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JEFFREY FLUID FLOW DRIVEN BY PERISTALTIC PUMPING WITH NANOPARTICLES IN AN INCLINED TUBE

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Abstract:

The present paper is envisioned for exploring the mathematical model for Jeffrey model fluid with nanoparticle in an inclined tube propagated by peristalsis. The governing two-dimensional equations illustrating the fluid flow are first transformed to make dimensionless and then the exact results were obtained. Small, wave number and Reynolds number approximations are used. Expressions for temperature, concentration, velocity, average flux, pressure drop, coefficient of heat and mass transfer are computed. Streamlines are plotted against pertinent parameters. Also computed streamlines plots to illustrate trapping phenomenon and bolus dynamics to characterize peristaltic propulsion. This paper focuses on presenting the broad range of applications that involve nanofluids, emphasizing their improved heat transfer properties that are controllable. These nanofluids have unique properties that make them suitable for such applications. Applications of the study include peristaltic micropumps and novel drug delivery systems in pharmacological engineering.

Keywords: Jeffrey fluid, nano particles, peristalsis, HPM method

NOMENCLATURE

a'	radius of uniform cross section (m)
b'	Wave amplitude (m)
c'	Speed of the wave (m/s)
N_b	Brownian motion parameter
N_{t}-	Thermophoresis parameter
p	Pressure in wave (N/m^2)
P	Pressure in fixed frame
B_r	local nanoparticle Grashof number
G_r	local temperature Grashof number
F	Frictional Force (N)
r	Radial coordinate
t	Time (s)
U, W	Velocity components in the laboratory frame (m/s)
u, w	Velocity components in the wave frame (m/s)

Greek symbols

μ	Coefficient of viscosity (Nsm^{-2})
λ^*	Wavelength (m)
τ	Cauchy stress tensor
λ'	Ratio of relaxation to retardation
λ''	Retardation time (m/s²)
γ	Shear rate
θ^*	Temperature (K)
σ^*	Concentration
α	Inclined angle

1. Introduction

In recent times many investigators have concentrated on non-Newtonian fluid models owing to its vast applications in engineering and industries to study the thermo-physical properties of various parameter to augment the heat transmission properties of these liquids. For the investigation of diverse rheological possessions several researchers studied various non-Newtonian model fluids, Jeffrey fluid is one among them. Hayat et al (2007) stood first to study the Jeffrey model fluid in a circular tube. Shehzad et al (2015) discussed the mixed convection 3-D flow of Jeffrey model over a surface, effects of radiation and thermophoresis are also considered. Nisar et al., (2020) analyzed buoyancy impact on Jeffrey model fluid over

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a sheet incidence of heat source/absorption parameter. In recent times, Sivaiah et al., (2019) considered the two-fluid peristaltic pumping of Jeffrey model with a Newtonian model in a perpendicular conduit.

It is acknowledged that peristaltic pumping can be produced by the circulation of waves along the stretchy ramparts of a conduit. The peristaltic transport of viscous and non-Newtonian model fluid is of substantial significance from the physiology and engineering points of view. In biomedical sciences, it is found in the narrowing of smooth muscles to drive contents over the digestive tract. These movements happen in urine passage from kidney to bladder, conveyance of food grains and liquid mixture in the esophagus. Since the initiation made by Latham (1966), several researchers (Radhakrishnamacharya and Murthy, 1993, Raju, Maruthi Prasad, et al.,) committed to examine peristaltic pumping using mathematical, investigative approaches.

Munawwar Ali et al., (2019) e studied non-uniform hemodynamic nanofluid flow in the presence of an external magnetic field Hayat et al., (2021) studied magnetohydrodynamic (MHD) flow of unsteady Jeffrey nanofluid due to vertical stretchable cylinder. Subadra et al., (2021) focused on the effect of slip on a Jefferey fluid flow with nanoparticles in an inclined tube. Hayat et al., (2017) examined magnetohydrodynamic (MHD) flow of Jeffrey nanofluid due to a nonlinear stretching surface. Haroon Ur Rasheed et al., (2021) e investigates unsteady magnetohydrodynamic (MHD) mixed convective and thermally radiative Jeffrey nanofluid flow in view of a vertical stretchable cylinder.

Research in the area of nanofluids have acknowledged a lot of consideration for the past few decades. Nanofluid dynamics is a branch of nano-science that concerned to study concentration, and transportation of energy of nanoparticle in base liquids. Nanofluid technology was first introduced by Choi (1995). A complete study of nanofluids was discoursed by Buongiorno (2006). Peristaltic transport of nanofluid in vertical annulus is discussed in the paper. Experimental heat transfer coefficients are described for unadulterated water and water Alumina mix in fully turbulent situations in the article by Peyghambarzadeh (2011). Effect of space on peristaltic transport have been observed, study is intended for flow of nano fluid through eccentric conduits by Sohail Nadeem (2014). Peristaltic motion of nanofluid through inclined tube is examined by K. Maruthi Prasad et al., (2015). Effect of Hall and Ohmic heat on peristaltic motion of Cu-Water nano fluid in the incidence of magnetic field is examined theoretically which can be applied in drug delivery mechanism by F.M. Abbasi et al., (2015). Peristaltic motion of nano particles of a micropolar fluid in an inclined conduit investigated. The effect of convective conditions for peristaltic pumping of pseudoplastic nanofluid studied by Hayat et a., (2016) adopting a mathematical model. Impact of thermal radiation and heat source on micropolar nanofluid flow in asymmetric conduit is investigated by Mohamed Abou-zeid, (2016). Nanofluid flow with interaction of transfer of heat and shape factor in a flexible tube with viscosity modification reported in the article. Peristaltic movement of couple-stress model with the effect of transfer of heat and mass studied theoretically by K Maruthi Prasad et al., (2017).

