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Peristaltic pumping of a power – Law fluid in contact with a Jeffrey fluid in an inclined channel with permeable walls

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KEYWORDS

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Abstract The paper investigates peristaltic flow of a Power-law fluid in contact with a Jeffrey fluid in an inclined channel with permeable walls under long wavelength and low Reynolds number approximations. Power-law fluid is considered in the core region and Jeffrey fluid in the peripheral region. Expressions for the shape of interface between the two fluids and the pressure rise are obtained. It is observed that an increase in permeability parameter increases the thickness of the core layer in the channel. It is also observed that pressure rise increases with decrease in the Jeffrey parameter.

1. Introduction

Peristaltic transport is one of the major mechanisms by which viscous fluids are transported, generally from a low pressure region to a high pressure region. The required force to pump the fluids against the pressure gradient is derived in many methods in engineering and biological systems. In biological systems, a progressive wave of contraction and expansion of the muscles pumps the biological fluids. This mechanism occurs in swallowing of food through oesophagus, movement of chyme through intestine, colonic transport in large intestine, passage of urine from kidney to urinary bladder through urethra, spermatic flows in the male reproductive systems, flow of blood through blood vessels, etc. In engineering applications, the principles of peristalsis are used in the design of roller pumps.

Some of the well-known biofluids are intestinal fluid, lymph, cerebrospinal fluids, saliva, mother's milk, sweat, gastric juices, etc. None of the Newtonian fluid models explain the characteristics of these fluids in detail. Therefore they are modelled as non-Newtonian fluids. Some of the non-Newtonian fluid models which are accepted by researchers for the study of these fluids are Jeffrey fluid, Casson fluid, Herschel–Bulkley fluid, Bingham fluid, Power-law fluid, etc.

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Nomenclature

a	half-width of the channel	ψ	steam function
b	amplitude of peristaltic wave	α	permeability parameter
λ	wave length of the peristaltic wave	β	inclination parameter
c	wave speed	m	the slip parameter
u, v	velocity components in laboratory frame	m_1	consistency parameter
p	pressure	k	permeability
ϕ	amplitude ratio	$\overline{Q}$	average non-dimensional volume flow rate
μ	viscosity	q	total flux
τ_{yx}	shear stress	q_1	core flux
λ_1	Jeffrey parameter	η	gravitational parameter
n	the dimensionless Power-law index (fluid behaviour index)		

The Jeffrey model is the simplest and is accepted as a model for blood in many investigations. Shapiro et al. [1] have used the long wavelength approximation and low Reynolds number to study the peristaltic pumping. Jaffrin and Shapiro [2] laid the foundation of analysis of peristaltic pumping in 1971, from where onwards it became a focal point for many investigators. The transportation of many other physiological fluids of anatomy is preferably modelled as Jeffrey fluids in the literature [3,4].

Bugliarello and Sevilla [5] and Cokelet [6] have shown experimentally that for the blood flowing through narrow blood vessels, there exists a peripheral layer of plasma and a core region of suspension of all the erythrocytes of blood. Thus it is established that the realistic description of blood flow may be approximated through two fluid model with the suspension of all the erythrocytes in the core region as a non-Newtonian fluid and the plasma in the peripheral region as a Newtonian fluid. Most of the ducts in living bodies contain thick mucus secretions at the inner surface of the walls. This layer of mucus, having a viscosity different to that of the biofluid flowing in the duct, serves as lubricant and assures smoother flow. The composition and the fluid properties may differ in different ducts of a living body. Therefore the study of peristaltic transport of two layered fluids with different viscosities has its own importance in understanding the physiological fluid transport in living things (see Fig. 1).

