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MHD Peristaltic Transport of Couple Stress Fluid in an Inclined Channel with Hall Current and Slip Flow

***Nirmala P. Ratchagar*[1], *V. Balakrishnan*[2] and *R. Vasanthakumari*[3]**

[1]Department of Mathematics, Annamalai University, TamilNadu, INDIA.
E-mail: nirmalapasala@yahoo.co.in
[2]Department of Mathematics, Tagore Govt. Arts & Science College
Puducherry, INDIA. E-mail: prasaanthbala@yahoo.com
[3]Department of Mathematics, Kanchimamunivar Centre for Post Graduate Studies
Puducherry, INDIA. E-mail: vasunthara1@gmail.com
[2]Corresponding author

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Abstract. This paper describes the impact of the Hall current on MHD flow of a couple stress fluid in an inclined channel. The fluid is electrically conducting through a porous medium in the presence of uniform magnetic field. The system of governing partial differential equations are solved analytically. The analytical solution is carried out under long wave length and low Reynolds number. Closed form expression for velocity, pressure gradient and pressure rise are presented. Important results reflecting the influence of embedded parameters in the problem have been pointed by plotting the graphs and discussed in detail.

Keywords: Hall current, MHD, peristaltic flow, couple stress fluid, inclined channel.

AMS Mathematics Subject Classification (2010): 76S05, 76Z05

1. Introduction

It is well established fact that peristaltic process is a mechanism for mixing and transporting fluids, which is caused by a progressive wave of contraction and expansion travelling on the walls of the channel/tube. Such process is encountered in the transport of urine from kidney to bladder, swallowing of food through esophagus, lymph transport in the lymphatic vessels and in vasomotion of small blood vessels such as arterioles, venules and capillaries etc. Roller and finger pumps also work under the peristaltic mechanism. Beginning with the first investigation of Latham [8], several theoretical and experimental attempts have been made to understand peristaltic action in different situation. Shapiro et al., [13] discussed the theoretical results for both plane and axisymmetric geometries. This has attracted several investigators to study the peristaltic transport under long wavelength and low Reynolds number.

Mekheimer [9] analysed the MHD flow of a conducting couple stress fluid in a slit channel with rhythmically contracting walls. Nirmala et al. [10] contributed the hall current effect in oscillatory flow of a couple stress fluid in an inclined channel. Eldabe et al. [1] studied the effects of heat and mass transfer on the MHD flow of an incompressible, electrically conducting couple stress fluid through a porous medium in an asymmetric flexible channel over which a traveling wave of contraction and expansion is produced, resulting in a peristaltic motion. Sankad and Radhakrishnamacharya[12] contributed towards the effect of magnetic field on the peristaltic transport of couple stress fluid in a channel with different wall properties. Shit and Roy[14] discussed the effect of slip velocity on peristaltic transport of a physiological fluid through a porous non-uniform channel under the long wave length and low-Reynolds number assumptions. Kothandapani and Srinivas [7] analysed the effect of elasticity of the flexible walls on the MHD peristaltic flow of a Newtonian fluid in a two-dimensional porous channel with heat transfer under the assumptions of long wavelength and low-Reynolds number.

Gnaneswara et al. [3] studied the effect of thermal radiation and chemical reaction on peristaltic MHD slip flow of a couple stress fluid through a porous medium in an asymmetric channel. The influence of heat and mass transfer on a peristaltic flow of Jeffrey fluid in an inclined asymmetric channel with Hall currents through porous medium was analysed by Eldabe et al. [2]. Ravikumar [11] studied the MHD peristaltic transportation of a conducting blood flow with porous medium through inclined coaxial vertical channel. Hayat et al. [5] analysed the effect of hall current on peristaltic transport of couple stress fluid in an inclined asymmetric channel. The theoretical and computational study of peristaltic hemodynamic flow of couple stress fluids through a porous medium under the influence of magnetic field with slip condition was done by Swarnalathamma and Veerakrishna [15]. Govindarajan et al. [4] described the combined effect of Heat and Mass transfer on MHD peristaltic Transport of a couple stress fluid in a inclined asymmetric channel through a porous medium. Veerakrishna and Dharmaiah [16] discussed the hall current effect on pulsatile flow of a viscous incompressible fluid through a porous medium in a flexible channel under the influence of transverse magnetic field. Khalid Nowar [6] has presented the peristaltic flow of an incompressible viscous electrically conducting nanofluid in a vertical asymmetric channel through a porous medium.

The objective of present research is to venture further in the effect of Hall current in the peristaltic flow of couple stress fluid in an inclined asymmetric channel. The fluid is electrically conducting through an inclined magnetic field. It is to be noted here that the role of both slip boundary condition and Hall current [14, 5] on the dynamic fluid have not been studied previously and this may be the first to include both the conditions in the such study. In the following sections, the problem is formulated and solved. The analytical solutions to the axial velocity, pressure gradient and pressure rise are obtained using the assumptions of long wave length and low Reynolds number. The numerical solutions have been computed using MATHEMATICA software and presented them graphically.