In the current study, our concern is to examine peristaltic pumping of Jeffrey model with nanoparticles in an inclined tube. The flow patterns are studied under lubricant approximations. The expressions for temperature and concentrations are constructed by Homotopy Perturbation Method (HPM). Solutions for velocity, frictional force and pressure drop are attained analytically. Impact of appropriate parameters on flow variables of interest are perceived and discussed.

2. Mathematical Formulation

A two-dimensional peristaltic propulsion of an incompressible Jeffrey model in an inclined tube is examined. The motion of fluid is due to sinusoidal wave train is specified by choosing the cylindrical polar coordinate system (R, θ, z)

$$R = H(z,t) = b' \sin\frac{2\pi}{\lambda^*}(z - c't) + a' \tag{1}$$

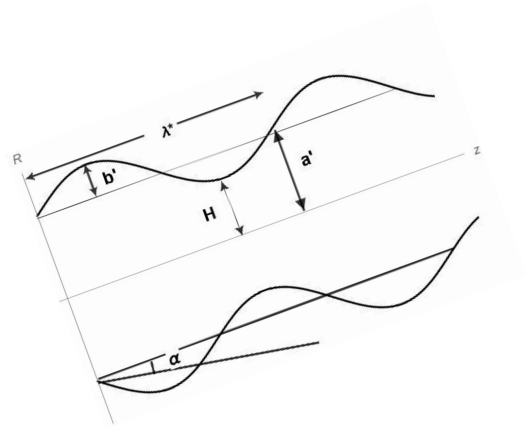

Fig.1: Geometry of the problem.

The equation governing for the extra stress tensor τ for Jeffrey model is

$$\tau = \frac{\mu}{1+\lambda'}\left(\frac{d\gamma}{dt} + \lambda'' \frac{d^2\gamma}{dt^2}\right) \tag{2}$$

The following transformations are used to shift to wave frame

$$r = R\,, z = Z - c'\,t, w = W - c', u = U, \theta = \theta$$

Utilizing the above quantities, under lubrication theory assumptions the resulting equations can be written as

$$\frac{\partial p}{\partial r} = 0 \tag{3}$$

$$\frac{1}{1+\lambda'}\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\frac{\partial w}{\partial r}\right) = -\frac{\partial p}{\partial z} + G_r\,\theta^* + B_r\,\sigma^* + \frac{\sin\alpha}{F} \tag{4}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\frac{\partial \theta^*}{\partial r}\right) + N_b\frac{\partial \sigma^*}{\partial r}\frac{\partial \theta^*}{\partial r} + N_t\,\left(\frac{\partial \theta^*}{\partial r}\right)^2 = 0 \tag{5}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\frac{\partial \sigma^*}{\partial r}\right) + \left(\frac{N_t}{N_b}\right)\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\frac{\partial \theta^*}{\partial r}\right) = 0 \tag{6}$$

Boundary conditions are

$$-\frac{\partial w}{\partial r} = 0, \frac{\partial \theta^*}{\partial r} = 0, \frac{\partial \sigma^*}{\partial r} = 0\ at\ r = 0 \tag{7}$$

$$w = -1\ at\ r = h(z) = 1 + \epsilon\,\sin 2\pi z \tag{8}$$

3. Solution of the Problem

To find temperature and concentration expressions, equations (5) and (6) are solved employing Homotopy Perturbation Method.

$$\theta^* = (N_b - N_t)(N_b - 2N_t)\left(\frac{r^6 - h^6}{1152}\right) - (N_b - 2N_t)\left(\frac{r^4 - h^4}{64}\right) \tag{9}$$

$$\sigma^* = -\frac{N_t}{N_b}(N_b - 2N_t)\left(\frac{r^4 - h^4}{64}\right) \tag{10}$$

Considering the expressions (9) and (10) in Equation (4) and on imposing the conditions we get the expression for velocity

$$w = -1 + (1+\lambda')\frac{\partial p}{\partial z}\left(\frac{r^2 - h^2}{4}\right) + (1+\lambda')\frac{\sin\alpha}{F}\left(\frac{r^2 - h^2}{4}\right) - \frac{G_r}{64}(1+\lambda')(N_b - 2N_t)\left(\frac{r^6}{36} - r^2\frac{h^4}{4} + \frac{2}{9}h^6\right) - \frac{G_r}{1152}(1+\lambda')(N_b - N_t)(N_b - 2N_t)\left(\frac{r^8}{64} - r^2\frac{h^6}{4} + \frac{15}{64}h^8\right) - \frac{B_r}{64}(1+\lambda')\left(\frac{N_t}{N_b}\right)(N_b - N_t)\left(\frac{r^6}{36} - r^2\frac{h^4}{4} + \frac{2}{9}h^6\right) \tag{11}$$

