INFLUENCE OF VELOCITY SLIP AND HEAT TRANSFER ON PERISTALTIC TRANSPORT OF JEFFERY FLUID IN AN INCLINED ELASTIC TUBE

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ABSTRACT

The present study investigates the combined effects of slip and heat transfer on a Jeffery fluid through an inclined elastic tube with porous walls. The modeled governing equations are solved analytically by considering the long wavelength and small Reynolds number approximations. The closed-form solutions are obtained for total volumetric flow rate, and the theoretical determination of flux is calculated with the help of equilibrium condition given by Rubinow and Keller. A parametric analysis has been presented to study the effects of Jeffery parameter, Darcy number, the angle of inclination, velocity slip, thermal slip, amplitude ratio, Prandtl number and Eckert number on flow rate and temperature. The study reveals that an increase in the angle of inclination and Jeffery parameter has a proportional increase in the flow rate. Also, an increase in the velocity slip and thermal slip parameter has a significant role in decreasing flow rate and temperature.

Keywords: Angle of inclination; Jeffery parameter; Velocity slip; Thermal slip.

INTRODUCTION

Peristalsis is a mechanism induced by the progressive wave of area contraction and expansion which travels along the walls of the distensible tube. Over the previous decades, various researchers have explored the peristaltic transport because of its extensive application in the field of biomedical engineering to design and construct numerous helpful devices, like, blood pump machine and dialysis machine (Jaggy et al. 2000). Also, it is a neuromuscular property of a biological system in which biofluids are transported along a tube by the propulsive developments of the tube wall. Numerous biological fluids in the human body have the peristaltic nature, for example, movement of the bolus in the throat locale, chime development in the cervical canal, the stream of blood in supply routes, transportation of urine through the ureter, and so forth.

The preliminary examination on peristaltic stream was done by Latham (1966) to investigate the flow of urine through the ureter. Later, Burns and Parkes (1967) contemplated peristaltic transport by taking two cases, in the primary case they considered peristaltic stream without pressure gradient, and for the second instance, they considered peristaltic flow under pressure along a channel or tube. The initial studies on peristalsis were carried by taking the Newtonian fluid to comprehend the physiological behavior of biological fluids. The Newtonian approach might be adequate to understand the urine flow through the ureter, yet it neglects to clarify the complex rheological activity in the stomach, lymphatic vessels and stream of blood in conduits. This underscores to utilize the non-Newtonian models to examine the physiological conduct of such frameworks. The underlying endeavor on peristaltic transport of non-Newtonian fluid was done by Raju and Devanathan (1972) by utilizing Power-law model. Further, various researchers have examined the peristaltic transport by using different non-Newtonian models coursing through various geometries (Srivastava and Srivastava (1984), Mernone and Mazumdar (2002), Maiti and Misra (2013), Manjunatha et al. (2013,2014). The examination of non-Newtonian nature of blood flow has been of most interest to the researchers recently because of their application in investigating the flow of blood in microvessels. In such conditions, the presence of slip on the boundary because of the permeability of the walls has a necessary effect in reviewing the non-Newtonian nature of blood. Thus, slip effects are more verbalized for fluids going through geometries which have flexible property, like blood vessels. This slip flow of fluids is used in polishing of the internal cavities and artificial heart valves. The exploratory examinations on non-Newtonian fluids revealed the centrality of slip at the walls. The peristaltic stream of blood through a tube can be idealized better by considering slip and permeability. Studies on the utilization of porous walls on peristaltic transport have been initially explored by Elshehawey et al. (1999). Later, various scientists examined the impact of slip velocity on the peristaltic mechanism by using different models under different assumptions and geometries (Nadeem and Akram (2011), El koumy et al. (2012), Tripathi and Beg (2012)).

All the studies mentioned earlier do not explain the heat transfer effects on peristaltic transport. However, the study of heat transfer effects along with slip conditions on peristalsis has acquired the attention of researchers in past decades due to their extensive application in the field of biofluid mechanics, chemical engineering, and medicine. Several researchers examined the interaction between peristalsis and heat transfer in different geometries with and without slip conditions. By considering the elastic nature of the tube Radhakrishnamacharya and Srinivasulu (2007) investigated peristaltic transport with the effects of heat transfer. Nadeem and Akbar (2009) studied the effects of heat transfer on peristaltic transport by using the Herschel-Bulkley model in a non-uniform inclined tube. Vajravelu et al. (2013) investigated the impact of heat transfer for the peristaltic transport by using Jeffery model in a vertical channel.

Among the several non-Newtonian models, Jeffery model is more significant in describing the flow of blood in arteries. The studies on the use of Jeffery model was carried out by Hayat et al. (2007) to investigate the peristaltic transport in a circular tube. Nadeem and Akram (2010) analyzed the peristaltic transport in a rectangular duct and obtained the exact solutions for pressure rise and pressure gradient. Further, several authors used Jeffery model for investigating the peristaltic transport with different geometries and assumptions to represent the specific living situation (Vajravelu et al. (2014)).

