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Wall consequences for the peristaltic movement of non-Newtonian fluid in an inclined conduit

G. Durga Priyadarsini [a], G.C. Sankad [b,*]

[a] Department of Mathematics, Geethanjali College of Engineering and Technology, Cheeryal, Hyderabad, Telangana 501301, India
[b] Department of Mathematics, B.L.D.E.A's V. P. Dr P. G. Halkatti College of Engineering and Technology, Vijayapur, Karnataka 586103, India

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ABSTRACT

The ongoing work elaborates the development of non-Newtonian fluid utilizing Jeffrey fluid model through an inclined non-uniform peristaltic conduit considering under the lubrication approach. Axial and transverse mean velocities have been solved analytically and the effect of promising flow parameters on the velocity, trapping phenomenon has been analyzed through graphs. The current study has a wide range of applications in science and biomedical designing.

1. Introduction

Peristalsis is a sequence of uncontrollable movements of the circular and longitudinal muscles, mostly in the gastrointestinal tract. They manifest as contractions that grow in waves. The gut canal encounters peristaltic waves. Peristaltic oscillations in the esophagus emerge at the top of the tube/conduit and move down the entire length, forcing food into the stomach ahead of the wave. It is additionally utilized in material taking care of frameworks in industry, since the material being pushed is contained within a tube, the media is kept in pristine condition, enabling them mainly preferred for high refinement applications. Various clinical applications depend upon the peristaltic pumping system, similar to the blood pump where in a genuinely more prominent worth is considered for the Reynolds number.

Peristaltic liquid transport has attracted scientific attention from researchers since initial analysis by Latham [1]. Many hypothetical and exploratory methodologies have investigated the peristaltic movement under different circumstances then later. The previous works accepted the amplitude ratio, small Reynolds number and wave number [2–4].

The role of peristalsis in the involuntary of tiny blood veins that periodically differ in diameter was hypothesized by Yin and Fung [5]. This peristaltic mechanism is also utilized in biomedical engineering to create and construct a variety of useful devices. The two better cases have been identified by Jaggy et al. [6] and are those for blood pumping and dialysis.

The flow of fluid in porous media plays a critical role for the retrieval of the crude oil beneath the reservoir, for filtration, and for many other additional applications. The Maxwell model was taken into account by Akram et al. [7] in their research of peristaltic transport in porous conduits. An investigation of the Slip and chemical reaction effects on peristaltic transport of a couple stress fluid through a permeable medium with complaint wall was performed by Sankad and Dhange [8].

Williamson fluid movement in an asymmetric inclined peristaltic channel while heated and with partial slide was kept in mind by Akbar et al. [9]. Ambreen et al. [10] examined the peristaltic flow along an inclined channel withboundary slip conditions and varying viscosity while considering the non-Newtonian fluid. For the heat and mass transport, couple stress fluid was taken into consideration.

Saravana et al. [11] analysis of the MHD peristaltic flow of a Jeffrey fluid in a non-uniform porous channel considered slip, wall property, and heat transfer effects. Dheia et al. [12] report on the impact of wall properties and heat on the transport of a Jeffrey fluid in a porous peristaltic channel. In their study published, Sucharitha et al. [13], investigated the outcomes of wall and warmth parameters at the peristalsis-caused flow of a Herschel-Bulkley liquid via ainclined non-uniform conduit. The peristaltic motion affected by heat and mass effect while taking into account hyperbolic tangent fluid in a non-uniform MHD conduit was examined by Saravana et al. [14]. Jagadeesh et al. [15] takes into account

* Corresponding author.
E-mail address: math.gurunath@bldeacet.ac.in (G.C. Sankad).

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the impacts of the progression of a Jeffrey fluid when it is impacted by a measured attractive fieldwithin an inclining peristaltic permeable channel. In a study, Dhange et al. [16] examined the flow with multiple stenoses in a force field.

According to the ongoing research, axial and transverse mean peristaltic flows of Jeffery fluid model solutions have been found. The analysis examines in detail into blood flow through confined vessels, clots, and food bolus transit across a large intestinal tract.