In the moving frame, flow rate is specified as

$$q = \int_0^h 2\,r\,w\,dr \tag{12}$$

Substituting Equation (8) in Equation (9) and solving for the flux is

$$q = -h^2 - \frac{(1+\lambda')}{2}\frac{\partial p}{\partial z}\left(-\frac{h^4}{4}\right) + \frac{(1+\lambda')}{2}\frac{\sin\alpha}{F}\left(\frac{-h^4}{4}\right) - \frac{G_r}{32}(1+\lambda')(N_b - 2N_t)\left(\frac{5}{96}\right)h^8 + \frac{G_r}{576}(1+\lambda')(N_b - N_t)(N_b - 2N_t)h^{10}\left(\frac{9}{160}\right) - \frac{Br}{32}(1+\lambda')\left(\frac{N_t}{N_b}\right)(N_b - N_t)\left(\frac{5}{96}\right)h^8 \tag{13}$$

From the above Equation (13), the expression for Pressure gradient

$$\frac{\partial p}{\partial z} = \frac{8}{1+\lambda'}\frac{q}{h^4} + \frac{8}{1+\lambda'}\frac{1}{h^2} + \frac{\sin\alpha}{F} + G_r\,(N_b - 2\,N_t)\,\frac{5}{384}h^4 - G_r(N_b - N_t)\,(N_b - 2\,N_t)\left(\frac{9}{11520}\right)h^6 - B_r\left(\frac{N_t}{N_b}\right)(N_b - N_t)\left(\frac{5}{384}\right)\frac{5}{384}h^4 \tag{14}$$

Integrating Equation (14) in between 0 and 1 and taking negative of it we get the expression pressure drop

$$\Delta P_\lambda = -\int_0^1 \frac{\partial p}{\partial z}\,dz \tag{15}$$

Utilizing expression for $\frac{\partial p}{\partial z}$ in equation (15), it becomes

$$\Delta P_\lambda = q\,L_1 + L_2 \tag{16}$$

Where $L_1 = -\frac{8}{1+\lambda'}\int_0^1 \frac{q}{h^4}\,dz$ and

$$L_2 = -\frac{8}{1+\lambda'}\int_0^1 \frac{1}{h^2}\,dz - \frac{\sin\alpha}{F} + G_r\,(N_b - 2\,N_t)\left(\frac{5}{384}\right)\int_0^1 h^4 dz - G_r(N_b - N_t)\,(N_b - 2\,N_t)\left(\frac{9}{11520}\right)\int_0^1 h^6 dz - B_r\left(\frac{N_t}{N_b}\right)(N_b - N_t)\left(\frac{5}{384}\right)\int_0^1 h^4 dz \tag{17}$$

The time-mean flow rate over a period in laboratory frame $\bar{Q}$ is given as

$$\bar{Q} = 1 + \frac{\epsilon^2}{2} + q \tag{18}$$

From Equation (16) the above equation can be expressed as

$$\bar{Q} = 1 + \frac{\epsilon^2}{2} + \frac{\Delta P_\lambda}{L_1} - \frac{L_2}{L_1} \tag{19}$$

The dimensionless frictional force $\bar{F}$ at the channel wall is

$$\bar{F} = \int_0^1 h^2 \left(-\frac{\partial p}{\partial z}\right) dz \tag{20}$$

Coefficient of Heat Transfer: The heat transfer coefficient at the wall is specified by

$$z_\theta(r, z) = \left(\frac{\partial h}{\partial z}\right)\left(\frac{\partial \theta^*}{\partial r}\right) \tag{21}$$

Coefficient of Mass Transfers: The mass transfer coefficient at the wall is defined by

$$z_\sigma(r, z) = \left(\frac{\partial h}{\partial z}\right)\left(\frac{\partial \sigma^*}{\partial r}\right) \tag{22}$$

4. Graphical Illustrations

Expressions for temperature, concentration, pressure drop, frictional force, time averaged flux, velocity, coefficient of transfer of heat and mass are obtained analytically. Of interest the graphical results of pertinent parameters for $\Delta P_\lambda, \bar{F}, \theta^*, \sigma^*, z_\theta, z_\sigma$ are illustrated through the figures in the following subsections.

4.1 Pressure drop

Figure 2 represent the pressure drop for various values of N_b, N_t, G_r, B_r, λ' and inclined angle(α) against averaged flow rate ($\bar{Q}$). From figure 2(a) and 2(e) it is clear that increasing in N_b and λ' there is adverse response in pressure drop (ΔP_λ). This has inferences in clinical applications, since for maintaining higher pressure gradients, which has an effect is clear significance in drug delivery system. From figures 2(b), 2(c), 2(d), 2(f) we note that ΔP_λ increases for greater magnitude of thermophoresis N_t, G_r, B_r and α.