It is important to note that, the Poiseuille's law indicates that for a fluid which is incompressible, the flux in the tube is a linear function of the pressure difference between the ends of the rigid tube through which it flows. Hence, the non-Newtonian fluids obey Poiseuille’s law in most of the theoretical as well as experimental studies. The nonlinearity in vascular beds of warm-blooded creatures is ascribed to the flexible idea of veins and their immense distensibility. This elastic property of veins was first perceived by Young (1968). Further, Rubinow and Keller (1972) exhibited that the scope of the tube could be controlled by the strain in the dividers and the transmural weight contrast by accepting that the Poiseuille law holds locally. Consequently, there is a necessity for the subjective speculation of blood flow through tubes which are elastic. The stream designs acquired by the models with rigid tube can't clarify the flow of blood in narrow arteries completely. Henceforth, it becomes important to consider the elasticity in the present model.

To the best of authors knowledge, no attempts have been made in the literature to investigate the role of slip, heat transfer and inclination on peristaltic transport of Jeffery fluid in an axisymmetric elastic tube with porous walls. The present investigation is helpful in filling the gap in this direction. The resulting equations are solved analytically under the appropriate slip boundary conditions. The influence of amplitude ratio, Darcy number, slip parameter and elastic parameters on flux are represented graphically. The outcomes of the present model help in understanding the complex physiological response of blood in the circumstances mentioned above, which intern helps medical people to investigate the blood flow in arteries much better way than the earlier and also, helps in modeling the heart-lung and dialysis machines.

BASIC EQUATIONS

The constitutive equation for an incompressible Jeffery fluid are

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

$$\bar{S} = \frac{\mu}{1+\lambda_1}\left(\dot{\gamma} + \lambda_2 \ddot{\gamma}\right) \quad (1)$$

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

FORMULATION AND CLOSED FORM SOLUIONS

The flow of a blood is modelled to be laminar, steady, incompressible, two-dimensional, fully-developed, axisymmetric and exhibiting peristalsis in an elastic tube with porous walls (Fig. 1). The fluid is characterized by the Jeffery model and facilitates the choice of the cylindrical coordinate system to study the problem. The wall deformation due to the propagation of an infinite sinusoidal wave train of peristaltic waves is represented by

$$h(\mathrm{z},\mathrm{t}) = a + b\sin\left[\frac{2\pi}{\lambda}(z-t)\right]. \quad (2)$$

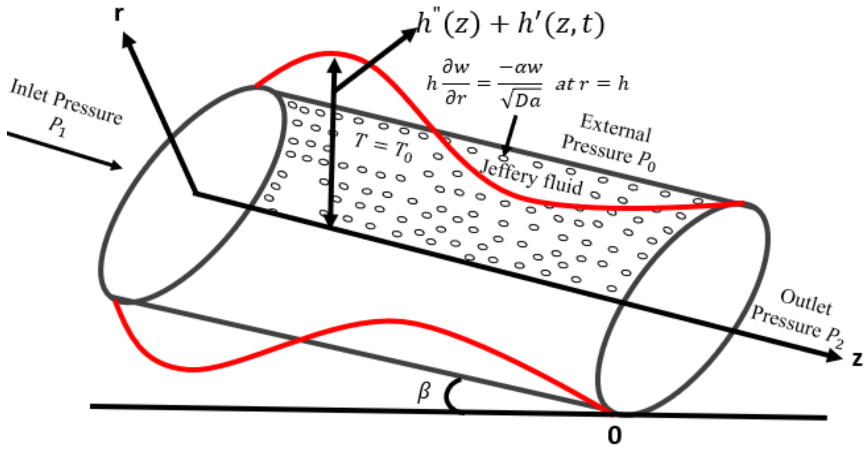

Fig. 1. Geometrical representation of Peristaltic waves in an elastic tube.

The pressure p remains constant at any axial station of the tube under the assumption of long wavelength approximation. Using the following nondimensional variables

$$\bar{r}=\frac{r}{h'},\ \bar{z}=\frac{z}{\lambda},\ \bar{t}=\frac{ct}{\lambda},\ \overline{\tau_{rz}}=\frac{\tau_{rz}}{\mu\left(\frac{c}{h'}\right)},\ \bar{p}=\frac{ph'}{\lambda c\mu},\ \varepsilon=\frac{b}{a},\ \Pr=\frac{\mu c_p}{k},\ \bar{u}=\frac{u}{c},$$

$$\bar{w}=\frac{w}{c},\ \theta=\frac{T-T_0}{T_0},\ Ec=\frac{c^2}{c_pT_0},\ Br=Ec\times\Pr,\ \delta=\frac{a}{\lambda},\ \ \mathrm{Re}=\frac{\rho ca}{\mu},F_1=\frac{\mu c}{\rho g a^2}. \tag{3}$$

