MATHEMATICAL MODELLING ON PERISTALTIC TRANSPORT OF JEFFERY FLUID UNDER THE EFFECTS OF VARIABLE VISCOSITY AND THERMAL CONDUCTIVITY IN A POROUS TUBE WITH CONVECTIVE BOUNDARY CONDITIONS

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Abstract- The present paper investigates the effects of slip, variable viscosity, variable thermal conductivity, and convective boundary conditions on peristaltic transport of Jeffery fluid in an inclined porous tube. The viscosity of the fluid varies across the thickness of the fluid, and the temperature-dependent thermal conductivity is taken into account. The resulting governing equations are solved using long wavelength and small Reynolds number approximations. The closed-form solutions are obtained for velocity, flow rate, temperature, pressure rise and frictional force when subjected to slip and convective boundary conditions. The analysis reveals quite an interesting and substantial influence of variable viscosity onpressure rise and frictional force. The study further reveals that an increase in the Biot number decreases the magnitude of temperature.

Keywords- Viscosity, thermal conductivity, Darcy number, Slip parameters, Inclination.

I. INTRODUCTION

Peristalsis is a mechanism induced by the progressive wave of area contraction and expansion which goes along the walls of the distensible tube or channel. The peristalsis usually happens in the movement of the bolus through the esophagus, urine flow through the ureter, chyme development in the gastrointestinal tract, transport of lymph in the lymphatic vessels, embryo transport within the uterine cavity and the flow of blood in vessels. This mechanism has been utilized by the researchers to outline a few modern applications, for example, in atomic industry, peristaltic pump, roller and finger pumps, transport of corrosive and noxious liquids and heart-lung machines. As a result of its far-reaching use in various fields of science, different researchers have explored the peristaltic transport under a different configuration. A significant number of such attempts have been done by assuming long wavelength and small Reynolds number approximation [1-3]. Since most of the fluids occurring in industries and physiology behave as a non-Newtonian fluid. Therefore, the examination of the peristaltic transport of non-Newtonian fluid has been of most extreme significance to numerous researchers because of its application in Bioengineering and Medicine [4-6]. Among the few non-Newtonian models, Jeffery model is precious because of its vast number of applications in the warm oil recuperation, polymer and sustenance preparing, nourishment and sluttery transportation and in the vasomotion of veins. The attempts on the utilization of Jeffery model to examine the fluid flow with different configuration can be seen in the literature [7-10].

Flow through porous media has attracted many researchers because of its application in filtration of fluids, bile duct, the human lung, wood, gallbladder, limestone, sandstone and in vasomotion of blood in microvessels. Specifically, the flow through porous arteries has been of most importance in investigating cardiovascular diseases. Motivated by such facts, the underlying examination on considering porosity was done by Elshehawey et al. [11]. Later, the impact of porous boundaries on peristaltic flow of viscous incompressible fluid was carried out by Elshehawey and Husseny [12]. Alsaedi et al. [13] investigated the peristaltic mechanism in a porous medium by using couple stress fluid. They obtained the closed form solutions for axial velocity and pressure gradient and they found that an increase in the permeable parameter decreases the pumping region. Further, Ramesh and Devkar [14] studied MHD couple stress fluid through the vertical porous medium and obtained exact solutions for various physiological parameters. Bhatti and Abbas [15] examined peristaltic transport of Jeffery fluid under the influence of slip through a porous medium. They found that the presence of slip and permeability parameter diminishes the pumping region of the fluid. Recently, Sreenadh et al. [16] investigated the peristaltic transport of two layered fluid by using Power-law fluid in the core region and Jeffery fluid in the peripheral region. They noticed that an increase in the value of permeability parameter increases the thickness of the core layer.

The effect of heat transfer on peristalsis is another crucial mechanism which has been of great importance in modern times, because of its comprehensive applications in the analysis of oxygenation, hemodialysis, and tissues. The examinations on heat transfer have revealed that the variation in temperature of any framework influences

