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Effect of Chemical Reactions on Dispersion of a Solute in Peristaltic Motion of Newtonian Fluid with Wall Properties

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ABSTRACT

This paper reports an analytical key for dispersion of a solute substance in the peristaltic pumping of a Newtonian fluid through a uniform channel under the influence of wall properties with combined homogeneous and heterogeneous chemical reactions by taking into account the equations of the deformable boundaries and the fluid. The mean effective coefficient of dispersion on combined homogeneous and heterogeneous chemical reactions has been studied through δ-approximation and conditions of Taylor's limit. The behavior of penetrating parameters like homogeneous reaction rate, heterogeneous reaction rate, amplitude ratio and elastic parameters (E_1, E_2, E_3) are inspected through the graphical results. It is noticed that average effective dispersion enhances with wall parameters and amplitude ratio. These results reveal that the peristalsis boost dispersion of a solute substance.

Keywords: Chemical reaction, dispersion, peristaltic motion, wall properties.

1. Introduction

Dispersion plays a central task in chyme transport and other applications like environmental pollutant transportation, chromatographic separation, the mixing and transport of drugs or toxic substances in physiological structures (Ng (2006)). The dispersion of a solute in a solvent flowing in a channel has wide applications in physiological fluid dynamics, biomedical and chemical industries. The basic theory on dispersion was first proposed by Taylor (1953, 954a,b) and he further discussed the dispersion of a solute in a circular pipe with an incompressible viscous fluid through laminar flow. Taylor investigated that, the solute disperses with an equivalent average effective dispersion coefficient, and the dispersion depends on the radius of the tube, coefficient of molecular diffusion and average speed of the flow, under the hypothesis that the solute material does not chemically react with the fluid. Aris (1956), Padma and Ramana Rao (1975), Gupta and Gupta (1972), Padma and Ramana Rao (1977), and other several investigators have investigated the dispersion of a solute in viscous fluid, under different limitations. Furthermore, Agarwal and Chandra (1983), Chandra and Philip (1993), Dutta et al. (1974), Hayat et al. (2014), and Hayat et al. (2015) extended this analysis to non Newtonian fluids. Several studies have been carried out on the dispersion with simultaneous chemical reactions for Newtonian and non-Newtonian fluids.

Peristalsis is the main technique for transporting many physiological fluids. This motion is involved in the urine passage from the kidney to the bladder, transport of food through the oesophagus after swallowing and movement of bile in the bile duct. In addition, this mechanism is used in some biomedical devices, such as – hose pumps, finger, roller pumps that use peristalsis to pump blood, slurries, and other fluids. Several researchers have studied the peristaltic transport of Newtonian and non- Newtonian fluids under different conditions (Fung and Yih (1968), Fung and Yin (1969), Jaffrin et al. (1969), Radhakrishnamacharya (1982), Misra and Pandey (2001)).

Mittra and Prasad (1973) have studied the wall effects on Poiseuille flow with peristalsis. In addition, several researchers have studied the wall effects on non- Newtonian fluids in peristalsis (Muttu et al. (2003), Sankad and Radhakrishnamacharya (2009)).

Few studies on the dispersion of a solute in the peristaltic transport of Newtonian and non- Newtonian fluids under various conditions have been conducted recently (Alemayehu and Radhakrishnamacharya (2010, 2012), Sobh (2013)). The effect of homogeneous and heterogeneous chemical reactions on the peristaltic flow of a micropolar fluid through a porous medium with wall and slip effects in presence of magnetic field has been studied by RaviKiran and Radhakrishnamacharya (2015, 2016), and is reported that the concentration increases with the wall parameters (rigidity, stiffness, and damping character).

Diffusion and peristalsis are more essential characteristics in bio-medical, natural and chemical processes. The liquids present in the ducts of living being can be classified as Newtonian and non-Newtonian fluids based on their behavior. The impact of simultaneous homogeneous, heterogeneous reactions with peristalsis of Newtonian fluid with wall properties has not received much attention. Peristalsis may have significant effects on the dispersion of a solute in fluid flow. Therefore, we have considered a mathematical model to study the peristaltic pumping of Newtonian fluid with complaint wall and chemical reactions through δ-approximation and conditions of Taylor's limit and dynamic boundary conditions. The applications to this issue are transport of water, nutrients to various branches of tree and moment of nutrients in blood veins which have peristalsis on its walls (Lightfoot (1974)).The analytical expression for the mean effective dispersion coefficient is obtained. The results are analyzed for different values of relevant parameters through graphs.