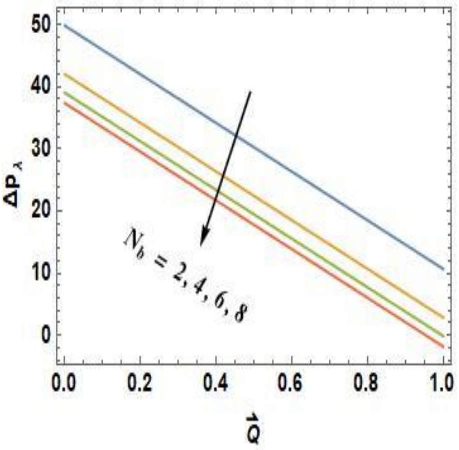

Fig. 2(a): Fluctuations in Pressure Drop For N_b

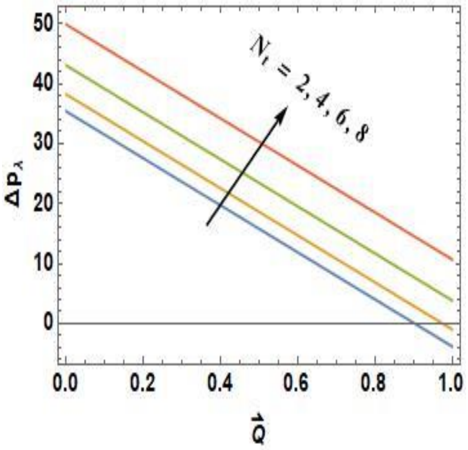

Fig. 2(b): Fluctuations in Pressure Drop For N_t

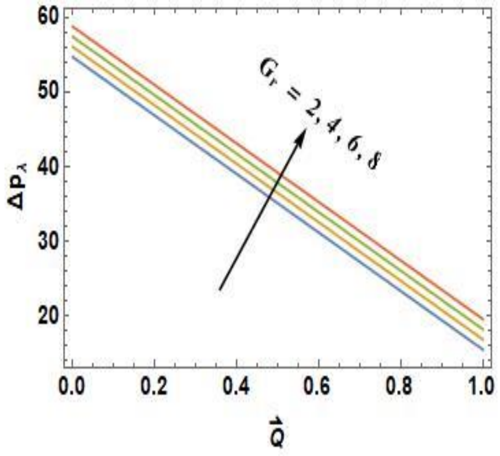

Fig. 2(c): Fluctuations in Pressure Drop For G_r

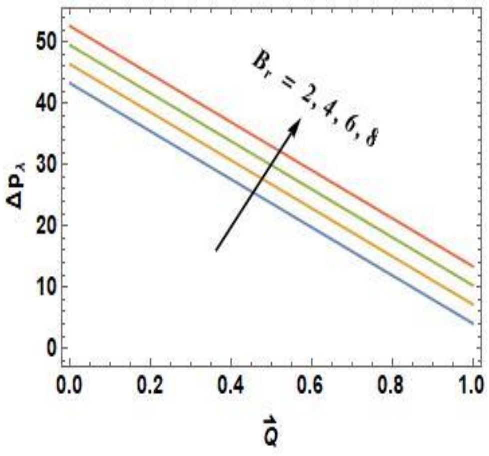

Fig. 2(d): Fluctuations in Pressure Drop For B_r

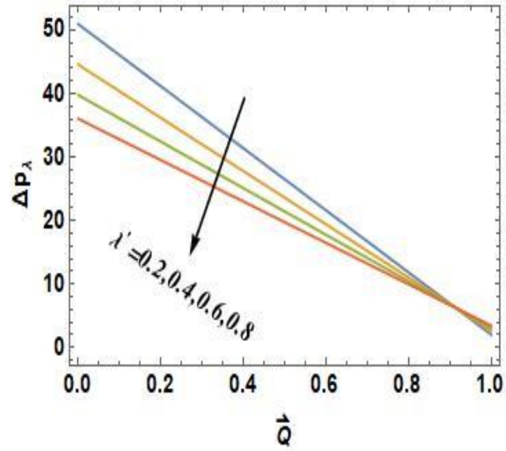

Fig. 2(e): Fluctuations in Pressure Drop For λ'

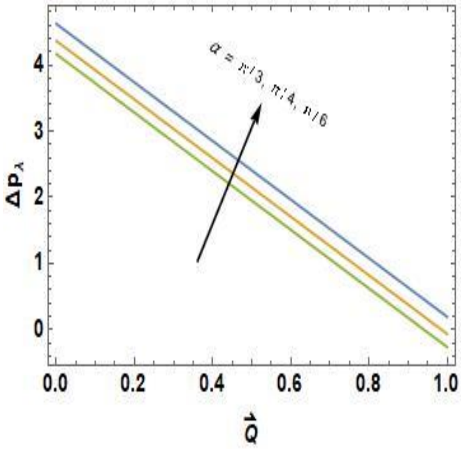

Fig. 2(e): Fluctuations in Pressure Drop For α

4.2 Frictional forces

The effects of N$_b$, N$_t$, G$_r$, B_r, λ' and α on Frictional forces $\bar{F}$ can be depicted from figure 3. It is perceived those frictional forces $\bar{F}$ is upsurged by growing N$_t$, G$_r$, B_r and inclined angle(α).