its physical properties, for example, in atomic power plants, in turbines, rocket innovation, rockets, space vehicles and pumps which are worked at high temperature. In this manner, the variation of temperature fundamentally influences thermal conductivity. Precisely, thermal conductivity is a measure of the capacity of a substance to direct heat under normal conditions. This behavior is evidence that any adjustment in temperature may change the rate at which the material is directing heat. Keeping this in mind, Hayat et al. [17] examined peristaltic transport with variable viscosity and thermal conductivity. Abbasi et al. [18] carried out the numerical examination of peristaltic flow utilizing Carreau-Yasuda fluid with variable thermal conductivity and convective boundary conditions. The study uncovered that an increase in the Biot number reduces the temperature. Hussain et al. [19] examined the peristaltic transport of Jeffery liquid with varying viscosity and thermal conductivity. Another essential factor which is substantially influenced by the variation of temperature is convective heat transfer at the boundary. Convective boundary conditions are utilized to characterize a direct convective heat exchange for one or more geometric entities in thermal mode. The investigation on the impacts of convective boundary conditions play a significant role in gas turbines, atomic plants, and thermal energy storage. The studies about the utilization of convective boundary conditions on the peristaltic transport were done by Alsaedi et al. [20].Later, Abbasi et al. [21] examined the impact of Joule heating and convective boundary conditions on peristaltic transport. They found that the presence of Joule heating enhances the temperature and an increase in the estimation of Biot number decreases the temperature. Hayat et al. [22] examined MHD peristalsis utilizing Carreau liquid affected by Joule heating and convective heat transfer. They come up with the similar observation made by Abbasi et al. [21] for Biot number. Further, Sayed et al. [23] investigated the effect of slip and convective boundary conditions on peristaltic transport. Recently, Misra et al. [24] carried out investigation on the peristaltic transport of blood flow under the influence of heat and mass transfer with temperature dependent properties. The study noticed that the volume of tapered bolus diminishes with increase in fluid viscosity and Hartmann number. Most of the examinations on peristaltic transport are done by taking constant viscosity. This supposition neglects to clarify the peristaltic movement engaged with the digestive system, conduits efferents of the male conceptive tract and flow of blood in microvessels. In these organs, the viscosity of the liquid differs over the thickness of the channel [25-28].

Motivated by the studies as mentioned earlier, the present investigation is carried out to examine the combined effects of slip, variable viscosity and thermal conductivity on peristaltic transport of Jeffery fluid. Thus, we intend to carry out heat transfer analysis for the peristaltic transport of Jeffery fluid in an inclined porous tube. The slip and convective boundary conditions on the tube are employed to solve the governing equations of the problem. The closed-form solutions are obtained for velocity, flow rate, pressure rise, frictional force and temperature. The effect of pertinent parameters on the flow quantities is discussed and analyzed through graphs.

II. MATHEMATICAL FORMULATION

Considered the peristaltic flow of a viscous incompressible Jeffry fluid in an inclined axisymmetric tube of radius a (Figure 1). The tube is inclined at an angle β to the horizontal axis. The flow is induced by the sinusoidal wave trains travelling with the wave speed c along the walls of the distensible tube. Mathematically it is given by

$$h(z,t) = 1 + \varepsilon \sin\left(\frac{2\pi}{\lambda}\left[z - ct\right]\right) \qquad (1)$$

where, z is the axial direction, ε is the amplitude ratio, λ is the wavelength and t is the time.

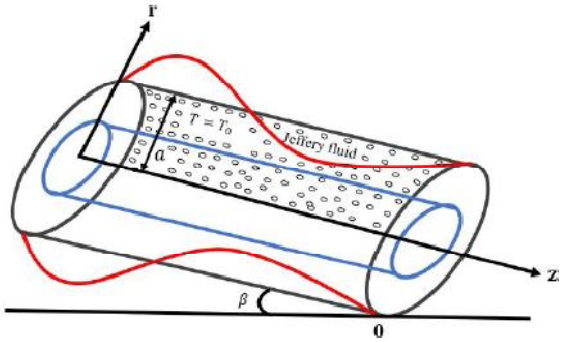

Figure 1. Geometrical representation of peristaltic transport in a porous tube

The governing equation for an incompressible Jeffery fluid are

$$\overline{T} = p\overline{I} + \overline{S}$$

$$\overline{S} = \frac{\mu}{1+\lambda_1}\left(\dot{\gamma} + \lambda_2 \ddot{\gamma}\right). \qquad (2)$$

Where, $\overline{S}$ is the extra tensor, $\overline{T}$ is the Cauchy's stress tensor, λ_1 is the ratio of relaxation to retardation time, λ_2 is the retardation time, $\overline{I}$ is the identity tensor and γ is the shear rate and dots over the quantities indicate differentiation with respect to time.