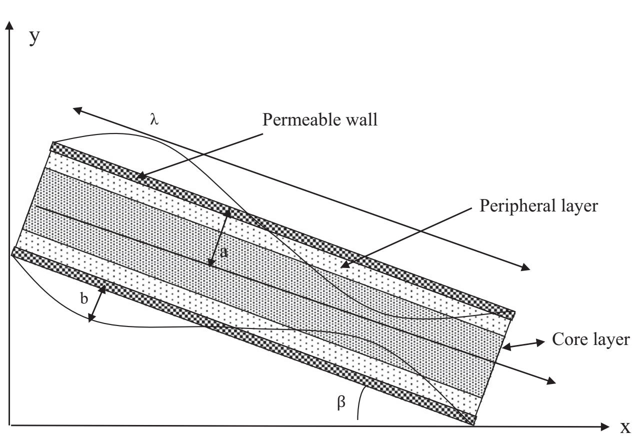

Figure 1 Physical model.

As two-fluid model fits very close to the mathematical model of blood with its rheology, a lot of research is being done on the peristaltic transport of two immiscible fluids. Shukla et al. [7] have investigated the effects of peripheral layer viscosity on the peristaltic transport of a biofluid. Brasseur et al. [8] have studied the influence of peripheral layer of different viscosity on peristaltic pumping with Newtonian fluid. Usha and Ramachandra Rao [9] have studied the peristaltic transport of two-layered – Power-law fluids. Ramachandra Rao and Usha [10] and Misra and Pandey [11,12] have studied the peristaltic transport of two or more fluids with different viscosities. Vajravelu et al. [13] studied the peristaltic transport of Casson fluid in contact with Newtonian fluid in a circular tube with permeable wall. Narahari and Sreenadh [14] investigated peristaltic transport of Bingham fluid in contact with Newtonian fluid. Vajravelu et al. [15,16] studied the influence of heat transfer on the peristaltic transport of Jeffrey fluid in a vertical porous stratum. Bohme and Muller [17] investigated the impact of nonlinear viscoelastic fluid properties on the peristaltic pumping characteristics of a non-Newtonian fluid in a tube. Akram el al. [18] studied the influence of heat and mass transfer on the peristaltic flow of a Bingham fluid in an inclined magnetic field and channel with different wave forms. Noreen Sher Akbar has discussed the effects of magnetic field on the CNT suspended copper nanoparticles in blood flow through stenosis with permeable walls [21]. Recently studies on generation of entropy in peristaltic flows are being reported. Noreen Sher Akbar has studied the impact of entropy generation on the peristaltic flow of an incompressible fluid through a uniform tube [22] and nanofluid with CNT suspension in Plumb ducts [23]. Akbar and Butt [24] has investigated the effects of heat transfer on the peristaltic flow of a fluid with nanoparticles in a curved channel. Akbar [25] has investigated the peristaltic flow of a Jeffrey six constant fluid in an endoscope. Akbar [26] also investigated the MHD peristaltic flow a nanofluid with convective surface boundary conditions.

Driven by this closer applicability to the biofluids, peristaltic transport of a Power-law fluid in contact with a Jeffrey fluid in an inclined channel with permeable walls is considered in this work. The core layer is Power-law fluid and the peripheral layer is a Jeffrey fluid. The investigation is carried out using long wavelength and low Reynolds number assumptions, as low Reynolds number is assigned to biological fluids, like urine [20].

2. Mathematical formulation of the problem

Consider a two-dimensional peristaltic motion of a Power-law fluid surrounded by a peripheral layer of a non-Newtonian Jeffrey fluid in an inclined channel with permeable walls under long wave length and low Reynolds number assumptions.

The wall deformation due to infinite waves is given by

$$h(X,t) = a + b\ \mathrm{Sin}\frac{2\pi}{\lambda}(X - ct) \quad (1)$$

where a = half-width of the channel, b = amplitude of peristaltic wave, λ = wavelength of the peristaltic wave and c = the wave speed.