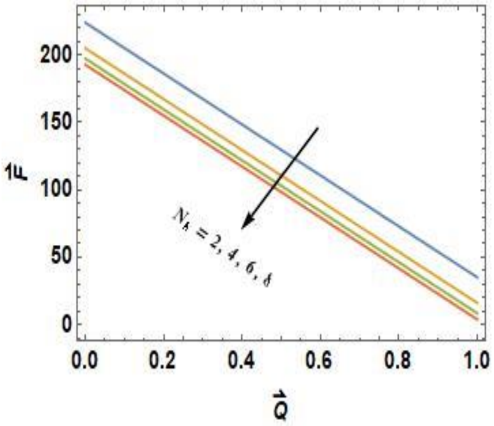

Fig. 3(a): Variations in Frictional Forces against N$_b$

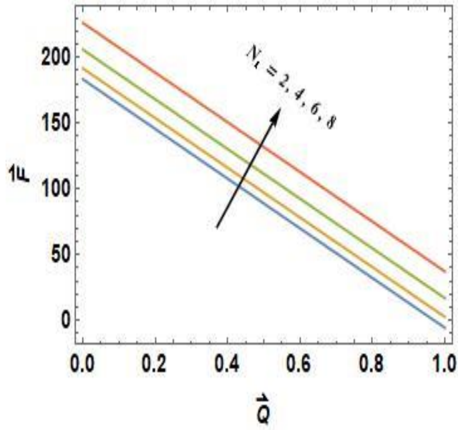

Fig. 3(b): Variations in Frictional Forces against N$_t$

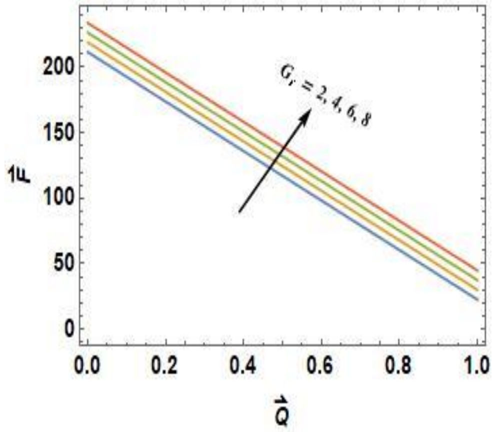

Fig. 3(c): Variations in Frictional Forces against G$_r$

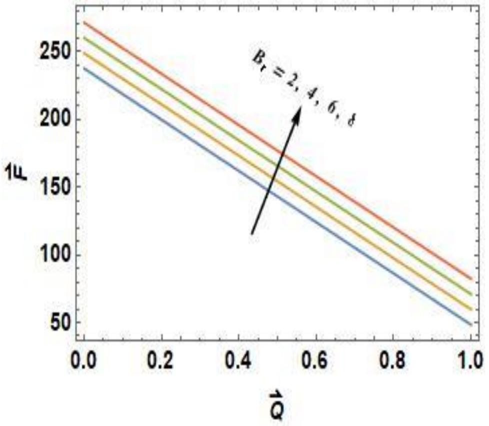

Fig. 3(d): Variations in Frictional Forces against B$_r$

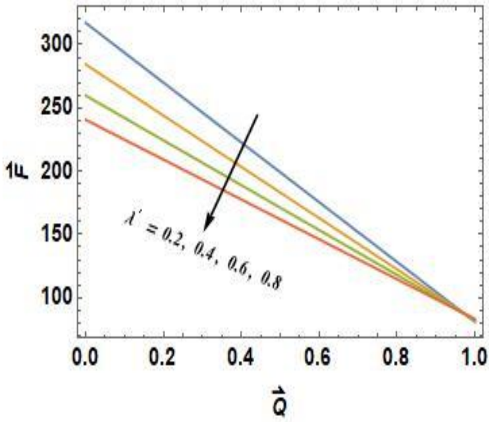

Fig. 3(e): Variations in Frictional Forces against λ'

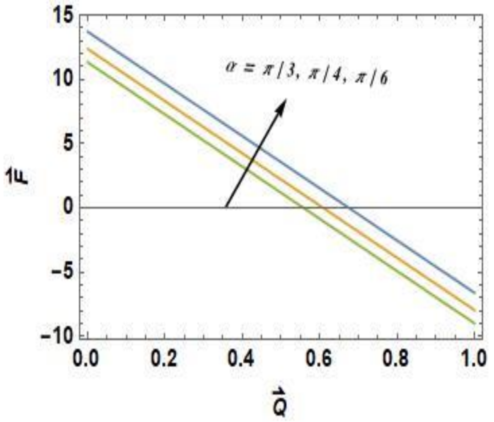

Fig. 3(f): Variations in Frictional Forces against α

4.3 Temperature

Figure 4 represents temperature distribution(θ^*) for Brownian motion (N_b) and thermophoresis (N_t) variations. Significant raise in temperature is sustained as the upsurges in Brownian motion (N_b) and an opposite behaviour is found with thermophoresis.