The non-dimensional equations of motion and energy in the wave frame of reference, moving with speed *c*, under the lubrication approach (Nadeem and Akbar 2009) is as follows:

$$\mathrm{Re}\,\delta\left(u\frac{\partial}{\partial r}+w\frac{\partial}{\partial z}\right)w=-\frac{\partial p}{\partial z}+\frac{1}{r}\frac{\partial}{\partial r}(r\tau_{rz})+\delta\frac{\partial}{\partial r}(\tau_{zz}) \tag{4}$$

$$\mathrm{Re}\,\delta^3\left(u\frac{\partial}{\partial r}+w\frac{\partial}{\partial z}\right)u=-\frac{\partial p}{\partial r}+\frac{\delta}{r}\frac{\partial}{\partial r}(r\tau_{rr})+\delta^2\frac{\partial}{\partial r}(\tau_{rz}) \tag{5}$$

$$\mathrm{Re}\,\delta\Pr\left(u\frac{\partial}{\partial r}+w\frac{\partial}{\partial z}\right)\theta=Br\left(\delta\frac{\partial u}{\partial r}\tau_{rr}+\frac{\partial w}{\partial r}\tau_{rz}+\delta^2\frac{\partial u}{\partial r}\tau_{zr}+\tau_{zz}\frac{\partial w}{\partial r}\delta\right)+\frac{\partial^2\theta}{\partial r^2}+\frac{1}{r}\frac{\partial\theta}{\partial r}+\delta^2\frac{\partial^2\theta}{\partial z^2} \tag{6}$$

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, Br is the Brinkmann number, r is radial coordinate, τ_{rr} is shear stress in radial coordinates τ_{zr} is shear stress in axial and radial coordinates, τ_{zz} is shear stress in axial coordinate and τ_{rz} is the shear stress along radial and axial coordinates.

Under the assumption of long wavelength $\delta << 1$ and small Reynolds number, Eqs. (4) - (6) takes the form

$$\frac{1}{r}\frac{\partial}{\partial r}(r\tau\ )=-\frac{\partial p}{\partial z}+\frac{\sin\beta}{F_1} \tag{7}$$

$$0=\frac{\partial p}{\partial r} \tag{8}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \theta}{\partial r}\right)=Br\left(-\frac{\partial w}{\partial r}\tau\right) \tag{9}$$

The constitutive equation for Jeffery fluid in the non-dimensional form is given by

$$\tau=\frac{1}{1+\lambda_1}\left(-\frac{\partial w}{\partial r}\right) \tag{10}$$

The corresponding non-dimensional boundary conditions are

$$h\frac{\partial w}{\partial r}=\frac{-\alpha w}{\sqrt{Da}},\ \theta+\phi\frac{\partial \theta}{\partial r}=0 \text{ at } r=h \tag{11}$$

$$\frac{\partial \theta}{\partial r}=0,\ \tau_{rz} \text{ is finite at } r=0. \tag{12}$$

Equation (11) corresponds to the velocity and thermal slip condition (Saffman, 1971). Further, Da is the porous parameter (Darcy number), α is the velocity slip parameter, ϕ is the thermal slip parameter and θ is the temperature.

The closed form solutions are obtained for the velocity expression (7) and (8) satisfying the boundary conditions (11) and (12), we obtain the velocity as

$$w=\frac{(1+\lambda_1)(P+f)}{4}\left[h^2-r^2+\frac{2h^2\sqrt{Da}}{\alpha}\right] \tag{13}$$

where $P=-\frac{\partial p}{\partial z}$.

Using equation (9) together with the boundary conditions (11) and (12), we obtain an expression for temperature as

$$\theta=\frac{Br(P+f)^2(1+\lambda_1)}{64}\left\{r^4-h^3(4\phi+1)\right\} \tag{14}$$

The instantaneous flow rate Q across any cross section of the artery is defined as:

$$Q=2\int_0^h w\,r\,\mathrm{dr}$$

$$Q=\frac{(1+\lambda_1)(P+f)h^4}{8}\left[1+\frac{4\sqrt{Da}}{\alpha}\right] \tag{15}$$

It is noticed that when $Da=0$, the solutions of Sumalatha and Sreenadh is recovered as a special case of our problem.