The flow becomes steady in the wave frame (r, θ, z) moving with velocity c away from the fixed frame (R, Θ, Z) given by

$$r = R,\quad z = Z - ct,\quad \psi = \Psi - \frac{R^2}{2},\quad p(Z,t) = P(z), \qquad (3)$$

where p and P are pressures, ψ and Ψ are stream functions, in the wave and fixed frames of references, respectively.

The pressure p stays consistent at any axial station of the tube under the supposition of long wavelength estimation. Utilizing the following non-dimensional quantities,

$$\bar{r} = \frac{r}{a},\ \bar{z} = \frac{z}{\lambda},\ \bar{t} = \frac{ct}{\lambda},\ \bar{p} = \frac{pa^2}{c\lambda\mu_0},\ \varepsilon = \frac{b}{a},\ Br = \Pr Ec,\ \bar{u} = \frac{u}{c}, \Pr = \frac{\mu_0 c_p}{k_0},\ Ec = \frac{c^2}{c_p T_0},$$

$$\mathrm{Re} = \frac{\rho c a}{\mu_0}, F_1 = \frac{\mu_0 c}{\rho g a^2},\ \overline{\mu(r)} = \frac{\mu(r)}{\mu_0}, \bar{w} = \frac{w}{c},\ \delta = \frac{a}{\lambda},\quad \bar{\tau} = \frac{\tau}{\mu_0\left(\frac{c}{a}\right)}. \qquad (4)$$

The non-dimensional equations of motion and energy in the wave frame of reference, moving with speed *c*, under the lubrication approach is as follows:

$$\mathrm{Re}\,\delta\left(u\frac{\partial}{\partial r} + w\frac{\partial}{\partial z}\right)w = -\frac{\partial p}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}(r\tau_{rz}) + \delta\frac{\partial}{\partial r}(\tau_{zz}), \qquad (5)$$

$$\mathrm{Re}\,\delta^3\left(u\frac{\partial}{\partial r} + w\frac{\partial}{\partial z}\right)u = -\frac{\partial p}{\partial r} + \frac{\delta}{r}\frac{\partial}{\partial r}(r\tau_{rr}) + \delta^2\frac{\partial}{\partial r}(\tau_{rz}), \qquad (6)$$

$$\mathrm{Re}\,\delta\,\Pr\left(u\frac{\partial}{\partial r} + w\frac{\partial}{\partial z}\right)\theta = Ec\,\Pr\left(\delta\frac{\partial u}{\partial r}\tau_{rr} + \frac{\partial w}{\partial r}\tau_{rz} + \delta^2\frac{\partial u}{\partial r}\tau_{zr} + \tau_{zz}\frac{\partial w}{\partial r}\delta\right) + \frac{\partial^2\theta}{\partial r^2} + \frac{1}{r}\frac{\partial\theta}{\partial r} + \delta^2\frac{\partial^2\theta}{\partial z^2}, \qquad (7)$$

where *u* and *w* are the radial and axial velocities, Re is the Reynolds number, θ is temperature, δ is wave number , Pr is the Prandtl number, Ec is the Eckert number, Br is Brinkman number, *r* is radial coordinate, τ is shear stress.

The viscosity of the fluid varies across the thickness of the tube and temperature dependent thermal conductivity is defined as

$$\mu(r) = 1 - \alpha_1 r,\quad k(\theta) = 1 + \phi\theta,\quad \text{for } \alpha_1 \ll 1 \text{ and } \phi \ll 1, \qquad (8)$$

where, α_1 and ϕ are the dimensional viscosity and thermal conductivity coefficients respectively.

Making use of variable viscosity, thermal conductivity and considering of long wavelength and small Reynolds number approximation, Eqs. (5) - (7) takes the form

$$\frac{1}{r}\frac{\partial}{\partial r}\left\{\frac{r\mu}{1+\lambda_1}\left(-\frac{\partial w}{\partial r}\right)\right\} = -\frac{\partial p}{\partial z} + \frac{\sin\beta}{F_1}, \qquad (7)$$

$$0 = \frac{\partial p}{\partial r}, \qquad (8)$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\theta}{\partial r}\right) = Br\left(-\frac{\partial w}{\partial r}\left[\frac{\mu}{1+\lambda_1}\left\{-\frac{\partial w}{\partial r}\right\}\right]\right). \qquad (9)$$

