+1}$ (18)

As in the case of the peristaltic transport of Herschel-Bulkley fluid in circular tube in an axi-symmetric flow, we have the radius of tube under consideration as $0 \le r \le h$ and $h_1 \le r \le h$

$$v^f = [C_2 r^{m-1}]^{\frac{1}{n_i}}\left\{\frac{(R - R_p)^{k_i+1} - (r - r_p)^{k_i+1}}{k_i + 1}\right\}$$

For core layer $r - h_1$ and for mucus layer $h_1 - h$

$v_i{}^f = -1 + |C_2|^{k_i}\left[\frac{r^{mk_i+1} - h_1{}^{mk_i+1}}{mk_i+1}\right] - |C_2|^{k_2}\left[\frac{h_1{}^{mk_2+1} - h^{mk_2+1}}{mk_2+1}\right]$ (19)

For i = 1, the velocity for core layer is given by

$$v_1^{f} = -1 + |C_2|^{k_1}\left[\frac{r^{mk_1+1} - h_1^{mk_1+1}}{mk_1+1}\right] - |C_2|^{k_2}\left[\frac{h_1^{mk_2+1} - h^{mk_2+1}}{mk_2+1}\right] \quad (20)$$

For i = 2, the velocity for peripheral layer is given by

$$v_2^{f} = -1 + |C_2|^{k_2}\left[\frac{r^{mk_2+1} - h^{mk_2+1}}{mk_2+1}\right] \quad (21)$$

The instantaneous volume flow rate for two layers is given by,

$q = q_1 + q_2$

The flow rate $q_1: 0 \le r \le h_1$ [For chyme layer]

$$q_1 = 2\int_0^{h_1} r v_1^f dr$$

$$q_1 = -h_1^{2} + \frac{|C_2|^{k_1} h_1^{mk_1+3}(mk_1-1)}{(mk_1+1)^2(mk_1+3)} + |C_2|^{k_2}\left[\frac{-h_1^{mk_2+3} + h^{mk_2+1} h_1^{2}}{mk_2+1}\right] \quad (22)$$

The flow rate $q_2: h_1 \le r \le h$ [For mucus layer]

$q_2 = 2\int_{h_1}^{h} r v_2^f dr$

$$q_2 = -h^2 + h_1^{2} + |C_2|^{k_2}\left\{\frac{2\left(h^{mk_2+3} - h_1^{mk_2+3}\right)}{(mk_2+1)(mk_2+3)} - \frac{h^2 h_1^{mk_2+1} - h_1^{mk_2+3}}{(mk_2+1)}\right\} \quad (23)$$

Under the lubrication approach, across any cross section, flow rate 'q' is independent of 'z'. Then the instantaneous volume flow rate in terms of two layers is given by,

$$q = q_1 + q_2$$

$$q = -h_1^{2} + \frac{|C_2|^{k_1} h_1^{mk_1+3}(mk_1-1)}{(mk_1+1)^2(mk_1+3)} + $$

$$+ |C_2|^{k_2}\left[\frac{-h^2 h_1^{mk_2+1} + h^{mk_2+1} h_1^{2}}{mk_2+1}\right] + |C_2|^{k_2}\left\{\frac{2\left(h^{mk_2+3} - h_1^{mk_2+3}\right)}{(mk_2+1)(mk_2+3)}\right\} \quad (24)$$

Dimensionless time average flux in terms of flow rate is obtained as,

$$Q = q + 1 + \frac{\epsilon^2}{2}$$

Where ϵ- the amplitude ratio

The prescription of these values Q serves as boundary conditions at the ends of the tube.

$$\bar{Q} = -|C_2|^{k_1}\left[\frac{h_1^{mk_1+3}}{mk_2+3}\right] - |C_2|^{k_2}\left\{\frac{\left(h^{mk_2+3} - h_1^{mk_2+3}\right)}{(mk_2+1)}\right\} \quad (25)$$

The conservation of mass across the interface at the every axial station is modeled for computing two stream functions ψ_1 and ψ_2 respectively for core layer [0, h_1] and for mucus layer [h_1, h], as the solutions can be obtained using,