2. Mathematical formation

The analysis takes into account an irregularly angled channel that is transporting an unsteady Jeffery fluid. According to Fig. 1, the fluid is considered to flow between two elastic, porous peristaltic walls. Consider: width of the channel $2d$, time t, wave length λ, and wave speed c and wave amplitude a, for the study. $\times$ axis denotes the axial coordinate and y is perpendicular to it. Only half the width of the channel is considered for analysis.

The wall equation is represented by

$$\dagger = \eta(x,t) = d + kx + asin\frac{2\pi}{\lambda}(x - ct). \tag{1}$$

The equation of the Jeffrey fluid is: $\overrightarrow{T} = -\overrightarrow{p}\overrightarrow{I} + \overrightarrow{s}$.

Here T: Cauchy stress $\overrightarrow{s}$: the extra stress tensor $\overrightarrow{I}$: the identity tensor and $\overrightarrow{p}$: the pressure, where $\overrightarrow{s} = \frac{\mu}{1+\lambda_1}\left(\dot{\overrightarrow{\gamma}} + \lambda_2\ddot{\overrightarrow{\gamma}}\right)$.

Again here μ is the viscosity of the fluid, $\dot{\overrightarrow{\gamma}}$ the shear rate and dots $(\cdot)$ over the quantities indicate derivative w. r. t time, λ_1 the ratio of relaxation to retardation and λ_2 the retardation time.

The wall equation is given by

$$\mathcal{L}(\eta) = \mathcal{P} - \mathcal{P}_0, \tag{2}$$

where operator $\mathcal{L}$ is given by

$$\mathcal{L} = -\tau\frac{\partial^3\eta}{\partial\S^3} + m\frac{\partial^3\eta}{\partial\S\partial t^2} + C\frac{\partial^2\eta}{\partial\S\partial t}. \tag{3}$$

Here 'τ' represents elastic tension in the wall, 'C' the viscous damping force and 'm' the mass per unit area.

The governing equations are given by

$$\frac{\partial\sqcap}{\partial\S} + \frac{\partial\sqsubseteq}{\partial\dagger} = 0, \tag{4}$$

$$\rho\left(\frac{\partial\sqcap}{\partial t} + \sqcap\frac{\partial\sqcap}{\partial\S} + \sqsubseteq\frac{\partial\sqcap}{\partial\dagger}\right) = -\frac{\partial\mathcal{P}}{\partial\S} + \frac{\mu}{1+\lambda_1}\nabla^2\sqcap - \mu\frac{\sqcap}{\mathcal{K}} + \rho gsin\theta, \tag{5}$$

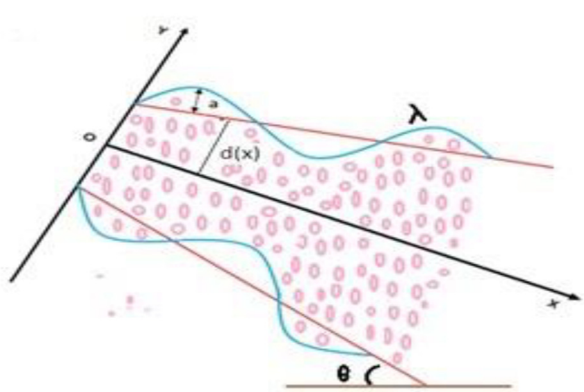

Fig. 1. Geometry of the model.

$$\rho\left(\frac{\partial\sqsubseteq}{\partial t} + \sqcap\frac{\partial\sqsubseteq}{\partial\S} + \sqsubseteq\frac{\partial\sqsubseteq}{\partial\dagger}\right) = -\frac{\partial\mathcal{P}}{\partial\dagger} + \frac{\mu}{1+\lambda_1}\nabla^2\sqsubseteq - \mu\frac{\sqsubseteq}{\mathcal{K}} - \rho gcos\theta. \tag{6}$$

In the above equations $\sqcap$ and $\sqsubseteq$ are the components of velocity. It is proved experimentally that many physiological situations have very small Reynolds number. Therefore wavelength is assumed to be infinite ensuring the flow to be peristaltic flow at every local cross section. $\mathcal{K}$ is the permeability, ρ the fluid density and $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ further $\mathcal{P}$ is the pressure and pressure on the outside wall surface $\mathcal{P}_0$ is assumed to be zero.

$$\frac{\partial\sqcap}{\partial\dagger} = 0, at y = 0 (\text{the regularity condotion}), \tag{7}$$

$$\sqcap = -d\frac{\sqrt{Da}}{\beta}\frac{\partial\sqcap}{\partial y}at\dagger = \pm\eta(x,t), (\text{the slip condition}), \tag{8}$$

here β denotes slip parameter.