Under the assumptions that length of the tube is an integral multiple of the wavelength, pressure difference across the wavelength is constant and the nature of the interface is periodic, the flow frame becomes steady in the wave frame (x, y) moving with velocity c away from frame (X, Y) called laboratory frame. The transformations between the two frames are given by

$$\begin{aligned} &x = X - ct, y = Y, u = U - c, v = V, \\ &p(x,y) = P(X,Y,t), \psi = \psi - Y, q = \bar{Q} - 1 = q_1 + q_2 \end{aligned} \quad (2)$$

where U, V are velocity components, P is pressure and ψ is stream function in the laboratory frame. We assume that Darcy's law holds in the porous medium. The Ostwald–De waele Power-law model is used to model Power-law fluid, which is given by

$$\tau_{yx} = m_1\left|\frac{\partial U}{\partial Y}\right|^{n-1}\frac{\partial U}{\partial Y} \quad (3)$$

$$\left.\begin{aligned} u_1 &= -1 + \tfrac{(P-\eta\sin\beta)^K}{(K+1)}\left[y^{(K+1)} - h_1^{(K+1)}\right] - \tfrac{(P-\eta\sin\beta)}{2\mu}(h^2 - h_1^2 + 2\alpha h), && 0 \leqslant y \leqslant h_1 \\ u_2 &= -1 + \tfrac{(P-\eta\sin\beta)(1+\lambda_1)}{2\mu}(y^2 - h^2 + 2\alpha h), && h_1 \leqslant y \leqslant h \end{aligned}\right\} \quad (8)$$

where τ_{yx} is the shear stress, m_1 is consistency parameter, $\frac{\partial U}{\partial Y}$ is rate of deformation and n is the fluid behaviour index.

Using the following non-dimensional quantities:

$$\overline{u_1} = \frac{u_1}{c}, \overline{u_2} = \frac{u_2}{c}, \bar{y} = \frac{y}{a}, \bar{h} = \frac{h}{a}, \bar{t} = \frac{ct}{\lambda}, \bar{P} = \frac{a^{n-1}}{\lambda m_1 c^n}P,$$

$$\alpha = \left(\frac{am}{\sqrt{k}}\right)^{-1}, \overline{\psi_1} = \frac{\psi_1}{ac},$$

$$\overline{\psi_2} = \frac{\psi_2}{ac}, \bar{q} = \frac{q}{ac}, \phi = \frac{b}{a}, \bar{x} = \frac{x}{\lambda}$$

$$\bar{\mu} = \left\{\begin{matrix} 1 & 0 \leqslant \bar{y} \leqslant \overline{h_1} \\ \frac{\mu}{m_1}\left(\frac{a}{c}\right)^{n-1} & \overline{h_1} \leqslant \bar{y} \leqslant \bar{h} \end{matrix}\right\} \quad (4)$$

where ϕ is the amplitude ratio, $\bar{P}$ is the dimensionless pressure, α is the permeability parameter, m is the slip parameter, k is the permeability, $\bar{\mu}$ is the dimensionless quantity that yields the ratio of the slip parameter μ and consistency parameter m_1.

The governing equations of motion under lubrication approach (dropping the bars), may be written as

$$\left.\begin{aligned} &\tfrac{\partial}{\partial y}\left(\left(\tfrac{\partial u_1}{\partial y}\right)^n\right) + \eta\sin\beta = \tfrac{\partial P}{\partial x}, && 0 \leqslant y \leqslant h_1 \\ &\tfrac{\partial}{\partial y}\left(\tfrac{\mu}{1+\lambda_1}\left(\tfrac{\partial u_2}{\partial y}\right)^n\right) + \eta\sin\beta = \tfrac{\partial P}{\partial x}, && h_1 \leqslant y \leqslant h \end{aligned}\right\} \quad (5)$$

The dimensionless boundary conditions are

$$\frac{\partial u_1}{\partial y} = 0 \text{ at } y = 0$$

$$u_2 = -1 - \alpha\frac{\partial u_2}{\partial y} \text{ at } y = h \quad (6)$$

where η is the gravitational parameter, and α is dimensionless permeability (including slip) parameter. Second boundary condition is following Saffman [19] which is an improved condition to Beavers and Joseph slip condition.