2. Formulation of the Problem

We have considered peristaltic pumping of an incompressible Newtonian fluid in the 2- dimensional compliant wall channel, the Cartesian coordinates x and y with x- axis at the centre of the fluid flow and the homogeneous, heterogeneous reaction effects in the flow analysis. The peristaltic wave with speed c produces the flow travelling along walls of the channel. Figure 1 shows the travelling waves.

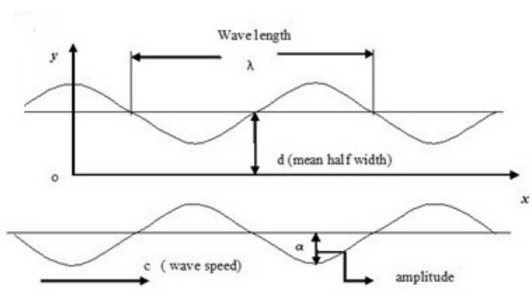

Figure 1: Geometry of the problem

The wave shape is given by the subsequent equation:

$$y = \pm h = \pm \left[d + a \sin \frac{2\pi}{\lambda}(x - ct) \right], \tag{1}$$

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

The equations governing the peristaltic motion of the 2 - dimensional flow of a Newtonian fluid through a uniform symmetric channel for the present problem are as follows

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{2}$$

$$\rho \left[\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} \right] = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right), \tag{3}$$

$$\rho \left[\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} \right] = -\frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right), \tag{4}$$

where ρ - the fluid density, p -the pressure, μ -the viscosity coefficient, u - the velocity component in the x direction, v - velocity component in y direction.

The governing equation of the stretchy wall motion may be represented as (Mittra and Prasad (1973))

$$L(h) = p - p_0, \tag{5}$$

where L-motion of an expanded membrane with the damping forces and is calculated using the following equation:

$$L = -T\frac{\partial^2}{\partial x^2} + m\frac{\partial^2}{\partial t^2} + \mathtt{C}\frac{\partial}{\partial t}. \tag{6}$$

Here m- the mass per/ area T - the tension in the membrane, and $\mathtt{C}$ - the viscous damping force coefficient.

After solving the equations (2) to (4) under long - wavelength approximation, we get

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{7}$$

$$-\frac{\partial p}{\partial x}+\mu\frac{\partial^2 u}{\partial y^2}=0, \tag{8}$$

$$-\frac{\partial p}{\partial y}=0. \tag{9}$$

The appropriate periphery conditions are

$$u=0, \quad \text{at} \qquad y=\pm h. \tag{10}$$

It is presumed that $p_0=0$ and the channel walls are inextensible; therefore, the straight displacement of the wall is nil and only lateral movement takes place, and

$$\frac{\partial}{\partial x}L(h)=\mu\frac{\partial^2 u}{\partial y^2} \qquad \text{at} \qquad y=\pm h, \tag{11}$$

where

$$\frac{\partial}{\partial x}L(h)=\frac{\partial p}{\partial x}=-T\frac{\partial^3 h}{\partial x^3}+m\frac{\partial^3 h}{\partial x\partial t^2}+\mathtt{C}\frac{\partial^2 h}{\partial x\partial t}. \tag{12}$$

After solving equations (8) and (9) with the conditions (10) and (11), we get

$$u(y)=\frac{1}{2\mu}\left(\frac{\partial p}{\partial x}\right)\left(y^2-h^2\right), \tag{13}$$

The mean velocity is expressed as

$$\bar{u}=\frac{1}{2h}\int_{-h}^{h}u(y)dy. \tag{14}$$

From equation (13) and (14), we get

$$\bar{u}=-\frac{1}{\mu}\left(\frac{\partial p}{\partial x}\right)\frac{h^2}{3}, \tag{15}$$