THORETICAL DETERMINATION OF FLUX AND APPLICATION TO FLOW THROUGH AN ARTERY

A theoretical calculation of the flux Q is carried out for an incompressible Jeffery fluid through an elastic tube of radius $h(z,t)=h'(z,t)+h''(z)$. The fluid is assumed to enter the tube with a pressure p_1 and leave the tube with pressure p_2, while the pressure outside the tube is p_0. If z denotes the distance along the tube from the inlet end, then the pressure $p(z)$ in the fluid at z diminishes from $p(0)=p_1$ to $p(\lambda)=p_2$. The tube may contract or expand due to the difference in pressure of the fluid $p(z)-p_0$. Subsequently, the cross section of the tube may have a deformation due to the elastic property of the walls. Thus, the difference in pressure influences the conductivity σ_1 of the tube at z. We consider the conductivity $\sigma_1=\sigma_1[p(z)-p_0]$ to be a known function of the pressure difference $(p(z)-p_0)$. This conductivity is assumed to be the same as that of a uniform tube having an identical cross section at z. The relation between Q and the pressure gradient is given by

$$Q=\sigma_1(p-p_0)(P+f) \tag{16}$$

Under the considerations of peristaltic motion and the elastic property of the tube wall, equation (16) can be written as,

$$\sigma_1(p-p_0)=\frac{F}{8}(h'+h'')^4 \tag{17}$$

where $F=(1+\lambda_1)\left[1+\frac{4\sqrt{Da}}{\alpha}\right]$ and h'' is the change in radius of the tube due to elasticity and is a function of pressure $p-p_0$ at each cross section due to the Poiseuille flow *i.e.*, $[h''(p-p_0)]$. Equation (16) with the inlet condition $p(0)=p_1$ gives

$$Qz = \int_{p(z)-p_0}^{p_1-p_0}\sigma_1(p')\,dp'+\int_0^1\frac{F}{8}f(h'+h'')^4dz \tag{18}$$

where $p'=p(z)-p_0$. This equation gives $p(z)$ in terms of z and Q. Setting $z=1$ and $p(1)=p_2$ in equation (18), we get Q as,

$$Q=\int_{p_2-p_0}^{p_1-p_0}\sigma_1(p')\,dp'+\int_0^1\frac{F}{8}f(h'+h'')^4dz \tag{19}$$

Now, using equation (17) in equation (19), we have

$$Q=\frac{F}{8}\left[\int_{p_2-p_0}^{p_1-p_0}(h'+h'')^4\,dp'+f(h'+h'')^4\right] \tag{20}$$

Equation (20) can be solved if we explicitly know the function $h''(p-p_0)$. If h'' is known as a function of the tension $T(h'')$ or stress, then $h''(p')$ can be determined from the equilibrium condition (Rubinow and Keller, 1972) given by

$$\frac{T(h'')}{h''}=p-p_0. \tag{21}$$

Rubinow and Keller (1972) carried out experimental investigations by controlling static pressure volume connection of a 4-cm long piece of a human iliac artery and gave an expression for tension in an elastic tube as:

$$T(h'')=t_1(h''-1)+t_2(h''-1)^5. \tag{22}$$

Using equation (22) with $t_1=13$ and $t_2=300$, equation (20) takes the following form

$$dp'=\left[\frac{t_1}{h''^2}+t_2\left(4h''^3-15h''^2+20h''-10+\frac{1}{h''^2}\right)\right]dh''. \tag{23}$$

Using equation (23), equation (20) can be written as

$$Q=\frac{F}{8}\left[\int_{p_2-p_0}^{p_1-p_0}(h'+h'')\left\{\frac{t_1}{h''^2}+t_2\left(4h''^3-15h''^2+20h''-10+\frac{1}{h''^2}\right)\right\}dh''+f(h'+h'')^4\right] \tag{24}$$

Letting $p=p_1$ and $p=p_2$ in equation (21) the solutions are obtained for h_1'' and h_2'' respectively.

Equation (24) can be rewritten as

$$Q=\frac{F}{8}\left[\left(g(h_1'')-g(h_2'')\right)+f\,h_2''^4\right], \tag{25}$$

Where,

$$g(h)=t_1\left(\frac{h''^3}{3}+2h'h''+6h'^2h''+4h'^3\log\log h''-\frac{h'^4}{h''}\right)+t_2\left(\frac{h''^8}{2}+\frac{h''^7}{7}(16h'-15)\right.$$
$$+\frac{h''^2}{2}\left(20h'^4-40h'^3+4h'\right)+\frac{h''^5}{5}\left(16h'^3-90h'^2+80h'-10\right)+\frac{h''^6}{6}\left(24h'^2-60h'+20\right)$$
$$+\frac{h''^3}{3}\left(-15h'^4+80h'^3-60h'^2+1\right)+\frac{h''^4}{4}\left(4h'^4-60h'^3+120h'^2-40h'\right)$$
$$\left.+h''\left(-10h'^4+6h'^2\right)+4h'^3\log\log h''-\frac{h'^4}{h''}\right). \tag{26}$$

RESULTS AND DISCUSSION

The present paper emphasizes on the combined effects of slip and heat transfer on peristaltic transport of Jeffery fluid in an inclined elastic tube with porous walls. The effects of various physiological parameters such as Jeffery parameter (λ_1), angle of inclination (β), porous parameter (Da), velocity slip parameter (α), amplitude ratio (ε), elastic parameters (t_1,t_2), inlet and outlet elastic radius (h_1'',h_2''), Eckert number (Ec), thermal slip parameter (ϕ) and Prandtl number $(\Pr)$ on volumetric flow rate (Q) and temperature (θ) are analyzed. MATLAB programming is used to plot the effects of physiological parameters and the results are portrayed in Figures 2-4.