The average non-dimensional volume flow rate over period $T\left(=\frac{\lambda}{c}\right)$ of the peristaltic wave is defined as

$$\bar{Q} = q + \frac{1}{T}\int_0^T h\, dt = q + 1 \quad (7)$$

3. Solution of the problem

Solving Eq. (5) together with the boundary conditions (6), we get

where $P = \frac{dp}{dx}, K = \frac{1}{n}$.

The flow rate q is given by

$$\begin{aligned} &q = q_1 + q_2 \\ &q = \textstyle\int_0^{h_1} u_1\, dy + \int_{h_1}^{h_2} u_2 dy \\ &q = -h - \tfrac{(P-\eta\sin\beta)^K h_1^{K+2}}{(K+2)} - \tfrac{(P-\eta\sin\beta)(1+\lambda_1)}{3\mu}\left[h^3 - 3\alpha h h_1 - h_1^3\right] \end{aligned} \quad (9)$$

The relation between $\bar{Q}$ and ΔP can be obtained by eliminating q from Eqs. (7) and (9) followed by integration of P with respect to x over one wavelength. But this relation cannot be presented, as P is not known explicitly as function of h_1 and $\bar{Q}$.

The solutions of the stream functions can be obtained by using the conditions $\psi_1 = 0$ at $y = 0$ and $\psi_2 = q$ at $y = h$ in (8) as

$$\left.\begin{aligned} \psi_1 &= y\left[\begin{matrix} -1 + \tfrac{(P-\eta\sin\beta)^K}{(K+1)(K+2)}\left[y^{(K+1)} - (K+2)h_1^{(K+1)}\right] \\ -\tfrac{(P-\eta\sin\beta)(1+\lambda_1)}{2\mu}(h^2 - h_1^2 + 2\alpha h) \end{matrix}\right], && 0 \leqslant y \leqslant h_1 \\ \psi_2 &= q + h - y + \tfrac{(P-\eta\sin\beta)(1+\lambda_1)}{6\mu}\left[y^3 - 3h^2 y + 2h^3 - 6\alpha h(y - h)\right], && h_1 \leqslant y \leqslant h_2 \end{aligned}\right\} \quad (10)$$

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The stream function reduces to the case of two Newtonian fluids with permeable walls when $K = 1$ and $\lambda_1 = 1$.

The interface equation is obtained from the condition $\psi_1 = q_1$ or $\psi_2 = q_2$.

Substituting in Eq. (10), we get

$$Q_1 = -\frac{(P - \eta \sin\beta)^K h_1^{K+2}}{(K+2)} - \frac{(P - \eta \sin\beta)(1+\lambda_1)}{2\mu} h_1 \left(h^2 - h_1^2 + 2\alpha h\right) \tag{11}$$

$Q_1 = q_1 + h_1$.

To determine P in Eq. (11), we use the continuity of the stream function at the interface given by $\psi_1 = q$ at $y = h_1$. We get

$$Q_1 = Q + \frac{(P - \eta \sin\beta)(1+\lambda_1)}{6\mu}\left[h_1^3 - 3h^2 h_1 + 2h^3 - 6\alpha h(h_1 - h)\right] \tag{12}$$

or

$$P = \frac{6\mu(Q_1 - Q)}{(1+\lambda_1)\left[h_1^3 - 3h^2 h_1 + 2h^3 - 6\alpha h(h_1 - h)\right]} + \eta \sin\beta$$

Eliminating P from Eqs. (11) and (12), the nonlinear equation governing the interface is given by

$$(Q - Q_1)\left[\frac{6^K \mu^K |Q - Q_1|^{K-1}}{(1+\lambda_1)^k \left[h_1^3 - 3h^2 h_1 + 2h^3 - 6\alpha h(h_1 - h)\right]^K} + \frac{3(K+2)(h^2 - h_1^2 + 2\alpha h)}{h_1^{K+1}\left[h_1^3 - 3h^2 h_1 + 2h^3 - 6\alpha h(h_1 - h)\right]} + \frac{(K+2)}{h_1^{K+2}}\right] - \frac{(K+2)Q}{h_1^{K+2}} = 0 \tag{13}$$