The dynamic boundary conditions referred by Mittra and Prasad [17] are

$$\frac{\partial}{\partial\S}\mathcal{L}(\eta) = -\rho\left(\frac{\partial\sqcap}{\partial t} + \sqcap\frac{\partial\sqcap}{\partial\S} + \sqsubseteq\frac{\partial\sqcap}{\partial\dagger}\right) + \frac{\mu}{1+\lambda_1}\nabla^2\sqcap - \mu\frac{\sqcap}{\mathcal{K}} + \rho gsin\theta, \quad y = \eta(\S, t). \tag{9}$$

Here

$$\frac{\partial\mathcal{P}}{\partial\S} = \frac{\partial\mathcal{L}(\eta)}{\partial\S}. \tag{10}$$

We introduce stream function ψ as

$$u = \frac{\partial\psi}{\partial y}, v = -\frac{\partial\psi}{\partial x}. \tag{11}$$

Dimensionless variables are

$$\S' = \frac{\S}{\lambda}, y' = \frac{y}{d}, \psi' = \frac{\psi}{cd}, t' = \frac{ct}{\lambda}, \sqcap' = \frac{\sqcap}{c}, \sqsubseteq' = \frac{\lambda\sqsubseteq}{cd}, \mathcal{P}' = \frac{d^2\mathcal{P}}{\mu\lambda c}, \eta' = \frac{\eta}{d}, \mathcal{K}' = \frac{\mathcal{K}\lambda}{d}. \tag{12}$$

Introducing non-dimensional variables in (4–9) results into the following equations

$$\frac{\partial\sqcap}{\partial x} + \frac{\partial\sqsubseteq}{\partial y} = 0, \tag{13}$$

$$R_e\delta\left(\frac{\partial\sqcap}{\partial t} + \sqcap\frac{\partial\sqcap}{\partial x} + \sqsubseteq\frac{\partial\sqcap}{\partial y}\right) = -\frac{\partial p}{\partial x} + \frac{1}{1+\lambda_1}\left(\delta^2\frac{\partial^2\sqcap}{\partial x^2} + \frac{\partial^2\sqcap}{\partial y^2}\right) - \frac{\sqcap}{Da} + \frac{sin\theta}{F}, \tag{14}$$

$$R_e\delta^3\left(\frac{\partial\sqsubseteq}{\partial t} + \sqcap\frac{\partial\sqsubseteq}{\partial x} + \sqsubseteq\frac{\partial\sqsubseteq}{\partial y}\right) = -\frac{\partial p}{\partial y} + \frac{\delta^2}{1+\lambda_1}\left(\delta^2\frac{\partial^2\sqsubseteq}{\partial x^2} + \frac{\partial^2\sqsubseteq}{\partial y^2}\right) - \delta^2\frac{\sqsubseteq}{Da} - \delta\frac{cos\theta}{F}, \tag{15}$$

Equations (7–9) becomes,

$$\frac{\partial\sqcap}{\partial y} = 0, at y = 0, \tag{16}$$

$$\sqcap = -\frac{\sqrt{Da}}{\beta}\frac{\partial\sqcap}{\partial y}, at y = \pm\eta(x,t) = \pm(1 + k\S + \varepsilon sin2\pi(x - t)), \tag{17}$$

&

$$-R_e\delta\left(\frac{\partial\sqcap}{\partial t}+\sqcap\frac{\partial\sqcap}{\partial x}+\sqsubseteq\frac{\partial\sqcap}{\partial y}\right)+\frac{1}{1+\lambda_1}\left(\delta^2\frac{\partial^2\sqcap}{\partial x^2}+\frac{\partial^2\sqcap}{\partial y^2}\right)+\frac{sin\theta}{F}-\frac{\sqcap}{Da}$$
$$=E_1\frac{\partial^3\eta}{\partial x^3}+E_2\frac{\partial^3\eta}{\partial x\partial t^2}+E_3\frac{\partial^3\eta}{\partial x\partial t}aty=\pm\eta(x,t), \tag{18}$$

here $\delta=\left(\frac{d}{\lambda}\right)$ is wall slope parameter and $\varepsilon=\left(\frac{a}{d}\right)$ is the amplitude ratio is the geometric parameter, $R_e=\left(\frac{\rho cd}{\mu}\right)$ is the Reynolds number,$Da=\frac{K}{d^2}$ is the Darcy number.