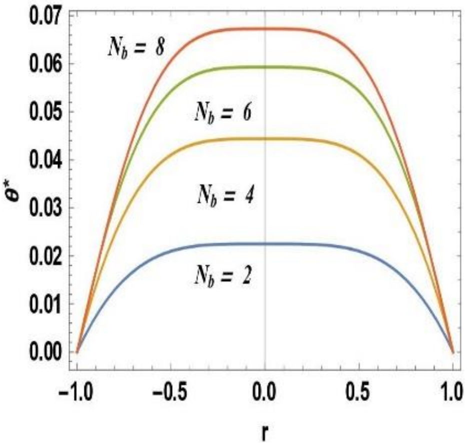

Fig. 4(a): Effect N_b on Temperature

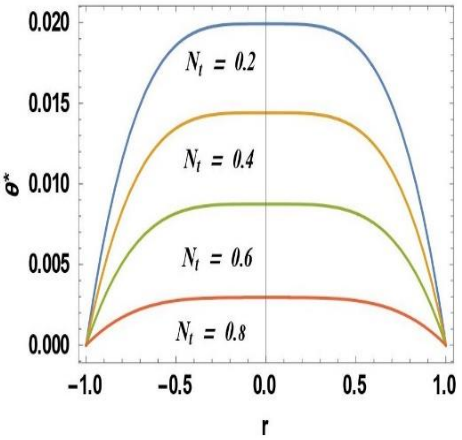

Fig. 4(b): Effect N_t on Temperature

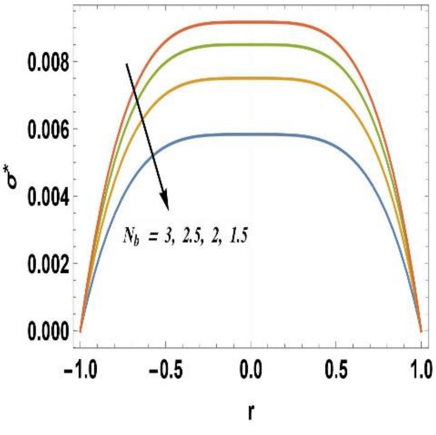

Fig. 5(a): Nanoparticle Phenomenon against N_b

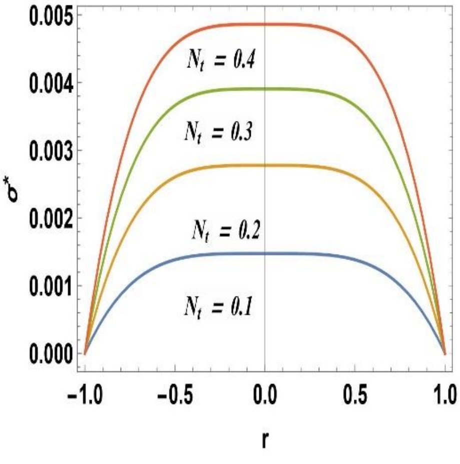

Fig. 5(b): Nanoparticle Phenomenon against N_t

4.4 Concentration

Figure 5 illustrates concentration, σ^*. Figure 5(a) exhibits with a rise in N_b, there is a strong reduction in concentration. Influence of thermophoretic parameter can be depicted from 5(b). From the graph we observe that concentration increases with rising N_t. It can be interpreted that the continuous upsurge in the firmness of thermophoretic effects consequences in bigger mass flux owing to temperature escalation which rises the concentration.

4.5 Heat transfer coefficient

Figure 6 is drawn to examine the effect of N_b, N_t on coefficient of heat transfer. It is interesting to observe absolute value of coefficient of heat transfer is increasing for N_b and N_t. As a significance, the nanoparticle boosts the heat transfer rate.

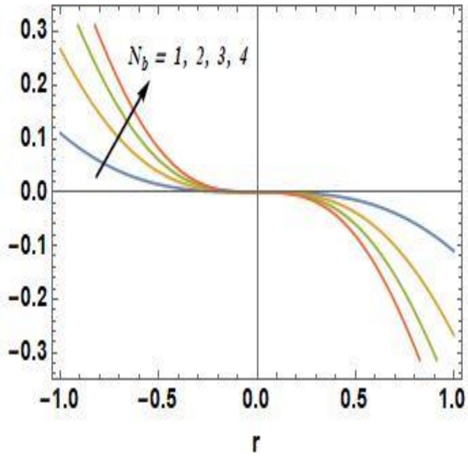

Fig. 6(a): Impact of N_b on Heat Transfer Coefficient

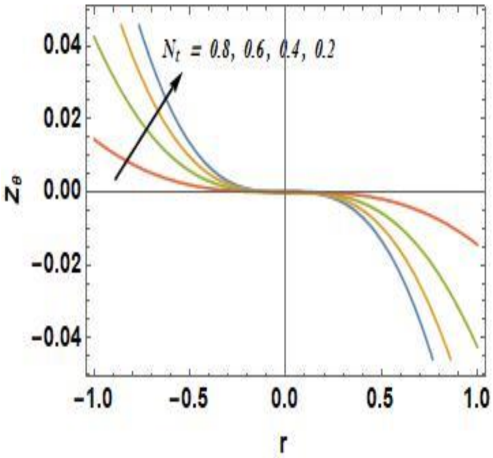

Fig. 6(b): Impact of N_t on Heat Transfer Coefficient

4.6 Mass transfer coefficient

Figure 7 is made to illustrate the effect of the pertinent parameters N_b, N_t. It can be detected that coefficient of mass transfer decreases with increasing magnitude of N_b and increases after getting zero. However, coefficient of mass transfer shows conflicting behavior with respect to N_t.