Eq. (13) reduces to fourth-order algebraic equation derived by Brasseur et al. [8] for two Newtonian fluids when $k = 1$ and $\lambda_1 = 0$. The values of q_1 or Q_1 are determined by solving Eq. (13) iteratively under the conditions $h_1 = \beta$ at $x = 0$. Later the same equation is solved iteratively for h_1 at every axial station x. The pressure gradient P is determined using Eq. (12) and then integrated over one wavelength to obtain the pressure rise ΔP across one wavelength.

4. Results and discussions

The effect of permeability parameter, Jeffrey parameter λ_1 on the pumping characteristics is discussed for different values of parameters of interest. We note that the results of the present work reduce to the case of two immiscible Newtonian fluids for $k = 1$ and $\lambda_1 = 0$. The viscosity near the wall of the ducts has been found to be different from that in the central region for many biological systems such as oesophagus.

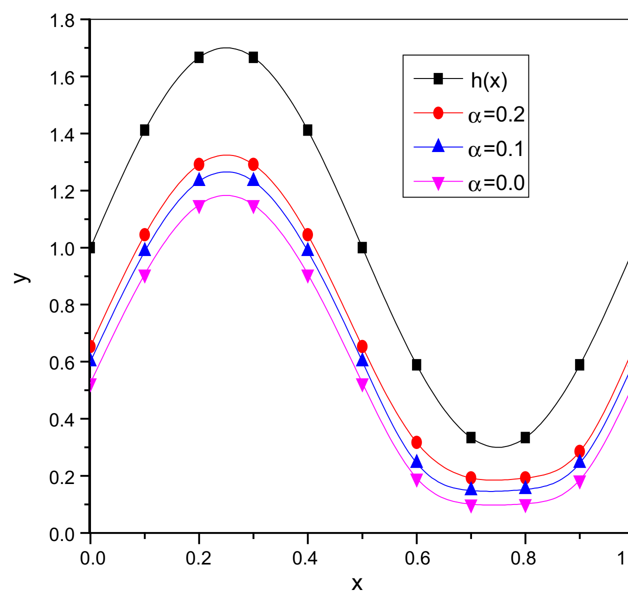

Figure 3 The variation of shape of interface with permeable parameter α.

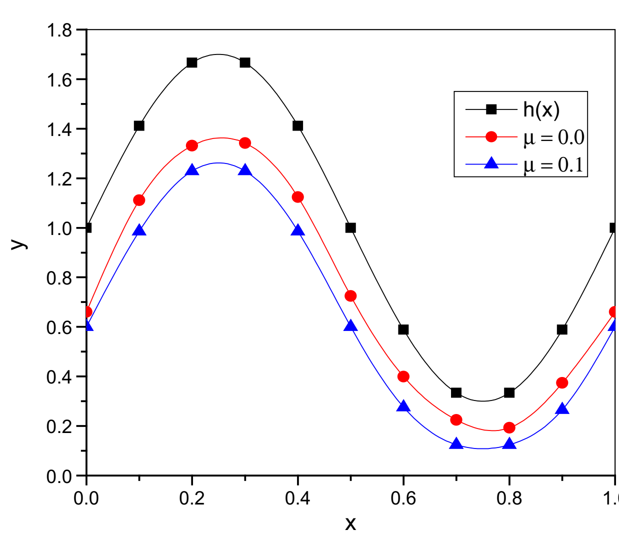

Figure 2 The variation of shape of interface with ratio of viscosities μ.