The elasticity factors are given by $E_1=\left(\frac{-\tau d^3}{c\mu\lambda^3}\right)$, $E_2=\left(\frac{\mu cd^3}{\mu\lambda^3}\right)$, $E_3=\left(\frac{Cd^3}{\mu\lambda^2}\right)$.The parameter E_1 signify the rigidity, E_2 the stiffness and E_3 the viscous damping force in the wall.

3. Method of solution

General solution is confined with the suppositions of small wave number that is long wavelength approximation is considered for the resolution. Therefore, equations (13–18) yield:

$$\frac{\partial\sqcap}{\partial x}+\frac{\partial\sqsubseteq}{\partial y}=0, \tag{19}$$

$$0=-\frac{\partial\mathcal{P}}{\partial\S}+\frac{1}{1+\lambda_1}\frac{\partial^2\sqcap}{\partial\dagger^2}-\frac{\sqcap}{Da}+\frac{sin\theta}{F}, \tag{20}$$

$$0=-\frac{\partial\mathcal{P}}{\partial y}, \tag{21}$$

The conditions at the boundary yield (16) – (18) as

$$\frac{\partial\sqcap}{\partial y}=0,aty=0, \tag{22}$$

$$\sqcap=-\frac{\sqrt{Da}}{\beta}\frac{\partial\sqcap}{\partial y},aty=\pm\eta(\S,t)=\pm(1+k\S+\varepsilon sin2\pi(\S-t)), \tag{23}$$

$$\frac{1}{1+\lambda_1}\frac{\partial^2\sqcap}{\partial\dagger^2}-\frac{\sqcap}{Da}+\frac{sin\theta}{F}=E_1\frac{\partial^3\eta}{\partial\S^3}+E_2\frac{\partial^3\eta}{\partial\S\partial t^2}+E_3\frac{\partial^2\eta}{\partial\S\partial t},aty$$
$$\pm\eta(\S,t). \tag{24}$$

Solving the above equations we obtain:

$$\sqcap=\frac{B}{G}\left[M_3-M_4-\frac{m_2}{m_1}e^{m_1y}+e^{m_2y}\right]. \tag{25}$$

Where,

$$E=-\varepsilon\left[(2\pi)^3cos2\pi(\S-t)(E_1+E_2)-E_3(2\pi)^2sin2\pi(\S-t)\right],$$

$$m_1=\frac{(1+\lambda_1)^{1/2}}{(D)^{1/2}},m_2=-\frac{(1+\lambda_1)^{1/2}}{(D)^{1/2}},B=E-\frac{sin\theta}{F},G$$
$$=M_1+M_2-\frac{(M_3-M_4)}{Da},$$

$$M_1=-\frac{m_2}{m_1}e^{m_1\eta}\left(\frac{{m_1}^2}{1+\lambda_1}-\frac{1}{Da}\right),M_2=e^{m_2\eta}\left(\frac{{m_2}^2}{1+\lambda_1}-\frac{1}{Da}\right),M_3$$
$$=\frac{m_2}{m_1}e^{m_1\eta}\left(1+\frac{(Da)^{1/2}}{\beta}m_1\right),M_4=e^{m_2\eta}\left(1+\frac{(Da)^{1/2}}{\beta}m_2\right).$$

Transverse velocity from equation (13) with condition $\sqsubseteq=0aty=0$

$$\sqsubseteq=\frac{\frac{E-sin\theta}{F}\left(T_1+T_2-\frac{1}{Da}(T_3-T_4)\right)}{\left(M_1+M_2-\frac{1}{Da}(M_3-M_4)\right)^2}\left((M_3y-M_4y)-\frac{m_2}{{m_1}^2}e^{m_1y}+\frac{e^{m_2y}}{m_2}\right)$$
$$-\left((M_3y-M_4y)-\frac{m_2}{{m_1}^2}e^{m_1y}+\frac{e^{m_2y}}{m_2}\right)\left(\frac{T_5}{M_1+M_2-\frac{1}{Da}(M_3-M_4)}\right)$$
$$-\frac{((T_3-T_4)y)\left(\frac{E-sin\theta}{F}\right)}{M_1+M_2-\frac{1}{Da}(M_3-M_4)}+C. \tag{26}$$