The corresponding non-dimensional slip and convective boundary conditions are [5,18]

$$h\frac{\partial w}{\partial r} = \frac{-\alpha w}{\sqrt{Da}},\quad (1+\phi)\frac{\partial\theta}{\partial r} + Bi\,\theta = 0 \text{ at } r = h. \qquad (10)$$

$$\frac{\partial\theta}{\partial r} = 0,\quad \tau_{rz} \text{ is finite at } r = 0. \qquad (11)$$

where, Da is the porous parameter (Darcy number), α is the velocity slip parameter, ϕ is the thermal conductivity, $Bi = \frac{la}{k_0}$ is the Biot number and l is the heat transfer coefficient of the wall and θ is the temperature.

We note that, the closed-form solutions to Eqs. (7) - (9) are obtained with the help of slip and convective boundary conditions as mentioned above.

The instantaneous volumetric flow rate in the wave frame is given by

$$Q = 2\int_0^h w\,r\,dr, \qquad (12)$$

The dimensionless time-averaged flux $\overline{Q}$ across one wavelength is

$$\overline{Q} = \int_0^1\int_0^h r(u_i - 1)\,dr\,dz = Q + \int_0^1 h^2\,dz = Q + 1 + \frac{\varepsilon^2}{2}. \qquad (13)$$

The non-dimensional expression for pressure rise (ΔP) and frictional force F across one wavelength is given as follows:

$$\Delta P = \int_0^1 \frac{\partial p}{\partial z} dz, \qquad (14)$$

$$F = \int_0^1 h^2 \left(-\frac{\partial p}{\partial z} \right) dz. \qquad (15)$$

III. RESULTS AND DISCUSSION

The effects of various physiological parameters on pressure gradient, pressure rise, frictional force, time averaged flow rate, temperature and tapered bolus are divided into four subsections. In Sections **4.1** and **4.2**, the effects of various physiological parameters on temperature and axial velocity are investigated. The pumping characteristics are examined in Section **4.3.** In all the figures shown in Sections **4.1**-**4.4**, we have used

$\phi = 0.1,\ \lambda_1 = 0.2,\ \alpha = 0.2,\ \alpha_1 = 0.1,\ \beta = \frac{\pi}{4},\ F_1 = 0.1,\ t = 0.01,\ \varepsilon = 0.5,$ $Da = 0.02,\ z = 0.1,\ Q = 0.6,\ Br = 0.25$ and $Bi = 0.5$.

3.1 Heat transfer effects:

The effects of variable thermal conductivity (ϕ), Biot number (Bi), porous parameter (Da), velocity slip parameter (α), Brinkmann number (Br) and Jeffery parameter (λ_1) on temperature (θ) are plotted in Fig. 2. The temperature profiles are non-parabolic and show the dual nature. The effect of ϕ plays a vital role in the determination of temperature. It means that, larger value of ϕ increasestemperature near the axis of the tube and it decreases near the walls of the tube (Fig. 2(a)). This is because of an increase in the value of ϕ allows the fluid to dissipate or absorb heat to its surroundings. Hence, an increase in ϕ decreases the temperature near the walls of the tube. Fig. 2(b) depicts the variation of temperature due to the influence of Bi. An increase in the value of Bi results in the reduction of temperature. The role of Da on temperatureis examined in Fig. 2(c). It is observed that the increasing values of Da decrease the temperature near the axis of the tube and opposite behavior is observed near the walls of the tube. The influence of α on temperature shows the opposite behavior as that of Da (Fig. 2(d)). Fig. 2(e) illustrates the effect of Br on temperature. It is found that an increase in the value of Br increases temperature. Since Ec occurs due to the viscous dissipation effects and it enhances temperature. Further, an increase in the value of $\Pr$ decrease thermal conductivity and thereby increases temperature. The role of λ_1 on temperature is shown in Fig. 2(f). It is clear that temperature decreases with increasing values of λ_1. Finally, it is noticed that for a fixed value of relevant parameters, temperature enhances with increasing value of viscosity.

3.2 Velocity profile:

Fig. 3 illustrates the effects of λ_1, Da, α and β on velocity (w). It is observed that the velocity profiles are parabolic in nature with maximum velocity occurs at the center of the tube. Fig. 3(a)-(c) are plotted to examine the effects of λ_1, Da and β on velocity. We noticed that the velocity increased by increasing λ_1, Da and β. The influence of α on velocity is shown in Fig. 3(d). The figure shows that the velocity is a decreasing function of α.