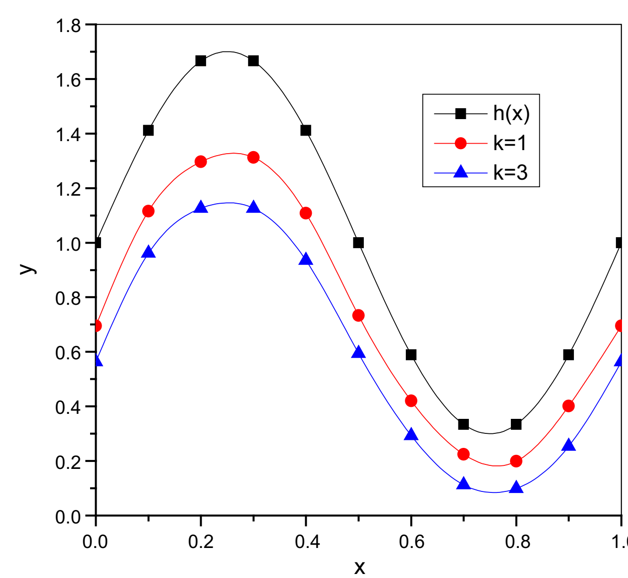

Figure 4 The variation of shape of interface with index k.

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4.1. Interface

The interface that is derived from (13) is a stream line in the wave frame. It is determined for varying parameters from its equation, using a numerical technique and is shown in Figs. 2–4. In Fig. 2, we observe that the shape of the interface is slightly affected when the viscosity ratio μ is changed. In Fig. 3 we notice that the increase in the permeability parameter α increases the thickness of the core layer in the channel. Increased wall permeability allows more of the peripheral fluid to leak out, which results in decreased thickness of the peripheral fluid, at the same time increasing the thickness of the core fluid. From Fig. 4, we infer that the increase in the index k gives rise to thinner core layer in the channel.

4.2. Pumping characteristics

The relationship between $\overline{Q}$ and ΔP is depicted in Fig. 5, for different values of amplitude ratio ϕ with the values of other parameters fixed as $\alpha = 0.1$, $\beta = 0.7$, $\mu = 0.1$, $\lambda_1 = 1$ and $k = 2$. It is seen that the pressure rise decreases linearly with the average flow. We observe that for a given ΔP, the flux $\overline{Q}$ increases with increasing amplitude ratio ϕ for $0 \leqslant Q \leqslant 0.08$. The behaviour is otherwise for $Q > 0.08$. It can be understood that for a given flux value, the pressure rise increases with an

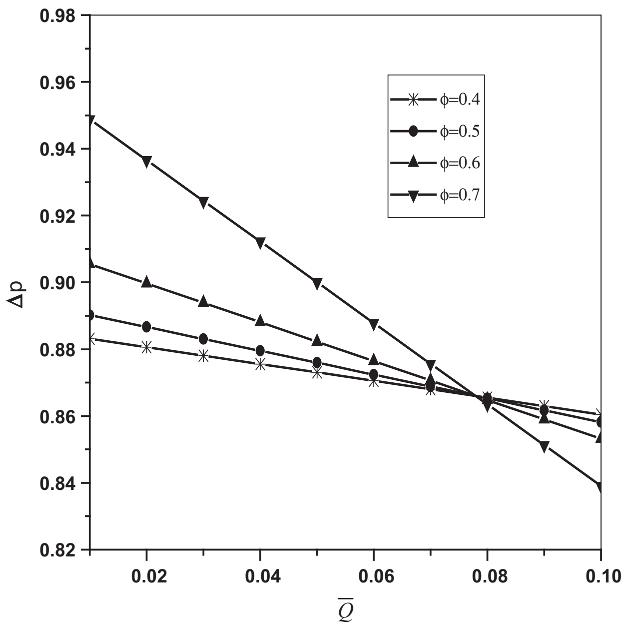

Figure 5 The variation of ΔP with $\bar{Q}$ for different values of amplitude parameter φ.