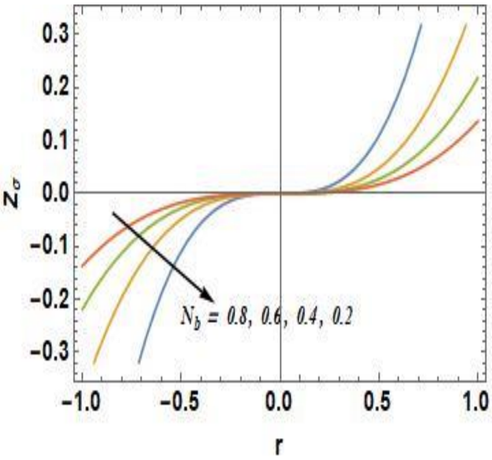

Fig. 7(a): Impact of N_b on Mass Transfer Coefficient

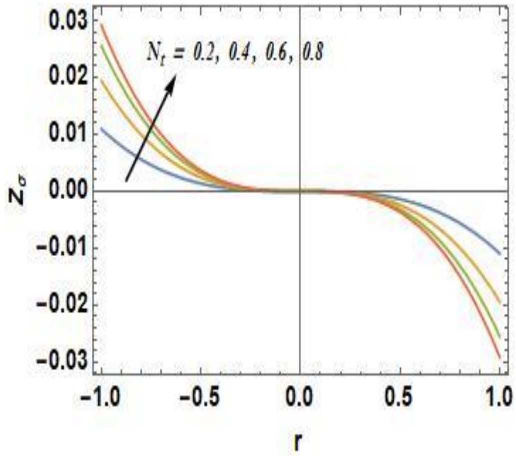

Fig. 7(b): Impact of N_t on Mass Transfer Coefficient

4.8 Trapping

The trapping phenomenon is additional thought-provoking in peristaltic motion. To illustrate the streamlines pattern and trapping phenomenon, Figure 8 is made for varying values of N_b, N_t, G_r, B_r, and λ'. These figures show that the size of the trapped in bolus declines by growing N_b where as it upsurges by N_t, G_r, B_r and λ'.