$\psi_1 = 0$ at $r = h$, $\psi_2 = q$ at $r = h$

The stream functions ψ_1 and ψ_2 in terms of velocities are given by,

$$\psi_1 = \frac{r^2}{2}\left\{1 - |C_2|^{k_1}\left[\frac{2r^{mk_1+1} - (mk_1+3)h_1^{mk_1+1}}{(mk_1+1)(mk_1+3)}\right] + |C_2|^{k_2}\left[\frac{h_1^{mk_2+1} - h^{mk_2+1}}{(mk_2+1)}\right]\right\} \quad (26)$$

$$\psi_2 = \left(\frac{r^2 + 2q - h^2}{2}\right) - |C_2|^{k_2}\left[\frac{2r^{mk_2+3} - (mk_2+3)h^{mk_2+1} r^2 - 2h^{mk_2+3} + (mk_2+3)h^{mk_2+3}}{2(mk_2+1)(mk_2+3)}\right] \quad (27)$$

The equation for interface in terms of stream function for a single layer fluid model (m = 1)

Equation of the interface is obtained for a particular case at $h_1 = \alpha$ and $\frac{1}{n_1} = \frac{1}{n}$ with the condition that the flow rate in core layer is twice the stream function (r = h_1) substituting equation (20) in q_1 and further $Q_1 = q_1 + h^2$ gives

$$Q_1 = 2\left\{\frac{\alpha^5 - \alpha^3(h^2 + 7\bar{Q}) - \alpha(h^4 + h^2) - 16\bar{Q}\alpha^2}{-13\alpha^4 - 3\alpha^2 h^2 - 23\alpha^2}\right\} \quad (28)$$

For a given flow rate, equation (28) is reduced to 5th degree polynomial in 'α'. Newton-Raphson method is employed with ten iterations in each step to obtain the set of values for α. Series of values of α represent interface.

The expressions for pressure difference (Δp) studied between the extreme locations of each wavelength as,

$$\Delta p = \frac{-8q[2 + 3\epsilon^2]}{[1-\epsilon^2]^{7/2}} - \frac{8}{[1-\epsilon^2]^{3/2}} \quad (29)$$

Friction force at the wall is given by,

$$F = \frac{8q}{[1-\epsilon^2]^{3/8}} + 8 \quad (30)$$

From finite range of flux $\overline{Q}_L$ the limitation of the flux $\overline{Q}_L$ is calculated as

$$\overline{Q}_L = \frac{\epsilon^2}{2} + \left[\frac{\alpha^{k+3} - (k+1) + 2(k+3)\alpha^{k+2} - (k+3)\alpha^{k+2} - (k+3)\alpha^{k+3}}{4\alpha^{k+1} - 2(k+3)\alpha^k + (k+3)\alpha^{k+1} - (\alpha+3)}\right] \tag{31}$$

The ratio of average pressure rise and the time averaged flux is determined as R_{f}.,

$$R_f = \left[\frac{-8q[2+3\epsilon^2]}{[1-\epsilon^2]^{7/2}\left(q+1+\frac{\epsilon^2}{2}\right)} - \frac{8}{[1-\epsilon^2]^{3/2}\left(q+1+\frac{\epsilon^2}{2}\right)}\right] \tag{32}$$

3. RESULT AND DISCUSSION

Use of Casson fluid with remodeled $\dot{\gamma}$ gives the shear rise behavior of flux, due to which there is a decrease in pressure difference. Flow consistency changes when the amplitude b exceeds the range of ε. Therefore the flow is motivated in the specified range of amplitude ratio. The bolus of the fluid forms around the axis above and below the axis as small fluid blocks separated from streamline location. Bolus so formed at this point constitutes the trapping zone for sinusoidal wall profile. Numbers of trials have been observed, the stagnation points are located at this trapping zone. Beyond the trapping range $\varepsilon = 0$ to 0.05, dilation occurs. This checks the axial velocity expected to be zero or very minimum near the axis. But on the axis, velocity is zero. Also upto certain height, where the trapped bolus occurs, there is no split of the streamline, but after the bolus ends; Reflux (backflow) starts from the trapped bolus moves to some distance in the negative axial direction, but due to the successive pumping, the net-trapped bolus moves towards the positive axial direction. Model proposed confirms that there is no back flow (figure (1)) indicates the occurrence of positive pumping with shear thickening and shear thinning nature of the fluid. Streamline movements corresponding to particle lines can be visualized from the experimental work compared with experimental values. We can visualize the split in the streamline so that the flow dilates in that region.