If convection is across the plane moving with the mean speed of the flow, then relative to this plane, the fluid velocity is given by the following equation (Alemayehu and Radhakrishnamacharya (2010), Sobh (2013)).

$$u_x = u - \bar{u}. \tag{16}$$

From equations (13), (15) and (16), we find

$$u_x = \frac{1}{2\mu}\left(\frac{\partial p}{\partial x}\right)\left(y^2 - \frac{h^2}{3}\right), \tag{17}$$

where $P' = \frac{\partial p}{\partial x} = -T\frac{\partial^3 h}{\partial x^3} + m\frac{\partial^3 h}{\partial x \partial t^2} + \mathtt{C}\frac{\partial^2 h}{\partial x \partial t}$.

3. Diffusion with Simultaneous Homogeneous and Heterogeneous Chemical Reactions

The first order irreversible reaction model in the peristaltic pumping of Newtonian fluid flow under isothermal conditions is considered as:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) - k_1 C. \tag{18}$$

Using Taylor's approximation $\frac{\partial^2 C}{\partial x^2} \leq \frac{\partial^2 C}{\partial y^2}$, the equation (18) is expressed as:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = D\frac{\partial^2 C}{\partial y^2} - k_1 C. \tag{19}$$

In the above equation, C - concentration of the fluid, D - the molecular diffusion coefficient and k_1 - the rate constant of first order chemical reaction. For the common values of physiologically important parameters of this issue, it is expected that $\bar{u} = C$ (Gupta and Gupta (1972)).

With this condition $\bar{u} = C$, and below dimensionlessl quantities,

$$\theta = \frac{t}{\bar{t}}, \quad \bar{t} = \frac{\lambda}{\bar{u}}, \quad \eta = \frac{y}{d}, \quad \xi = \frac{(x - \bar{u}t)}{\lambda}, \quad H = \frac{h}{d}, \quad P = \frac{d^2}{\mu c \lambda}P'. \tag{20}$$

Equations (12), (17) and (19) reduce to

$$P = -\epsilon\left[(E_1+E_2)(2\pi)^3\cos(2\pi\xi) - E_3(2\pi)^2\sin(2\pi\xi)\right], \tag{21}$$

$$u_x = \frac{d^2}{2\mu}\frac{\partial p}{\partial x}\left(\eta^2 - \frac{H^2}{3}\right), \tag{22}$$

$$\frac{\partial^2 C}{\partial \eta^2} - \frac{k_1 d^2}{D}C = \frac{d^2}{\lambda D}u_x\frac{\partial C}{\partial \xi}, \tag{23}$$

where

$\epsilon\left(=\frac{a}{d}\right)$ is the amplitude ratio, $E_1\left(=-\frac{Td^3}{\lambda^3\mu c}\right)$ is the rigidity, $E_2 = \left(\frac{mcd^3}{\lambda^3\mu}\right)$ is the stiffness, $E_3 = \left(\frac{\mathtt{C}d^3}{\mu\lambda^2}\right)$ is the viscous damping force in the wall.

Below, we discuss the diffusion with first order reaction taking place in the mass of the fluid medium and at the walls of the channel; the walls are catalytic to chemical reaction.

Hence, the boundary conditions at the walls (Chandra and Philip (1993)) are expressed by the following equations:

$$\frac{\partial C}{\partial y} + fC = 0 \quad \text{at} \quad y = h = [d + a\sin\frac{2\pi}{\lambda}(x-\bar{u}t)], \tag{24}$$

$$\frac{\partial C}{\partial y} - fC = 0 \quad \text{at} \quad y = -h = -[d + a\sin\frac{2\pi}{\lambda}(x-\bar{u}t)]. \tag{25}$$

If we use the equation (20), the conditions (24) and (25) reduces to

$$\frac{\partial C}{\partial \eta} + \beta C = 0 \quad \text{at} \quad \eta = H = [1+\epsilon\sin(2\pi\xi)], \tag{26}$$

$$\frac{\partial C}{\partial \eta} - \beta C = 0 \quad \text{at} \quad \eta = -H = -[1+\epsilon\sin(2\pi\xi)], \tag{27}$$

where $\beta = fd$ is the heterogeneous response rate parameter corresponding to catalytic response at the walls.