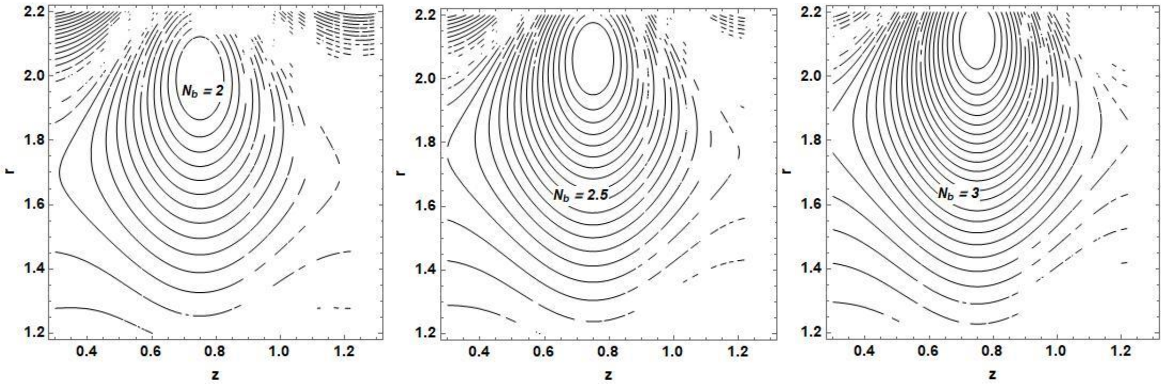

Fig. 8(a): Streamlines for several values of N_b

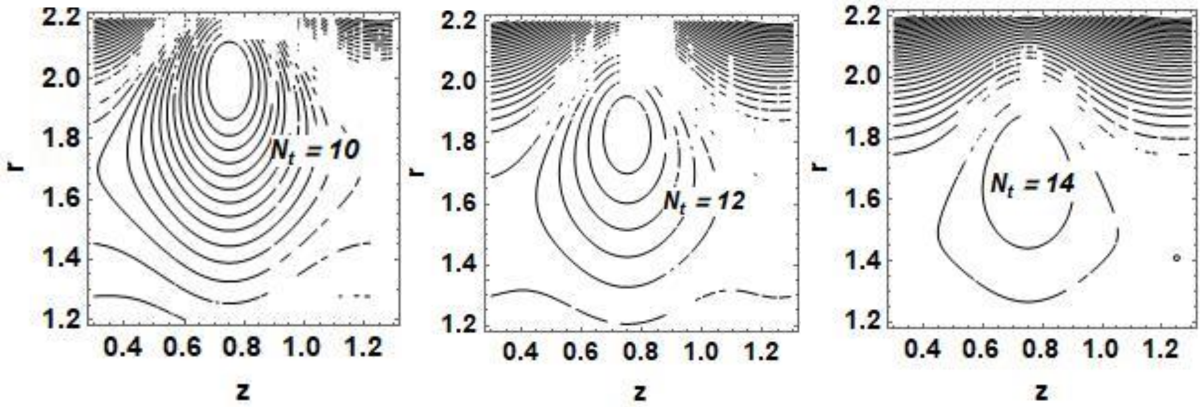

Fig. 8(b): Streamline pattern for several values of N_t

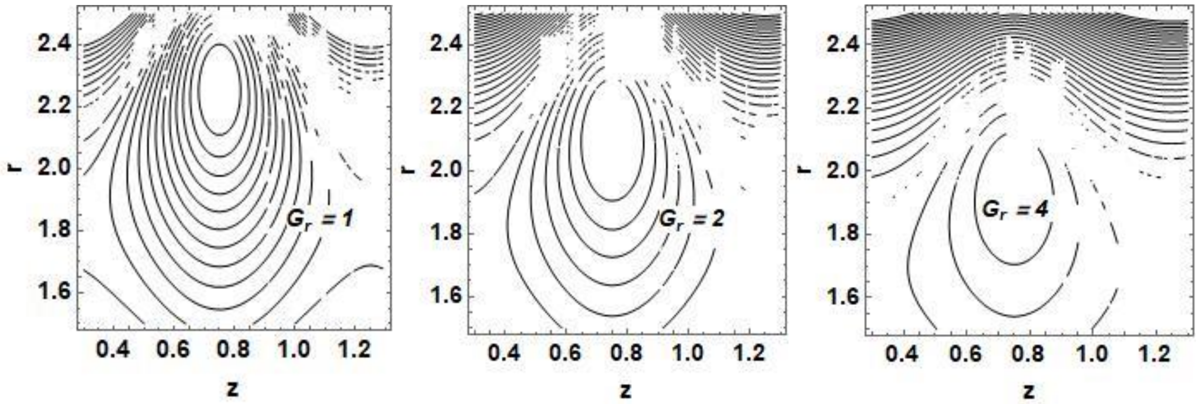

Fig. 8(c): Streamline pattern for several values of G_r

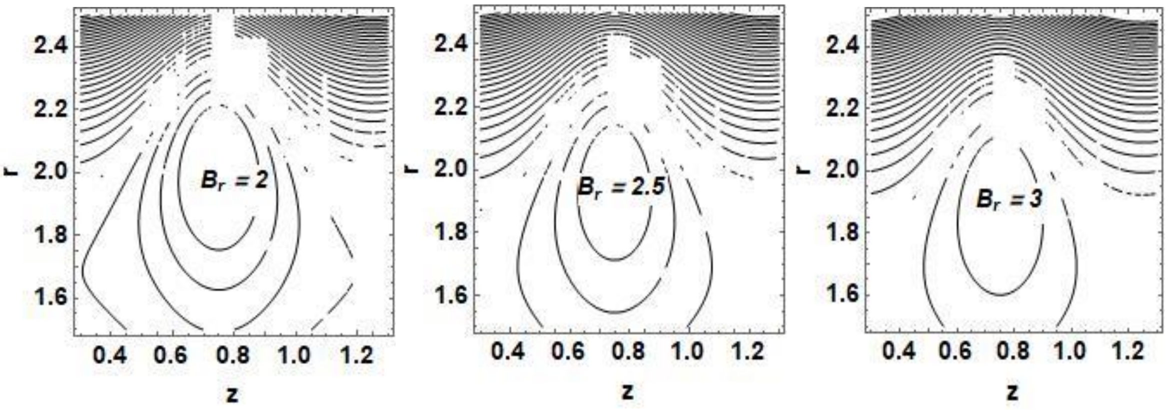

Fig. 8(d): Streamline pattern for several values of B_r

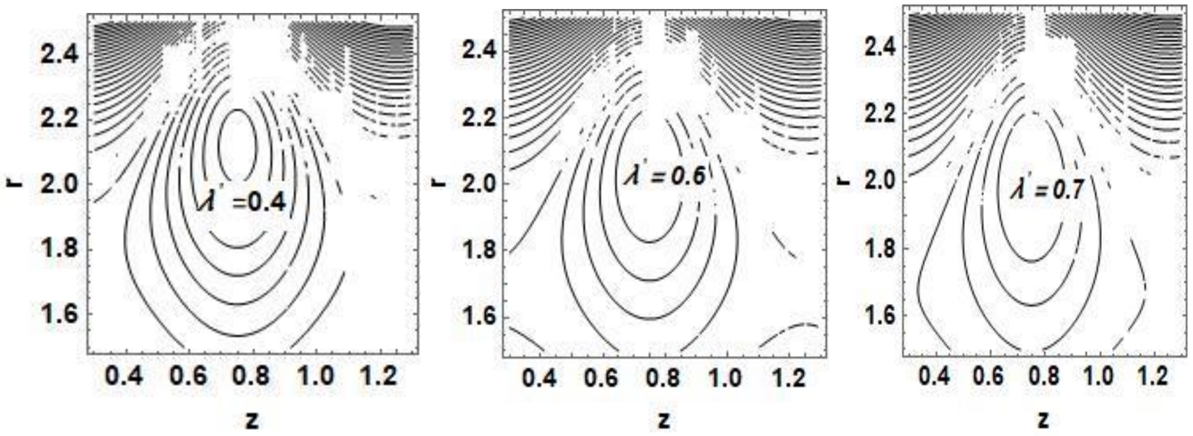

Fig. 8(e): Streamline pattern for several values of λ'

5. Conclusions

In this work, the peristaltic flow of a Jeffrey fluid is studied. The governing equations for a compressible Jeffrey fluid are modelled and then used for flow in a tube. The considered problem is important from the rheological point of view and has applications in various branches of science including stimulation of fluid flow. Special emphasis has been given to the effects of non-Newtonian parameters $\boldsymbol{\lambda'}$, nanoparticle Grashof number (B_r) temperature Grashof number (G_r) on the net flow rate. The main findings of the presented analysis are summarized as:

- Temperature rises significantly as Brownian motion (N_b) increases, and thermophoresis exhibits the opposite behaviour.
- Concentration rises as N_t rises. It is possible to interpret the constant increase in the strength of thermophoretic effects as resulting in greater mass flux due to temperature escalation, which raises the concentration.
- Heat transfer coefficient initially enhanced with Brownian motion and with thermophoresis.
- Increasing Brownian motion parameter (N_b) reduces pressure drop, whereas increasing thermophoretic parameter (N_t) strongly enhances pressure drop.
- The magnitude of trapped bolus is decreased with increasing the magnitude of Brownian motion (N_b).
- Increasing thermophoretic parameter (N_t), causes the size of boluses to be increased.
- With increasing Jeffrey fluid parameter $\boldsymbol{\lambda'}$ bolus size is increased.

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