Here,

$$N_1=k+\varepsilon2\pi cos2\pi(x-t),$$

$$T_1=\frac{m_2}{m_1}e^{m_1\eta}\left(\frac{{m_1}^2}{1+\lambda_1}-\frac{1}{Da}\right)m_1N_1,T_2=e^{m_2\eta}\left(\frac{{m_2}^2}{1+\lambda_1}-\frac{1}{Da}\right)m_2N_1,$$

$$T_3=\frac{m_2}{m_1}e^{m_1\eta}\left(1+\frac{(Da)^{1/2}}{\beta}m_1\right)m_1N_{1,}T_4$$
$$=e^{m_2\eta}\left(1+\frac{(Da)^{1/2}}{\beta}m_2\right)m_2N_{1,}$$

$$T_5=\varepsilon\left[(2\pi)^4sin2\pi(x-t)(E_1+E_2)+E_3(2\pi)^3cos2\pi(x-t)\right],$$

$$C=\frac{\left(E-\frac{sin\theta}{F}\right)\left(T_1+T_2-\frac{(T_3-T_4)}{Da}\right)\left(-\frac{m_2}{{m_1}^2}+\frac{1}{m_2}\right)}{\left(M_1+M_2-\frac{(M_3-M_4)}{Da}\right)^2}+\frac{T_5\left(-\frac{m_2}{{m_1}^2}+\frac{1}{m_2}\right)}{M_1+M_2-\frac{(M_3-M_4)}{Da}}.$$

The time average axial velocity $\bar{u}$ is

$$\bar{u}=\int_0^1\sqcap dt. \tag{27}$$

At $\dagger=0,\sqsubseteq=0$,

The time average transverse velocity $\bar{\sqsubseteq}$ is

$$\bar{\sqsubseteq}=\int_0^1\sqsubseteq dt. \tag{28}$$

4. Discussion of results

Through graphical demonstrations, the outcomes of non-Newtonian Jeffrey fluid flowing peristaltically in a non-uniformly

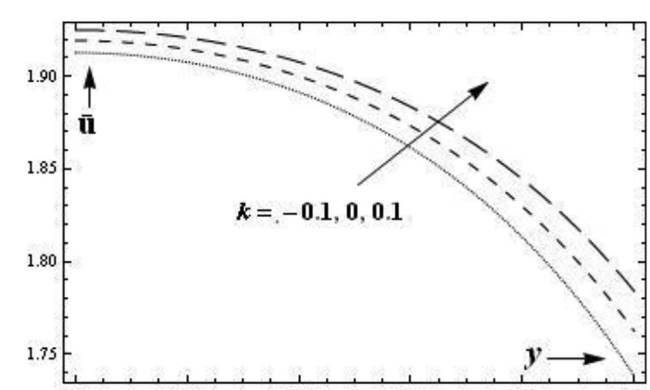

Fig. 2. Mean axial velocity profiles for various values of non uniform parameter.

inclined channel with porosity under the condition of slip are described in detail. In this segment, the time average axial and transverse velocity analytical solutions are found using the perturbation approach and described by modulating the various relevant factors. Using the MATHEMATICA tool, the analytical findings are visually represented in Figs. 2-13.

Graphs are plotted using the values: $\epsilon = 0.2$; $E_1 = 0.1$; $E_2 = 0.5$; $E_3 = 0.2$; $\lambda_1 = 7$; $Da = 0.3$; $\beta = 1.1$; $\theta = \pi/4$; $k = 0.1$; $\S = 0.5$; $F = 0.4$. The results from equation (27) are shown graphically in Figs. 2-7) to examine the outcomes of Jeffrey parameter λ_1, slip parameter β, inclination angle θ, Darcy number *Da*, non-uniform parameter k and elastic parameters on mean axial velocity $\bar{\sqcap}(\dagger)$. The variation of mean transverse velocity $\bar{\sqsubseteq}(\dagger)$ are shown in Figs. 8-13 using Eq. (28).