Assuming that $\frac{\partial C}{\partial \xi}$ is independent of η at any cross-section, we obtain the concentration of the solute C as follows:

$$C(\eta) = -\frac{d^4}{2\lambda\mu D}\frac{\partial C}{\partial \xi}\frac{\partial p}{\partial x}\left[\frac{A_1}{A_2}\cosh(\alpha\eta) + \frac{H^2}{3\alpha^2} - \frac{\eta^2}{\alpha^2} - \frac{2}{\alpha^4}\right], \tag{28}$$

where $A_1 = \alpha \sinh(\alpha H) + \beta \cosh(\alpha H)$, $\quad A_2 = \left(\frac{2H}{\alpha^2} + \frac{2\beta H^2}{3\alpha^2} + \frac{2\beta}{\alpha^4}\right)$.

The volumetric rate Q is defined as the rate in which the solute is pumping across a section of channel per unit breadth.

$$Q = \int_{-H}^{H} C u_x d\eta. \tag{29}$$

Using equations (22) and (28) in equation (29), we get

$$Q = -2\frac{d^6}{\lambda \mu^2 D}\frac{\partial C}{\partial \xi} G(\xi, \alpha, \beta, \epsilon, E_1, E_2, E_3), \tag{30}$$

where

$$G(\xi, \alpha, \beta, \epsilon, E_1, E_2, E_3) = \left[P\frac{A_2}{2A_1}\left(\frac{H^2}{3\alpha}\sinh(\alpha H) - \frac{H}{\alpha^2}\cosh(\alpha H) + \frac{1}{\alpha^3}\sinh(\alpha H)\right) - P\frac{H^5}{45\alpha^2}\right]. \tag{31}$$

Glancing at equation (31) with Fick's law of diffusion, the scattering coefficient D^* was calculated such that the solute diffuses comparative to the plane moving with the average speed of the flow and is given as:

$$D^* = 2\frac{d^6}{\mu^2 D} G(\xi, \alpha, \beta, \epsilon, E_1, E_2, E_3). \tag{32}$$

Let $\bar{G}$ be the average of G and is obtained by the following equation:

$$\bar{G} = \int_0^1 G(\xi, \alpha, \beta, \epsilon, E_1, E_2, E_3) d\xi. \tag{33}$$

4. Analysis of Results

This segment is prepared to investigate the impacts of different parameters on the concentration. The mean effective dispersion coefficient was observed through the function $\bar{G}(\xi, \alpha, \beta, \epsilon, E_1, E_2, E_3)$ for simultaneous homogeneous, heterogeneous reactions given by equation (33). $\bar{G}$ was computed by the software MATHEMATICA and end results are presented graphically. The penetrating parameters present in this argument are the amplitude ratio (ϵ), the homogeneous reaction rate (α), the heterogeneous reaction rate (β), the rigidity (E_1), the stiffness (E_2), and viscous damping force (E_3). We may ensure that E_1, E_2 and E_3 cannot be zero all together.

We have considered the figures 2, 3, 4, and 5 for the impact of the rigidity parameter (E_1) of the elastic wall on the mean effective dispersion coefficient ($\bar{G}$). Dispersion enhances with increase in wall rigidity (E_1) in the cases (a) $E_2 = 0$ and $E_3 = 0$ (Figures 2 and 4); (b) $E_2 \neq 0$ and $E_3 \neq 0$ (Figures 3 and 5). It is observed that $\bar{G}$ increases with the stiffness (E_2) when $E_3 \neq 0$ (Figures 7, 8).