3.3 Pumping characteristics:

In the study of peristalsis, pressure rise per wavelength plays a vital role in understanding the physiological behavior. We have investigated the effects of variable viscosity and physiological parameters on pressure rise (ΔP) versus time averaged flow rate. The numerical integration is carried out by using Weddle's rule in MATLAB and corresponding results are plotted in Fig. 4. It is well known that the behavior of many physical parameters strongly depends upon the range of flow rate $(\overline{Q})$. Specifically, the impact of physiological parameters shows opposite behavior before and after certain critical value of $\overline{Q}$. The influence of λ_1 on ΔP and $\overline{Q}$ are given in Fig. 4(a). It is found that an increase in the value of λ_1 decreases ΔP in the pumping region $(\Delta P > 0)$ and the opposite behavior is seen in the augmented region $(\Delta P < 0)$. The pumping curves for Jeffery fluid $(\lambda_1 \neq 0)$ and Newtonian fluid $(\lambda_1 = 0)$ intersects with each other when $\overline{Q} = 1.1$. This information helps in equalizing the pumping rate of Newtonian and Jeffery fluid for some value of $\overline{Q}$ by adjusting the peristalsis velocity. Fig. 4(b) illustrates the variation of Da on ΔP and $\overline{Q}$. It is observed thata sudden increase in the value of Da results in the reduction of ΔP. This is because of an increase in the value of Da increases the porosity of the wall and thus $\overline{Q}$ decreases. Influence of α on ΔP and $\overline{Q}$ are shown in Fig. 4(c). It reveals that an increase in the value of α increases the ΔP in the pumping region. Fig. 4(d) visualizes the impact of inclination (β) on ΔP and $\overline{Q}$. It is found that the pressure rise required for normal tube

$(\beta = 0)$ is less than that of the tube having an angle of inclination. Fig. 4(e) exhibit the variation of ε on ΔP and $\overline{Q}$. The effect of increasing value of ε increases ΔP in a porous tube. This is quite physical as the value of ε increases, the corresponding wave height also increases and thereby it increases the value of ΔP. Furthermore, the effects of λ_1, Da, α and β on frictional force (F) and time averaged flow rate $(\overline{Q})$ show the opposite behavior as that of ΔP and $\overline{Q}$ (Fig. 5). Fig. 6 illustrate the effect of λ_1, Da, α and β on P. As expected, the pressure gradient P is maximum at the narrowest part of the tube, that is, $z = 0.75$. The main reason is to maintain the same flow rate through narrow part in comparison to the wider part of the tube in order to satisfy the conservation of mass. Further, for positive P an adverse pressure gradient registered (which opposes the flow) in the range $z \in [0.25, 0.45]$. However, a favorable pressure gradient is seen when P is negative in the interval $z \in [0, 0.25]$ and $z \in [0.45, 1.2]$ which helps the flow. Fig. 6(a)-(c) are plotted to examine the effects of λ_1, Da and β on P. It is found that an increase in the value of λ_1, Da and β decreases P. Further, the opposite behavior is seen for an increase in the value of α (Fig. 6(d)).