Enhancing the non-uniform parameter k and the inclination θ increases the mean velocity as shown in Figs. 2 and 3. Fig. 4 depicts the results of Darcy number Da. It is observed that the mean velocity increases with *Da*. Figs. 5 and 6 illustrate that the mean velocity reduces with rise in slip parameter β and elastic parameters E_1, E_2, E_3. Fig. 7 is made to observe the behavior of Jeffrey parameter λ_1 that informs that rise in λ_1 enhances the mean velocity of the flow.

The outcomes of Jeffrey parameter are in agreement with that of Dheia et al. [12] and the non-uniform parameter result is in agreement with Sucharitha et al. [13]. The results of inclination parameter agree with those of Jagadeesh et al. [15].

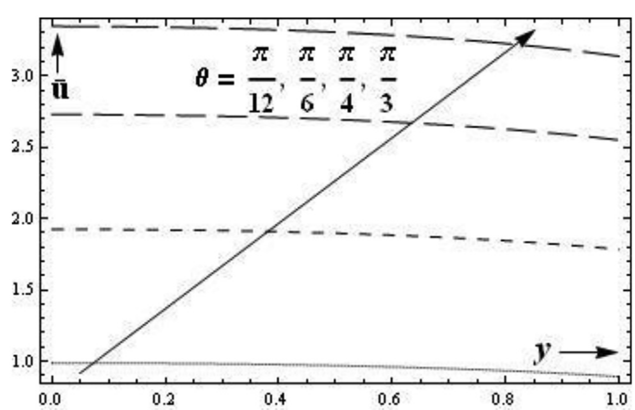

Fig. 3. Mean axial velocity profiles for various values of inclination parameter.

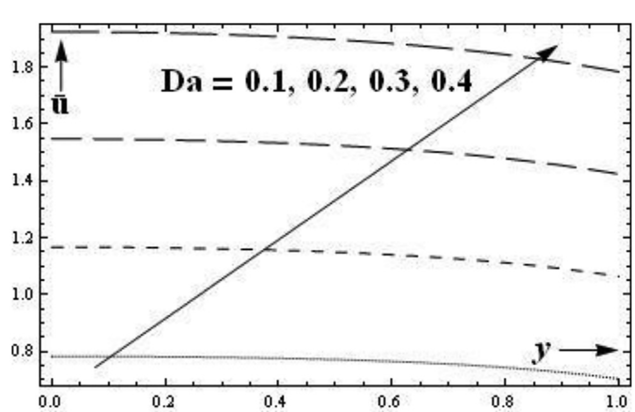

Fig. 4. Mean axial velocity profiles for variousvalues of Darcy number.

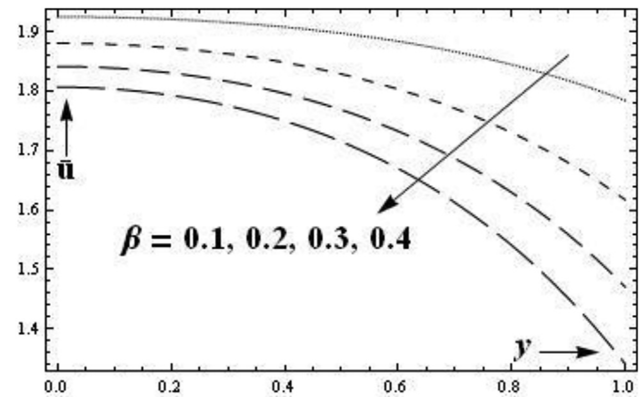

Fig. 5. Mean axial velocity profiles for various values of slip parameter.

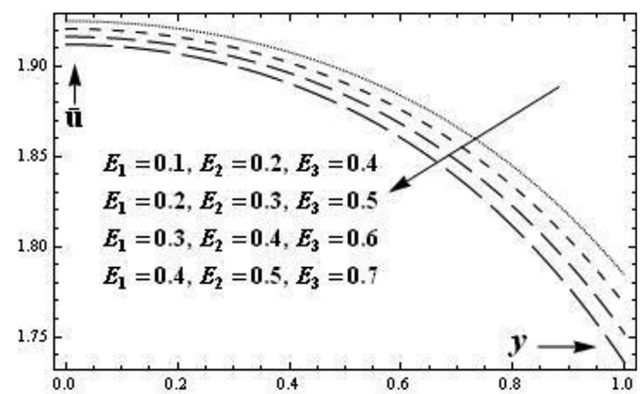

Fig. 6. Mean axial velocity profiles for various values of elastic parameters.