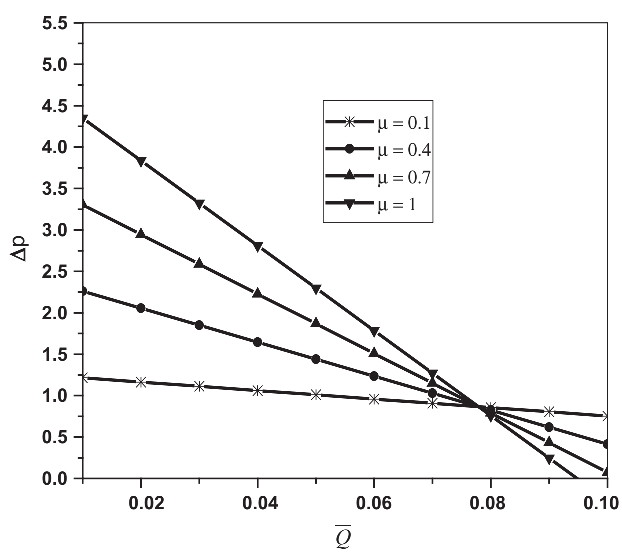

Figure 6 The variation of ΔP with $\overline{Q}$ for different values of ratio of viscosities μ.

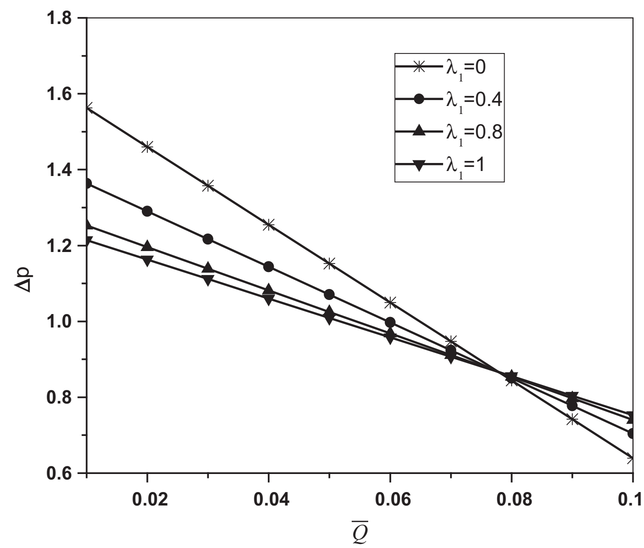

Figure 7 The variation of ΔP with $\overline{Q}$ for different values of Jeffrey parameter λ_1.

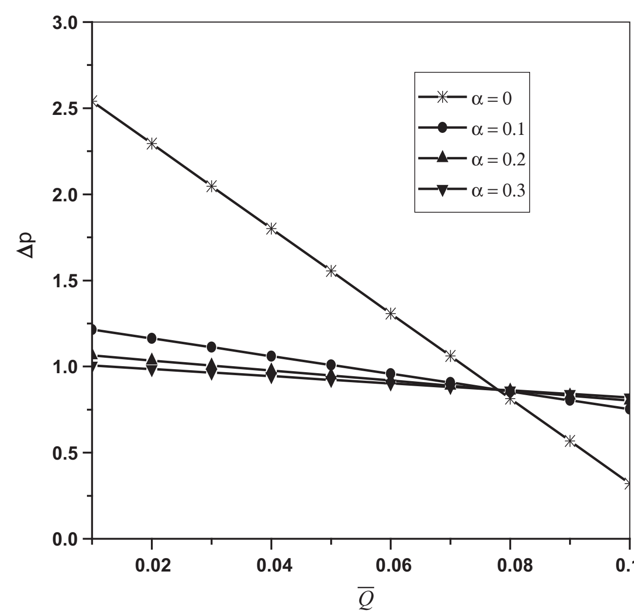

Figure 8 The variation of ΔP with $\overline{Q}$ for different values of permeable parameter α.