Figure 2(a) depicts the variation of λ_1 on Q. It is observed from the figure that an increase in the values of λ_1 enhances Q in an elastic tube. Vajravelu et al. (2014). Figure 2(b) shows the variation of Da on Q. It is noticed that an increase in the values of Da increases Q. The influence of α on Q show the opposite behavior as that of Da (Figure 2(c)). Figure 2(d) portrays the variation of β on Q. It is found that an increase in β slightly increases the Q. The variation of ε on Q is illustrated in Figure 2(e). It is clear from the figure that an increase in the value of ε increases Q. Figures 3(a) and 3(b) drawn to study the effects of t_1 and t_2 on Q respectively. We see from these figures that an increase in the values of t_1 and t_2 enhances the Q. Further, the variation of inlet and outlet elastic radius $h_1^{''}$ and $h_2^{''}$ on Q are plotted in Figures 3(c) and 3(d). For a fixed value of $h_2^{''}$, the effect of increasing values of $h_1^{''}$ makes Q to decrease (Figure 3(c)). However, the opposite behavior is observed when we fix $h_1^{''}$ and vary $h_2^{''}$ (Figure 3(d)).

Temperature profile is plotted for Equation (14) to study the effects of $\lambda_1, Da, \varepsilon, \phi$ and Br. In general, about the central region, these profiles exhibit the cross-flow behavior and exhibit the dual behavior with the increase in the pertinent parameters. Further, when $r \le 1.4$ or $r \le 1.5$, that is about 1.4 and 1.5, the cross-flow behavior is observed. From Figures 4(a) and 4(b) it is clear that an increase in the value of λ_1 and Da decreases the magnitude of temperature in the region $0 \le r \le 1.5$ and the opposite behavior is observed near the walls of the tube $(1.5 \le r \le 2)$. Figure 4(c) illustrate the variation of ε on temperature. It is found that, the magnitude of temperature decreases in the region $0 \le r \le 1.3$ and it increases in the region $1.3 \le r \le 2$. The variation of ϕ on temperature is plotted in Figure 4(d). It is observed that an increase in the value of ϕ increases the magnitude of temperature in an elastic tube. Figure 4(e) shows the effect of Br on temperature. Here an increment in $Br\,(Ec \times \Pr)$ enhances the temperature. This is because, Ec occurs due to the viscous dissipation effects and it therefore enhances the temperature. Further, an increase in the value of $\Pr$ decreases the value of thermal conductivity and thereby it increases the temperature.

CONCLUSIONS

The present study explains the influence of slip velocity and heat transfer on peristaltic flow of Jeffery fluid in an inclined elastic tube with porous walls. Also, from the current model one can deduce the results of a Newtonian model by taking $\lambda_1 = 0$. The present study provides a satisfactory outcome that represents some of the natural phenomena, especially, the flow of blood in narrow arteries which can be handled and processed in case of dysfunction. The conclusions can be summarized as follows:

- The flow rate in an incline elastic tube increases with an increase in the porous parameter, and it decreases with an increase in the slip parameter
- The influence of Jeffery parameter and angle of inclination enhances the flow rate.
- The effects of elastic parameters, outlet elastic radius and amplitude ratio increases the flow rate while inlet elastic parameter decreases the flow rate.
- The temperature in the porous tube increases with an increase in the values of thermal slip parameter and Brinkmann number.
- The effects of a porous parameter, velocity slip parameter, and thermal slip parameter play a significant role in controlling the flow rate and temperature of the Jeffery fluid in an inclined elastic tube with porous walls.