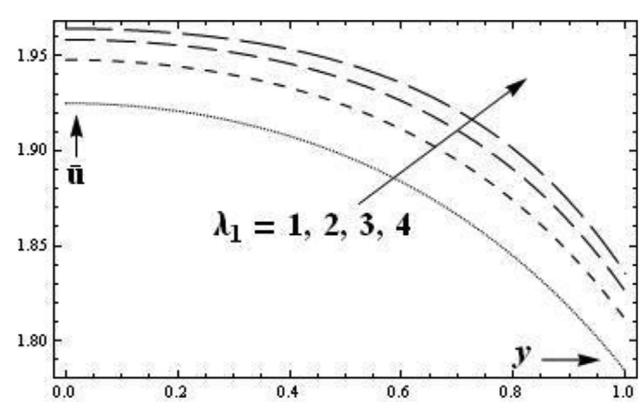

Fig. 7. Mean axial velocity profiles for various values of Jeffrey parameter.

The effect of transverse mean velocity on peristaltic motion is demonstrated in Figs. 8-13 for the above fixed parameters.

Fig. 8 helps to examine the outcomes of non uniform parameter on mean velocity. Rise in non uniform parameter, decreases the mean velocity of the fluid. As inclination parameter increases, mean velocity decreases as shown in Fig. 9. Fig. 10 says that mean velocity grows with rise in the values of Darcy number. The dis-

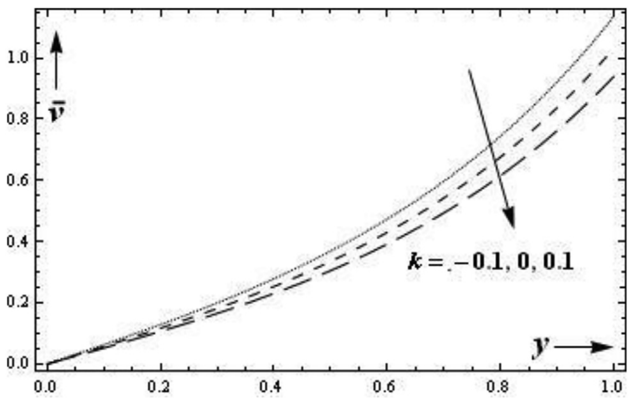

Fig. 8. Mean transverse velocity profiles forvarious values of non uniform parameter.

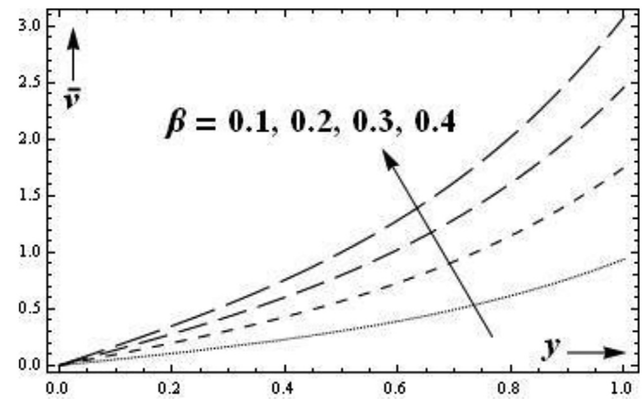

Fig. 11. Mean transverse velocity profiles forvarious values of slip parameter.

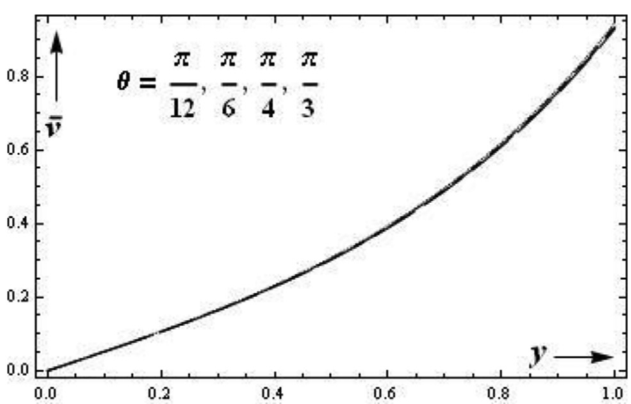

Fig. 9. Mean transverse velocity profiles forvarious values of inclination angle.