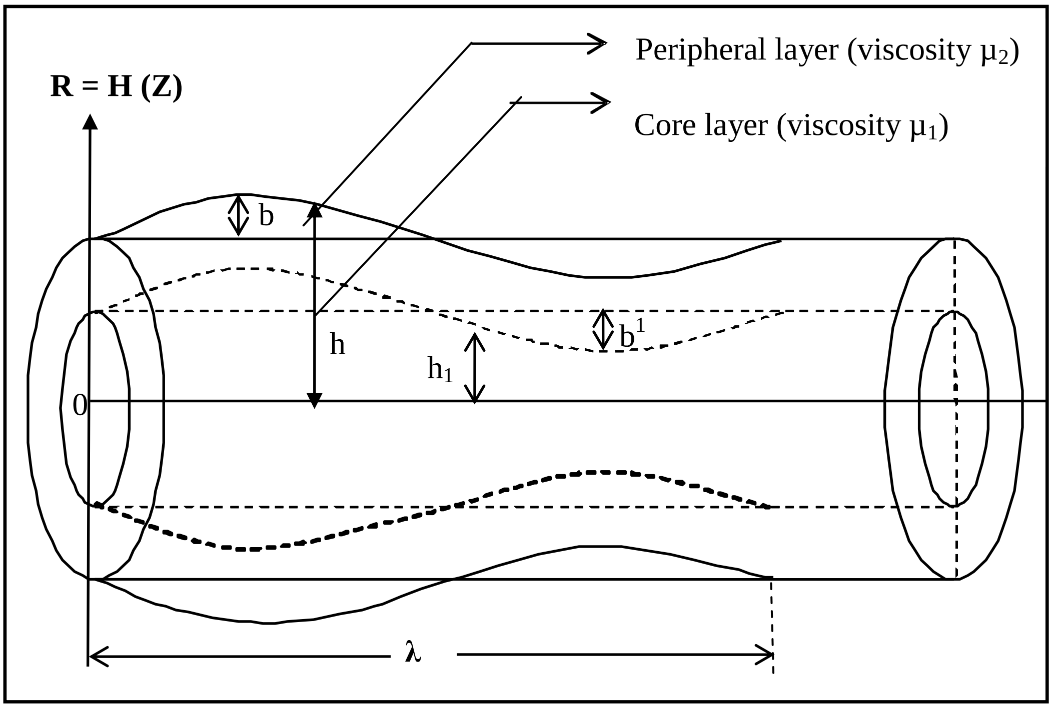

Figure 1: Geometry of two layered Peristaltic Transport

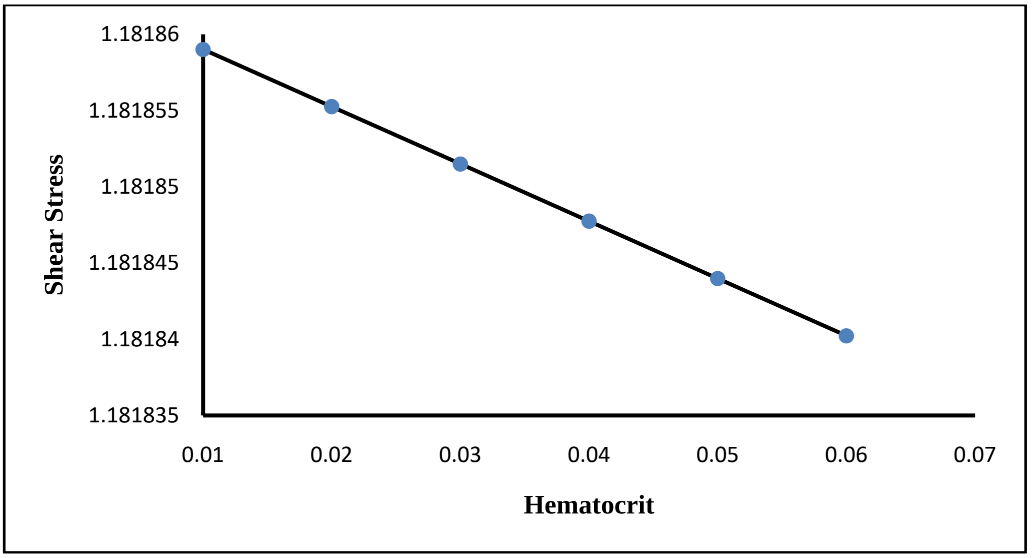

Figure 2: Shear Stress v/s Hematocrit