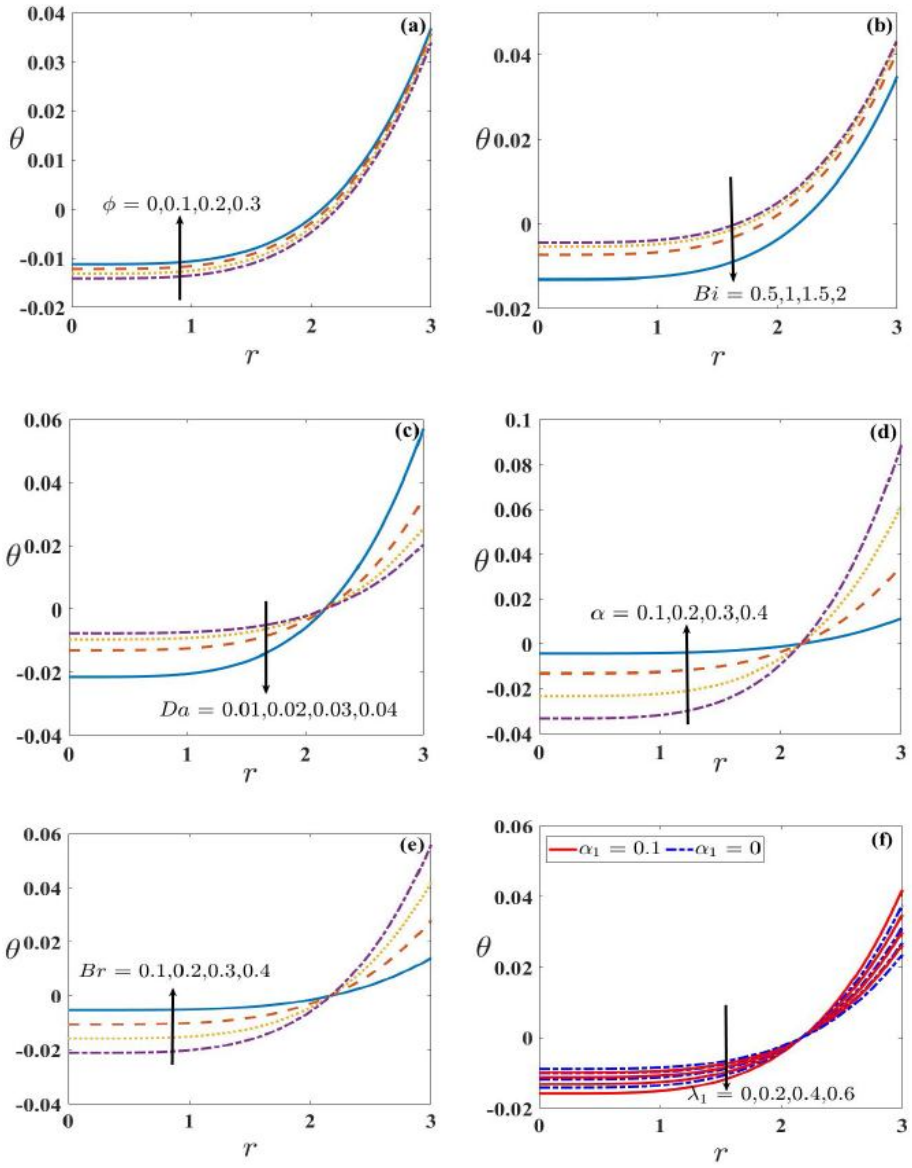

Figure 2. θ **versus** r **for varying (a) thermal conductivity** (ϕ)**, (b) Biot number** (Bi)**, (c) porous parameter** (Da)**, (d) velocity slip parameter** (α)**, (e) Brinkmann number** (Br) **and (f) Jeffery parameter** (λ_1)**.**

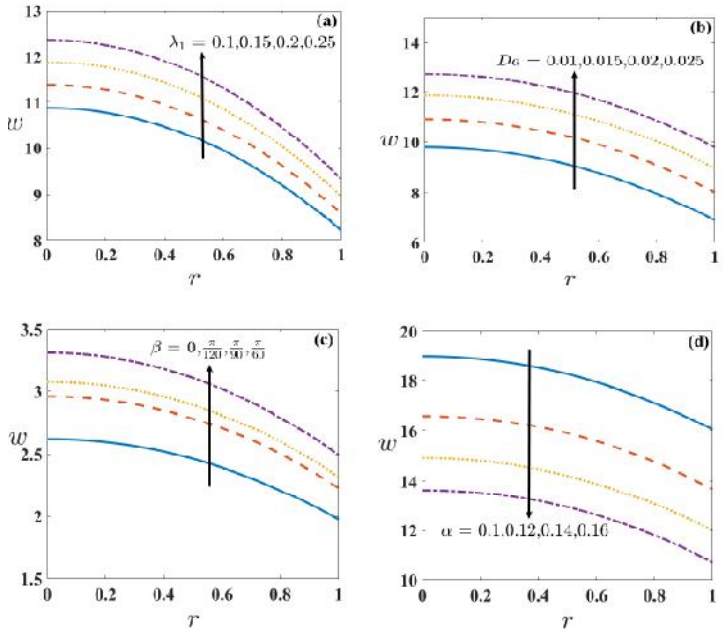

Figure 3. w **versus** r **for varying (a) Jeffery parameter** (λ_1)**, (b) porous parameter** (Da)**, (c) angle of inclination** (β) **and (d) velocity slip parameter** (α)**.**