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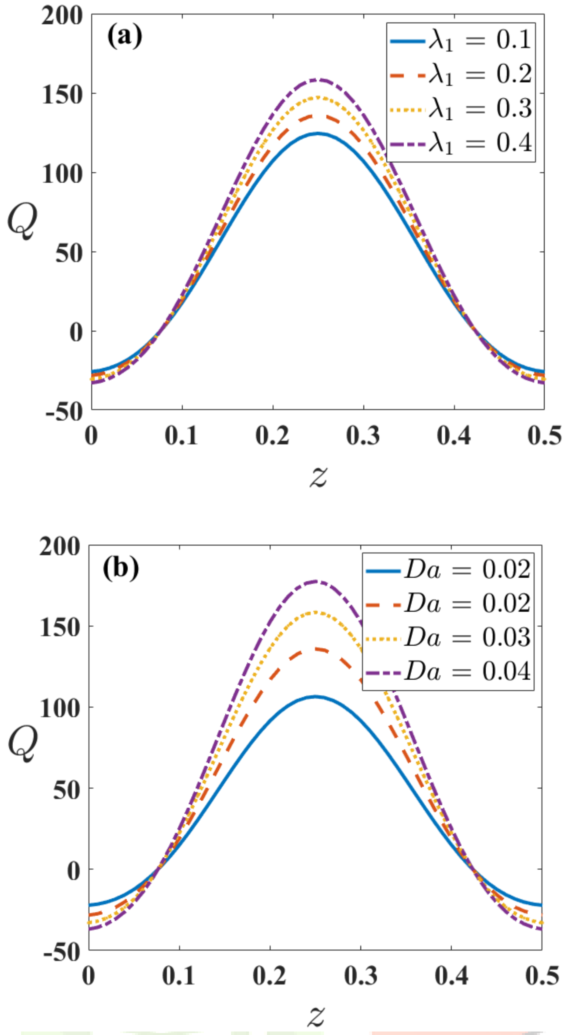

(a)
λ1 = 0.1
λ1 = 0.2
λ1 = 0.3
λ1 = 0.4
Q
z
(b)
Da = 0.02
Da = 0.02
Da = 0.03
Da = 0.04
Q
z

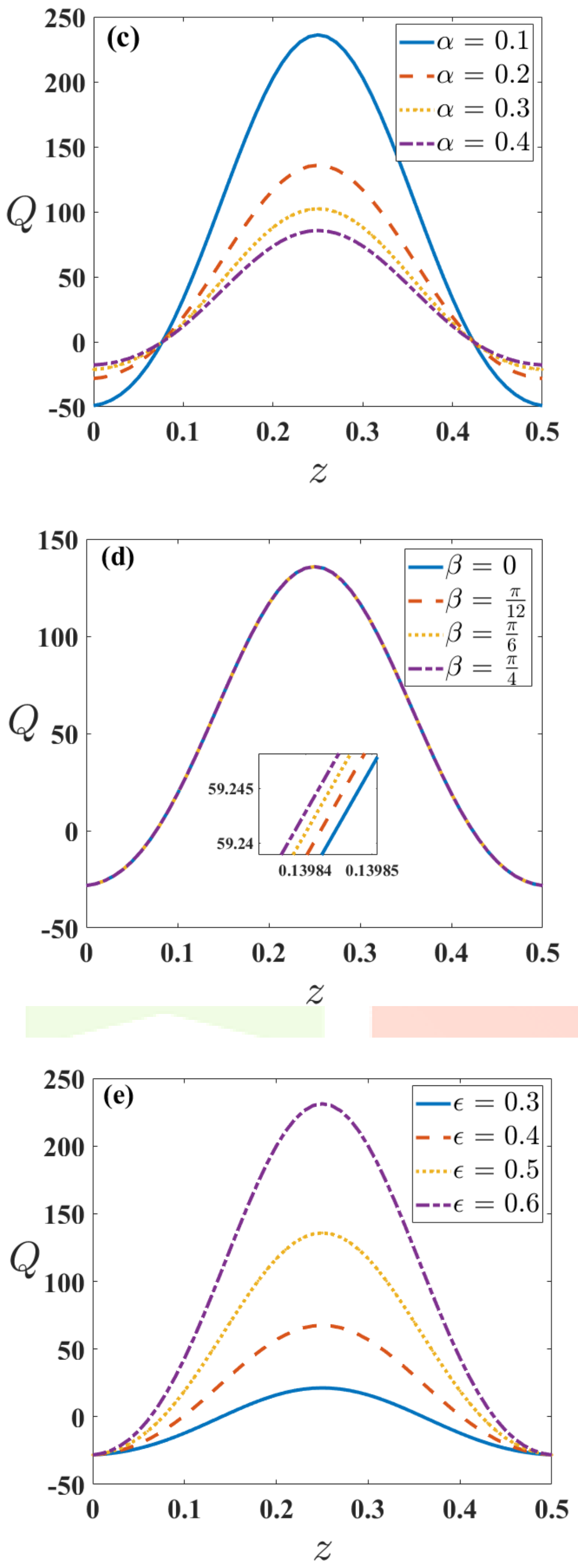
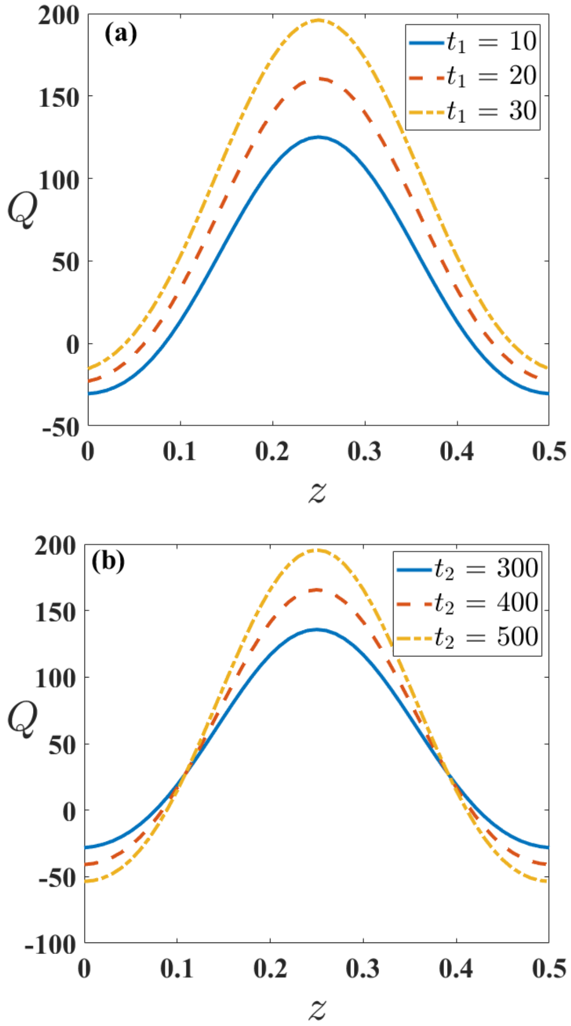