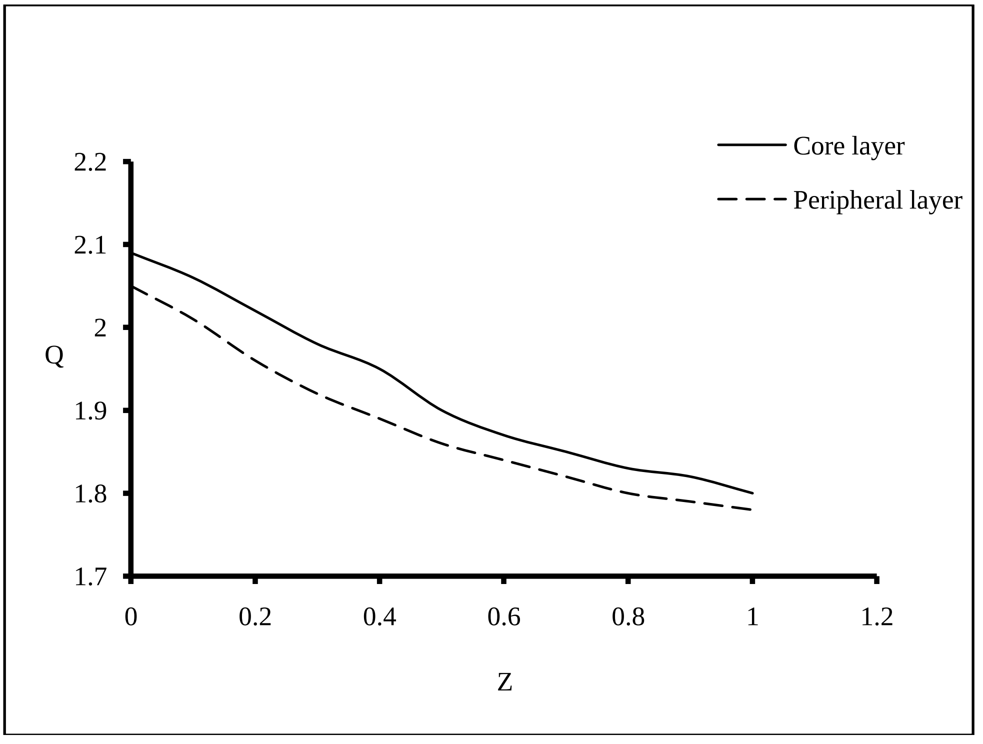

Figure 3:Variation of limitation of flux (Q) with Z

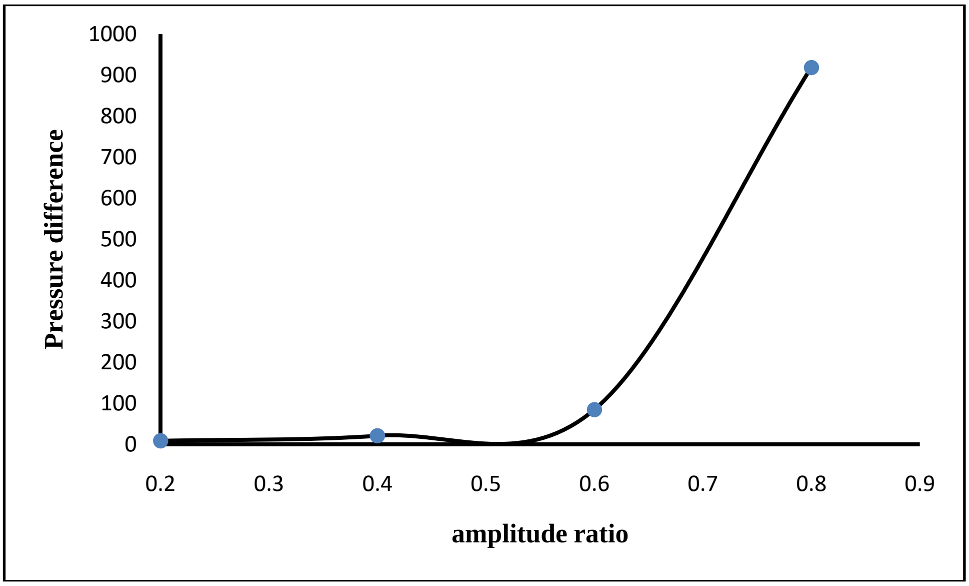

Figure 4: Pressure difference v/s amplitude ratio

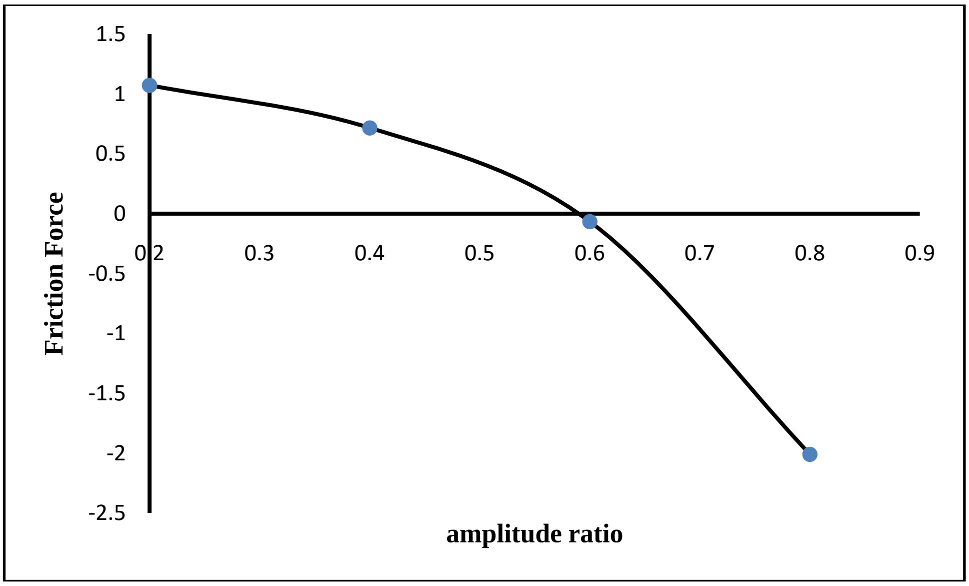