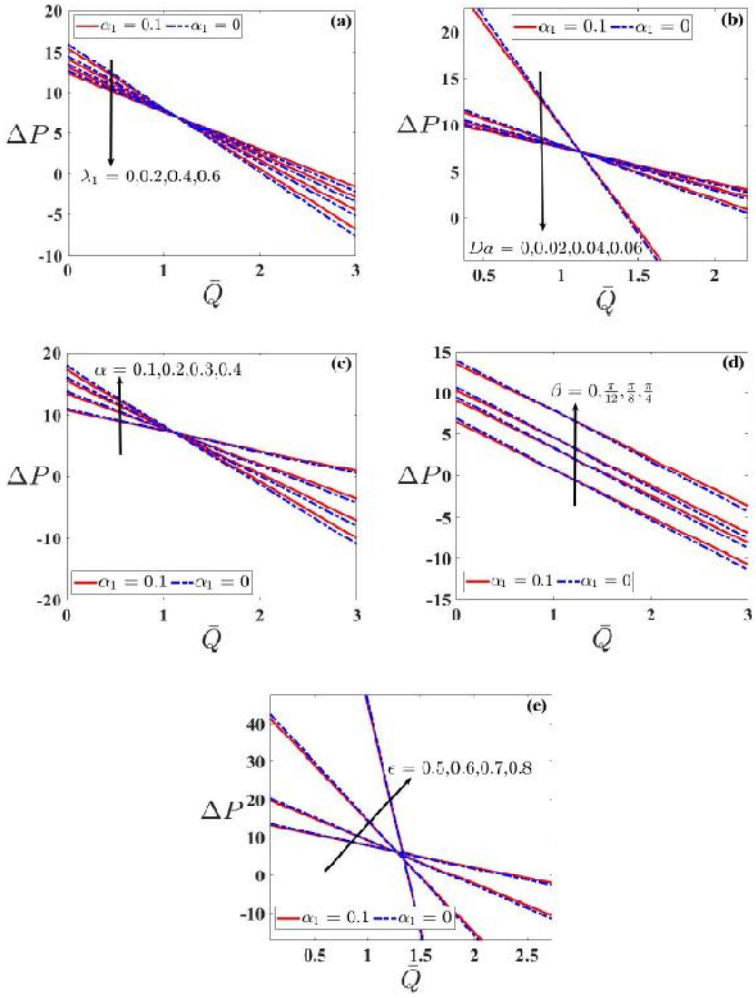

Figure 4. ΔP **versus** $\overline{Q}$ **for varying (a) Jeffery parameter** (λ_1)**, (b) porous parameter** (Da)**, (c) velocity slip parameter** (α)**, (d) angle of inclination** (β) **and (e) amplitude ratio** (ε)**.**