Figure 2. Q **versus** z **for varying (a) Jeffery parameter** (λ_1)**, (b) porous parameter** (Da)**, (c) velocity slip parameter** (α)**, (d) angle of inclination** (β) **and (e) amplitude ration** (ε)**.**


(a)
$t_1 = 10$
$t_1 = 20$
$t_1 = 30$
Q
z
(b)
$t_2 = 300$
$t_2 = 400$
$t_2 = 500$
Q
z

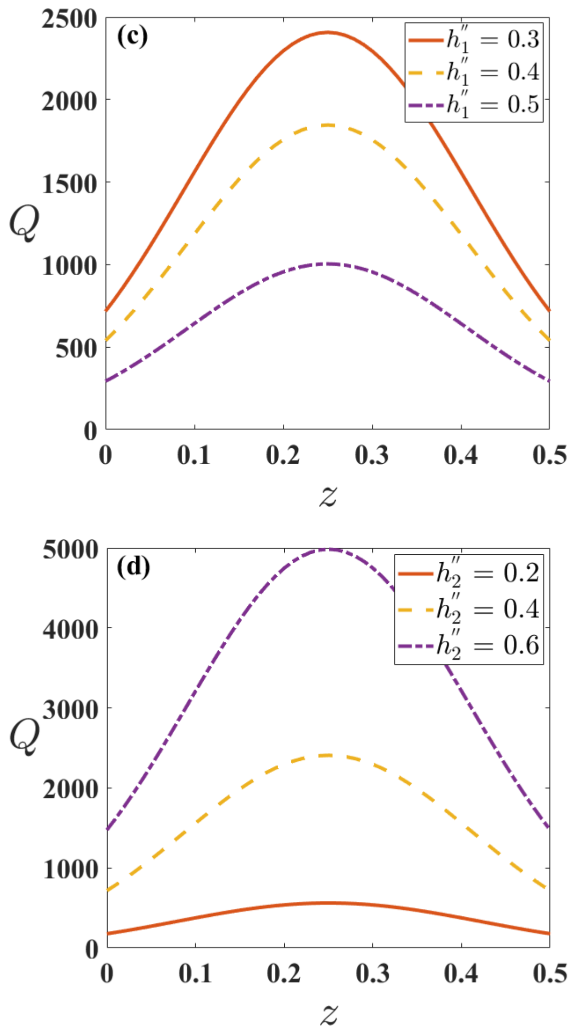
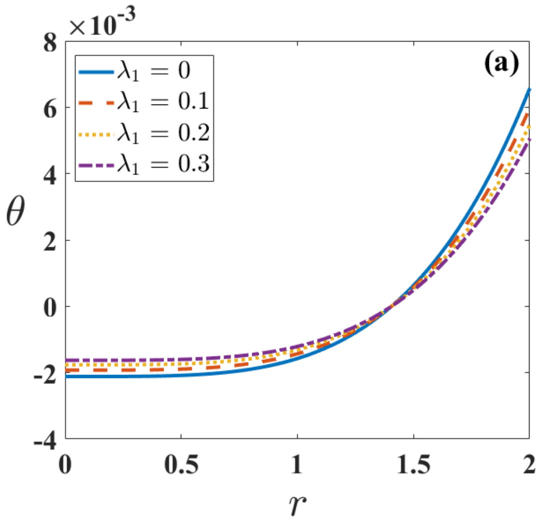
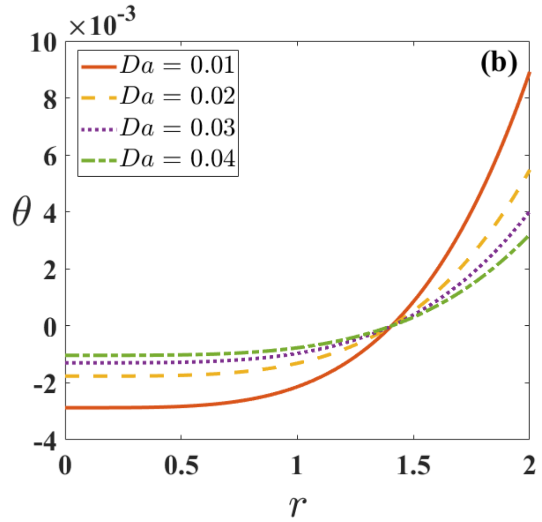