Figure 5: Friction Force v/s amplitude ratio

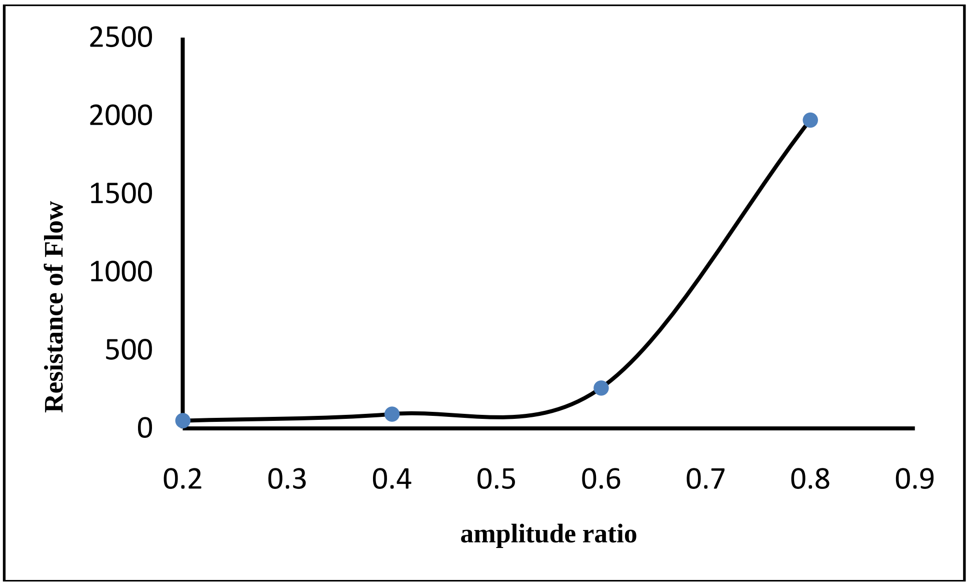

Figure 6: Resistance of Flow v/s amplitude ratio

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