Further, it is noted that boost in viscous damping force (E_3) increases $\bar{G}$ when $E_2 = 0$ (Figures 10 and 12) and $E_2 \neq 0$ (Figures 11 and 13). This understanding might be derived to the truths that increment in the flexibility of the channel walls help the stream moment which causes to enhance the scattering. It is also noticed that dispersion is more in presence of stiffness in the wall as compared to without stiffness in the wall. These results are in agreement with the results of RaviKiran and Radhakrishnamacharya (2015, 2016). Furthermore, the effective dispersion coefficient enhances with an increase in the amplitude ratio ϵ (Figures 6, 9, and 14).

As already known, increment in the amplitude ratio is the expansion in the amplitude of the wave across the channel and this cause to increase the fluid velocity within the channel and consequently dispersion may enhance. This outcome concurs with that of Sobh (2013) and Alemayehu and Radhakrishnamacharya (2010, 2012).

Diffusion reduces with homogeneous response rate parameter (α) (Figures: 2, 3, 7, 10, and 11) and heterogeneous response rate (β) (Figures: 4, 5, 8, 12, and 13), where as scattering diminishing with β is less significant. This outcome is normal since expansion in α prompts an expansion in number of moles of solute experiences chemical response. This result is consistent with the arguments of Gupta and Gupta (1972), Sobh (2013), Alemayehu and Radhakrishnamacharya (2010), Hayat et al. (2014), and RaviKiran and Radhakrishnamacharya (2015).

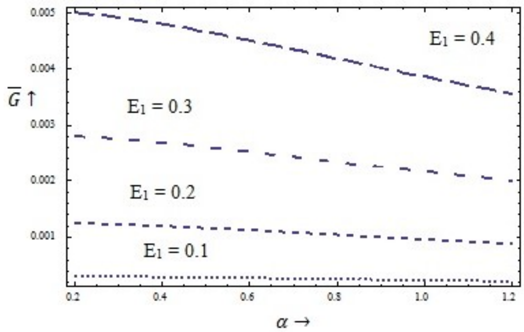

Figure 2: Plot of $\bar{G}$ for E_1 with $\epsilon = 0.2$, $\beta = 5.0$, $E_2 = 0.0$, $E_3 = 0.00$.

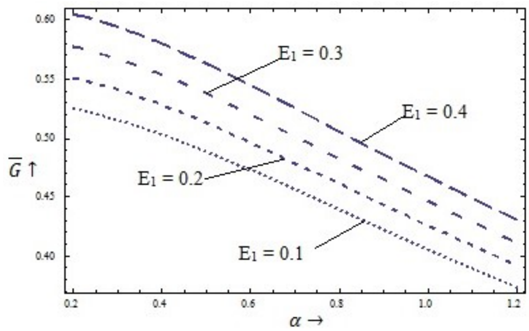

Figure 3: Plot of $\bar{G}$ for E_1 with $\epsilon = 0.2$, $\beta = 5.0$, $E_2 = 4.0$, $E_3 = 0.06$.

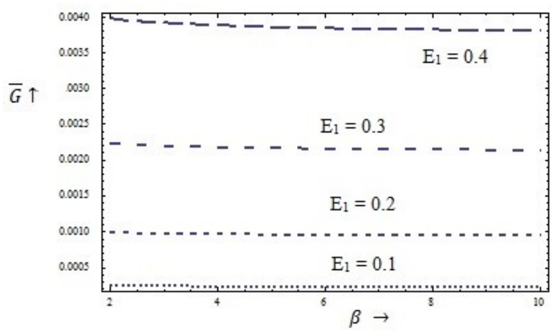

Figure 4: Plot of $\bar{G}$ for E_1 with $\epsilon = 0.2$, $\alpha = 1.0$, $E_2 = 0.0$, $E_3 = 0.00$.

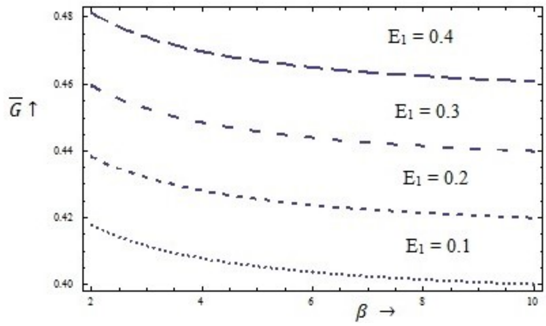

Figure 5: Plot of $\bar{G}$ for E_1 with $\epsilon = 0.2$, $\alpha = 1.0$, $E_2 = 4.0$, $E_3 = 0.06$.