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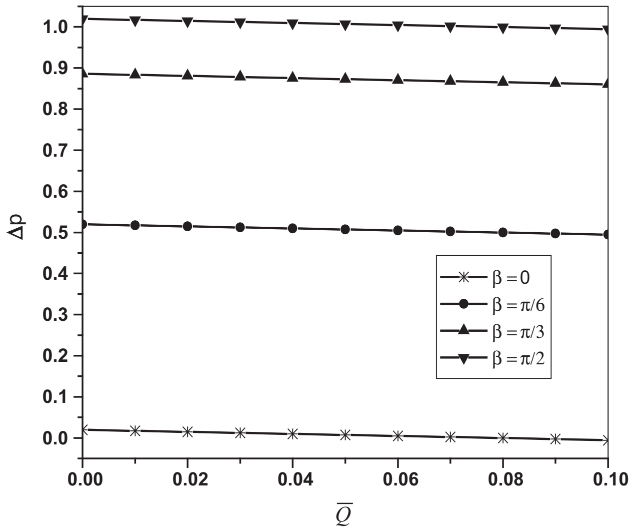

Figure 9 The variation of ΔP with $\overline{Q}$ for different values of inclination parameter β.

increase in the amplitude ratio for $0 \leqslant Q \leqslant 0.08$ and opposite behaviour is found for $Q > 0.08$. In Fig. 6, the relation between ΔP and $\overline{Q}$ is drawn for different values of viscosity ratio μ with other parameters fixed as $\alpha = 0.1$, $\beta = 0.7$, $\phi = 0.7$, $\lambda_1 = 1$ and $k = 2$. We observe that the larger the viscosity ratio, the greater is the pressure rise, against which the pump works. For a given ΔP, the flux $\overline{Q}$ depends on μ and is decreasing with the increasing μ. Fig. 7 shows the relation between $\overline{Q}$ and ΔP for different values of Jeffrey parameter λ_1. The other parameters are fixed as $\alpha = 0.1, \beta = 0.7, \phi = 0.7, \mu = 0.1$ and $k = 2$. We observe that for a given ΔP, the flux $\overline{Q}$ depends on λ_1 and it increases with the decreasing value of Jeffrey parameter λ_1.

Fig. 8 shows the relationship between $\overline{Q}$ and ΔP for different values of permeability parameter α, with other parameters fixed as $\mu = 0.1$, $\beta = 0.7$, $\phi = 0.7$, $\lambda_1 = 1$ and $k = 2$. We observe that for a given ΔP, the flux $\overline{Q}$ depends on α and increases with decreasing of permeability parameter α. Fig. 9 shows the relation between $\overline{Q}$ and ΔP for different values of inclination parameter β, for fixed $\alpha = 0.1$, $k = 0.2$, $\phi = 0.7$, $\mu = 0.1$ and $\lambda_1 = 1$. We observe the change in ΔP for the increasing flux $\overline{Q}$ is very small and so the pumping curves are approximately parallel lines. In fact the pressure rise is decreasing with increasing flux. It is also seen that for a given ΔP, the flux $\overline{Q}$ depends on β and it increases with the increasing value of inclination parameter β.

5. Conclusions

Driven by the closer applicability of two-fluid model to biofluids, the peristaltic transport of a Power-law fluid in contact with a Jeffrey fluid is investigated in an inclined channel. The problem is modelled with Power-law fluid in core region and Jeffrey fluid in peripheral layer. Expressions for the shape of interface and the pressure rise are evaluated. The effect of different parameters of interest on the interface and the pressure rise are presented graphically. The analysis shows that the permeability of the wall affects the interface and an increase in the permeability increases the thickness of the core layer. It is observed that the increase in the viscosity increases the pressures rise against which the pump works. Another interesting point observed is that for a given pressure rise, decreasing Jeffrey parameter increases the flux. The flux also found to increase with decreasing permeability parameter for a given pressure rise.

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