Figure 3. Q **versus** z **for varying (a) elastic parameter** (t_1)**, (b) elastic parameter** (t_2)**, (c) inlet elastic radius** (h_1'') **and (d) outlet elastic radius** (h_2'')



×10-3
(a)
λ1 = 0
λ1 = 0.1
λ1 = 0.2
λ1 = 0.3
θ
r



×10-3
(b)
Da = 0.01
Da = 0.02
Da = 0.03
Da = 0.04
θ
r

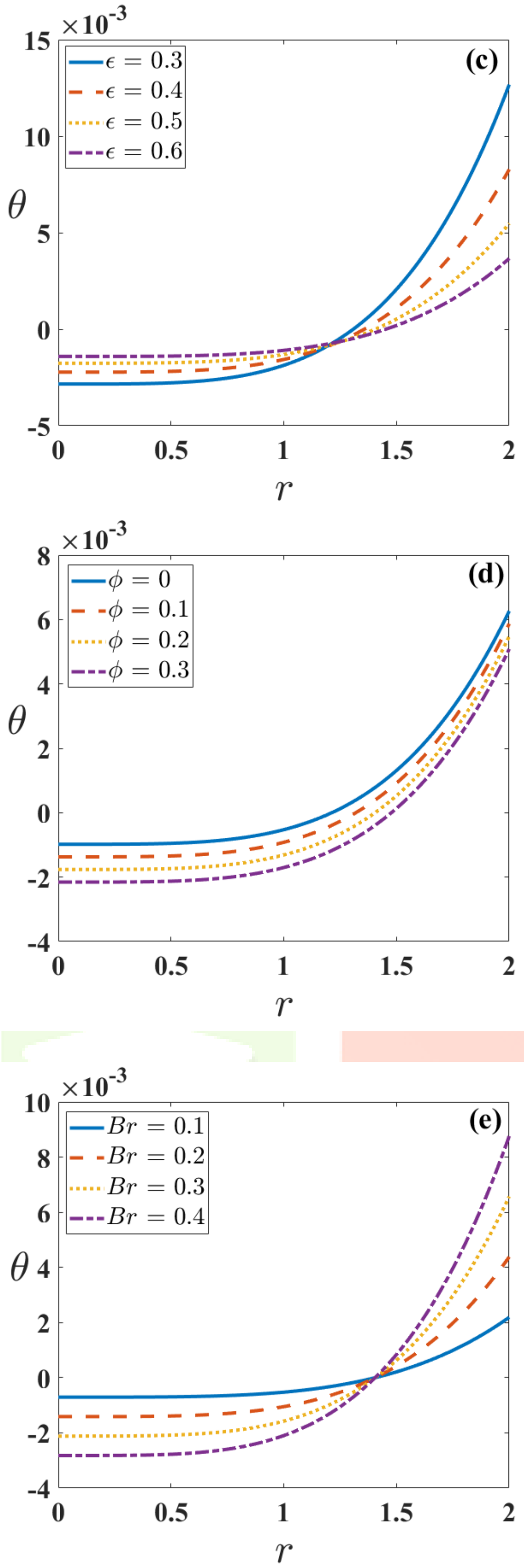


Figure 4. θ **versus** r **for varying (a) Jeffery parameter** (λ_1)**, (b) Porous parameter** (Da)**, (c) amplitude ratio** (ε)**, (d) thermal slip parameter** (ϕ) **and (e) Brinkmann number** (Br).