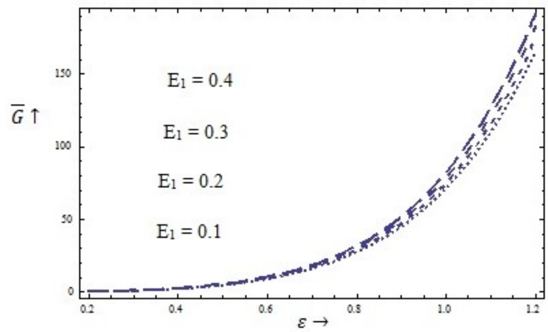

Figure 6: Plot of $\bar{G}$ for E_1 with $\alpha = 1.0$, $\beta = 5.0$ $E_2 = 4.0$, $E_3 = 0.00$.

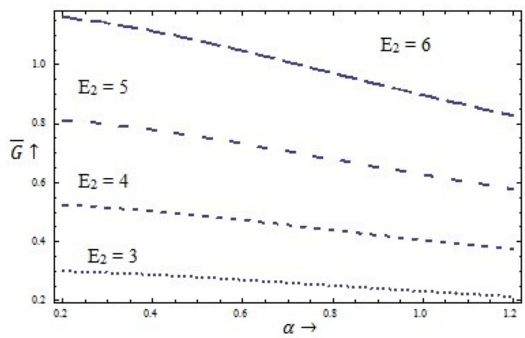

Figure 7: Plot of $\bar{G}$ for E_2 with $\epsilon = 0.2$, $\beta = 5.0$, $E_1 = 0.1$, $E_3 = 0.06$.

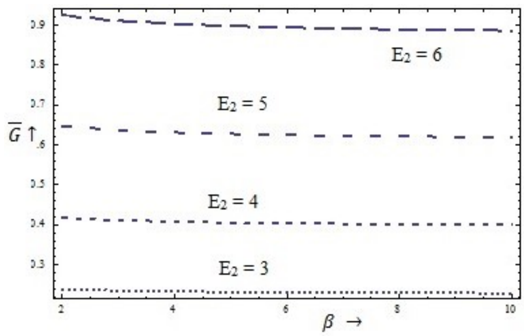

Figure 8: Plot of $\bar{G}$ for E_2 with $\epsilon = 0.2$, $\alpha = 1.0$, $E_1 = 0.1$, $E_3 = 0.06$.

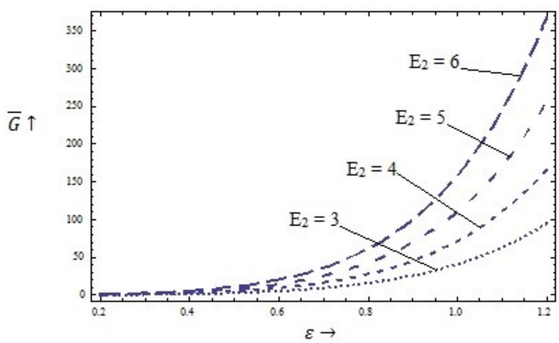

Figure 9: Plot of $\bar{G}$ for E_2 with $\alpha = 1.0$, $\beta = 5.0$ $E_1 = 0.1$, $E_3 = 0.06$.

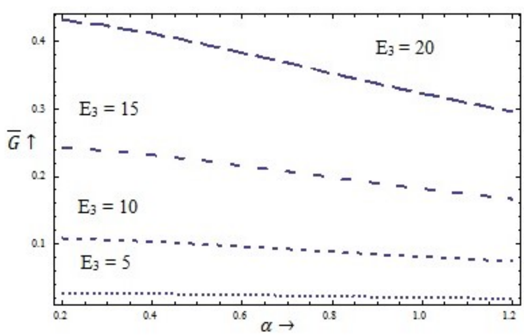

Figure 10: Plot of $\bar{G}$ for E_3 with $\epsilon = 0.2$, $\beta = 5.0$, $E_1 = 0.1$, $E_2 = 0.00$.