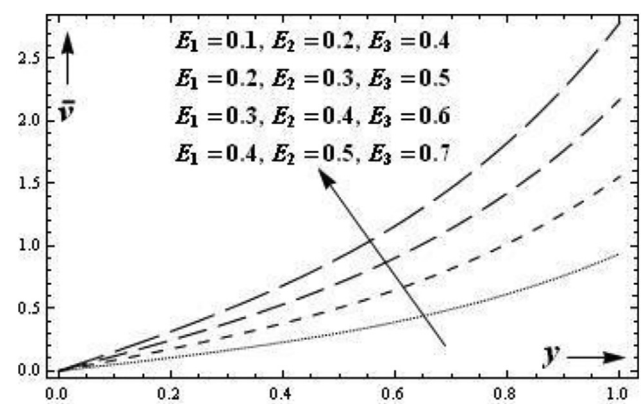

Fig. 12. Mean transverse velocity profiles forvarious values of elastic parameters.

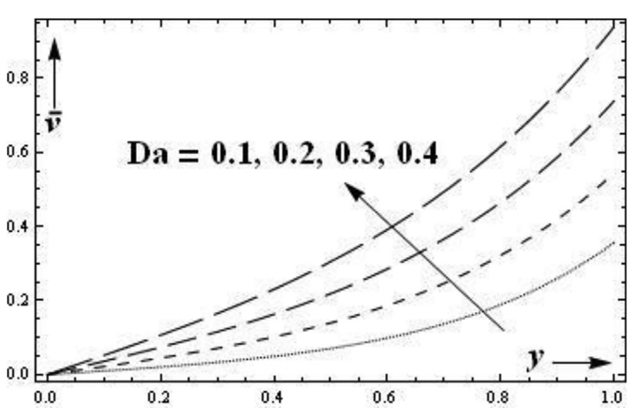

Fig. 10. Mean transverse velocity profiles for various values of Darcy number.

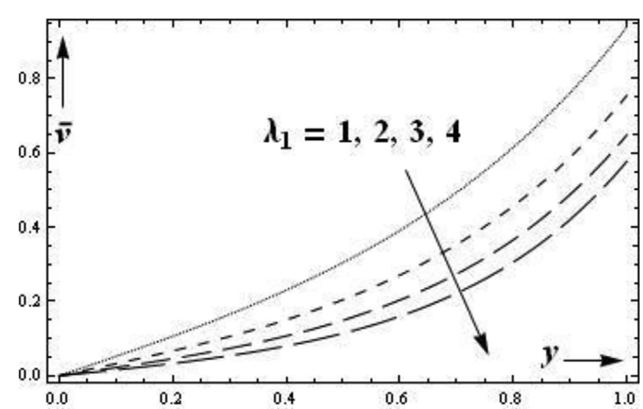

Fig. 13. Mean transverse velocity profiles for various values of Jeffrey parameter.

crepancy in mean velocity for varying values of slip and elastic parameters are revealed in Figs. 11 and 12. Clearly the growing slip parameter and elastic parameters increase the mean velocity. Fig. 13 tells that the mean velocity flow drops as the Jeffrey parameter is increased.

5. Conclusion

Under the assumption of a long wave length, an analytical method is used to investigate the peristaltic motion of a Jeffrey fluid at low Reynolds numbers in a flexible porous channel. On the flow characteristics, the effects of various physical parameters are visually examined. The key points are as follows:

- The axial mean velocity in a porous, non uniform inclined stratum increases with bigger values of inclination parameter, Jeffrey parameter, non uniform parameter and Darcy number.
- A contradictory behavior is noticed for slip parameter and elastic parameters.
- Transverse velocity profile increases for Darcy parameter, slip parameter and elastic parameters.
- Velocity profile decreases for increasing non uniform parameter and Jeffrey parameter.
- The analysis exposes interesting behaviors that affirm further study on various biological fluids.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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