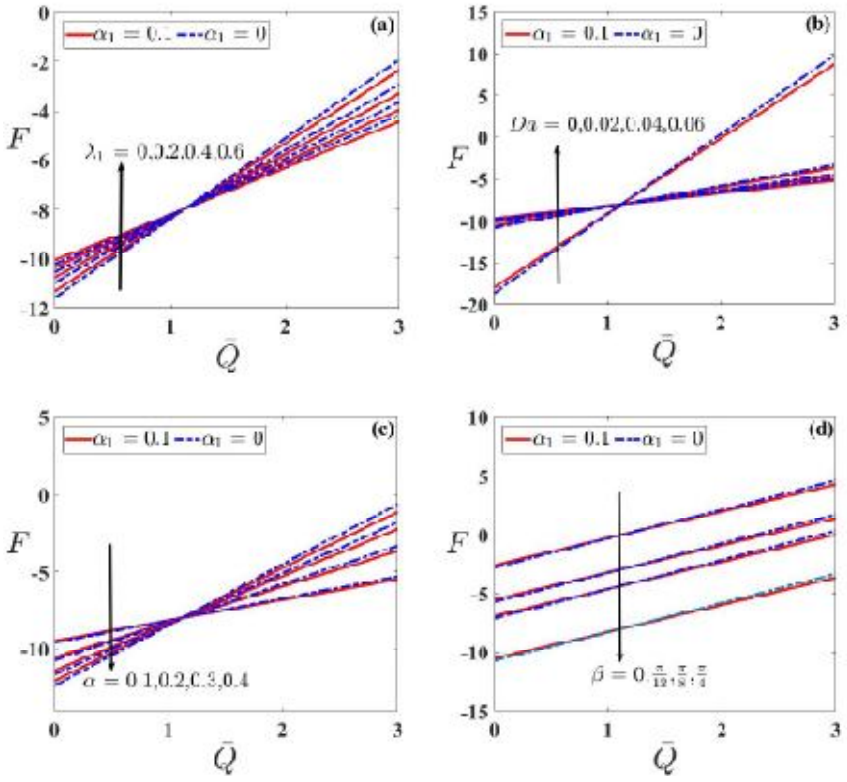

Figure 5. F **versus** $\overline{Q}$ **for varying (a) Jeffery parameter** (λ_1)**, (b) porous parameter** (Da)**, (c) velocity slip parameter** (α) **and (d) angle of inclination** (β)**.**

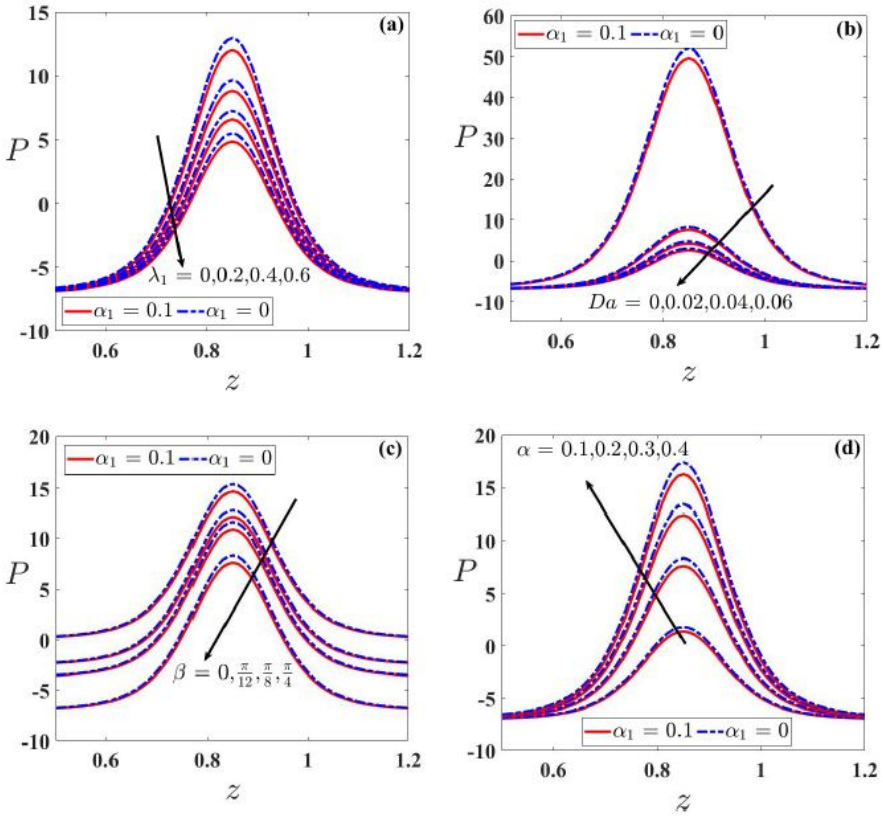

Figure 6. P **versus** z **for varying (a) Jeffery parameter** (λ_1)**, (b) porous parameter** (Da)**, (c)angle of inclination** (β) **and (d)velocity slip parameter** (α)**.**

IV. CONCLUDING REMARKS

The effects of slip, variable viscosity, thermal conductivity, and convective boundary conditions on peristaltic transport of Jeffery fluid in an inclined porous tube is investigated. The main findings are listed below.

- The presence of variable viscosity plays a vital role in diminishing pressure rise and temperature.
- The magnitude of temperature decreases with an increase in the Biot number and the temperature depended thermal conductivity increases the temperature near the axis of the tube and it decreases as we approach the walls of the tube.
- The axial velocity increases with increase in the value of Jeffery parameter, porous parameter, and angle of inclination, and it decreases with an increase in the value of velocity slip parameter.
- It is possible to enhance the pumping performance by increasing velocity slip parameter and angle of inclination, and it is lessened by increasing Jeffery and porous parameter.

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