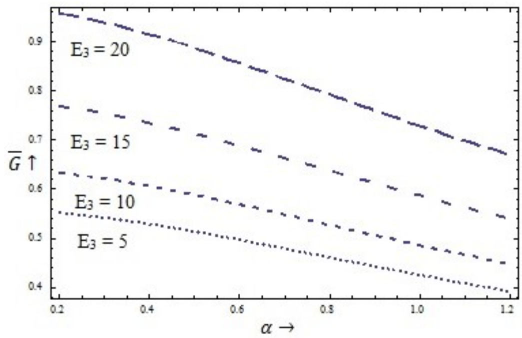

Figure 11: Plot of $\bar{G}$ for E_3 with $\epsilon = 0.2$, $\beta = 5.0$, $E_1 = 0.1$, $E_2 = 4.0$.

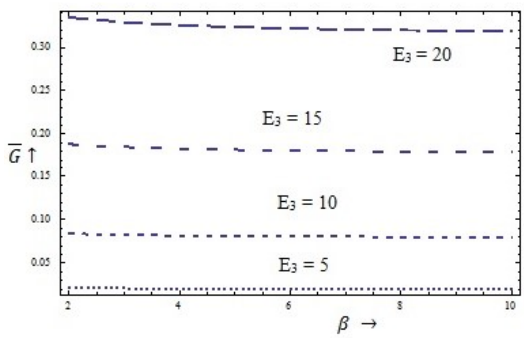

Figure 12: Plot of $\bar{G}$ for E_3 with $\epsilon = 0.2$, $\alpha = 1.0$, $E_1 = 0.1$, $E_0 = 0.00$.

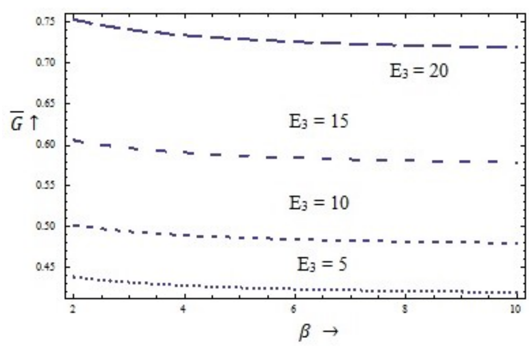

Figure 13: Plot of $\bar{G}$ for E_3 with $\epsilon = 0.2$, $\alpha = 1.0$, $E_1 = 0.1$, $E_2 = 4.0$.

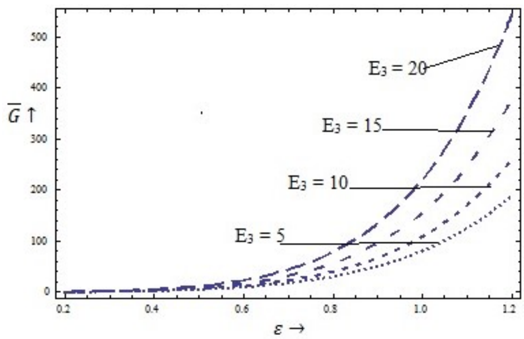

Figure 14: Plot of $\bar{G}$ for E_3 with $\alpha = 1.0$, $\beta = 5.0$ $E_1 = 0.1$, $E_2 = 4.0$.

5. Conclusions

The presents study investigates the effect of complaint wall and chemical reactions on Newtonian fluid with peristalsis. The imperative results of this article are summarized below.

• Identical effect is noticed for compliant wall parameters on dispersion coefficient.

• Opposite behavior of homogeneous response parameter (α) and heterogeneous response parameter (β) are observed on concentration profile.

• Similar behavior is noticed for an amplitude ratio (ϵ) on dispersion.

Finally, it concludes that wall parameters and amplitude ratio favor the dispersion while homogeneous response rate parameter α and heterogeneous response rate parameter β resist the dispersion. This study may help in understanding the transport phenomena occurring in the small intestine leading to absorption of nutrients and drugs.

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