2. Mathematical formulation

We consider the flow of an incompressible, viscous and electrically conducting couple stress fluid flowing through an inclined asymmetric channel under the action of external magnetic field. Let $Y' = h_1'$ and $Y' = h_2'$ are upper and lower wall of the channel. The medium is considered to be induced by a sinusoidal wave train propagating with a wave speed c along the length of the channel wall (cf. figure 1) such that

$$h_1^{'}(X^{'},t^{'}) = d_1 + a_1 \cos[\frac{2\pi}{\lambda}(X^{'} - ct^{'})] \quad (1)$$

$$h_2^{'}(X^{'},t^{'}) = -d_2 - a_2 \cos[\frac{2\pi}{\lambda}(X^{'} - ct^{'}) + \phi] \quad (2)$$

where d_1 and d_2 are the mean height of the upper and lower wall of the channel from the center line, a_1 and a_2 are the amplitudes of the waves of the channel walls, λ the wave length, $\phi(0 \le \phi \le \pi)$ the phase difference between the wave trains of both the walls, $X^{'}$ and $Y^{'}$ are the rectangular co-ordinates with $X^{'}$ measures the axis of the channel and $Y^{'}$ the transverse axis perpendicular to $X^{'}$. The fluid flow of the channel is exerted by an external transverse uniform constant magnetic field of strength B_0, in which the induced magnetic field is neglected because of the low magnetic Reynolds number.

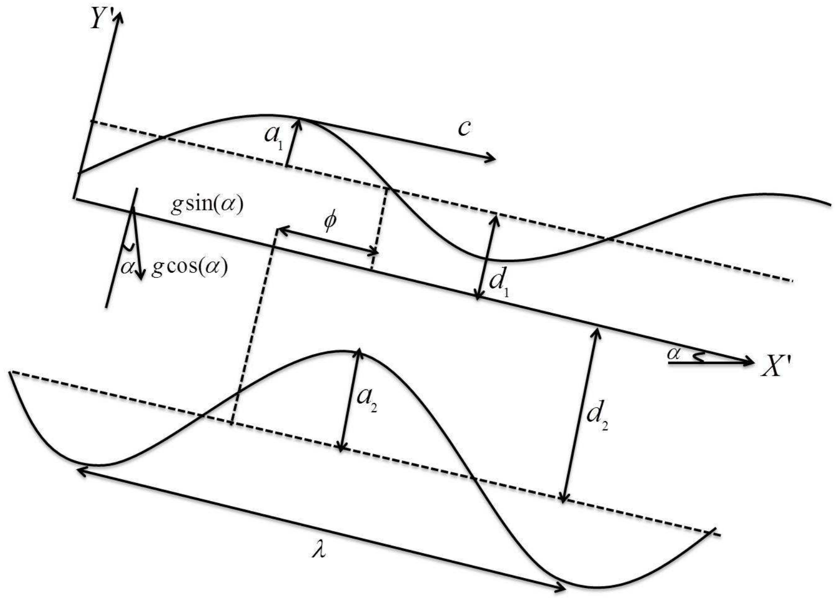

Figure 1: Geometry of the problem

Now, the equations of governing motion for the present problem are as follows:

$$\frac{\partial U'}{\partial X'} + \frac{\partial V'}{\partial Y'} = 0 \quad (3)$$

$$\rho(U'\frac{\partial U'}{\partial X'} + V'\frac{\partial U'}{\partial Y'}) = -\frac{\partial p'}{\partial X'} + \mu(\frac{\partial^2 U'}{\partial X'^2} + \frac{\partial^2 U'}{\partial Y'^2}) - \eta(\frac{\partial^4 U'}{\partial X'^4} + \frac{\partial^4 U'}{\partial Y'^4}) - \frac{\sigma B_o^2 U'}{(1+m^2)} + \rho g \sin\alpha \quad (4)$$

$$\rho(U'\frac{\partial V'}{\partial X'}+V'\frac{\partial V'}{\partial Y'})=-\frac{\partial \overline{p}}{\partial Y'}+\mu(\frac{\partial^2 V'}{\partial X'^2}+\frac{\partial^2 V'}{\partial Y'^2})-\eta(\frac{\partial^4 V'}{\partial X'^4}+\frac{\partial^4 V'}{\partial Y'^4})-\frac{\sigma B_o{}^2 V'}{(1+m^2)}+\rho g\cos\alpha \tag{5}$$

where (U',V') are the velocity components in the fixed frame, μ is the viscosity of fluid, η is the constant associated with couple stress, p' the fluid pressure, ρ is the fluid density, σ is the electrical conductivity, B_0 is the external magnetic field, α the inclination of the channel, g be the acceleration gravity, $m=\frac{\sigma B_0}{en}$ is the Hall parameter (e is the electric charge, n is the number of density of electrons) . Due to the assumption of the low magnetic Reynolds number, the induced electric field is neglected.

Let us consider a wave frame (x',y') that moves with the velocity c away from fixed frame (X',Y'). Here we use the relation between wave frame and fixed frame as follows:

$$x'=X'-ct, y'=Y', u'=U'-c, v'=V' \tag{6}$$

Due the time dependence of the channel wall, in the laboratory frame (X',Y') the flow is unsteady. Therefore all flow quantities analysed in the wave frame of reference.

Let us introduce the following dimensionless variables,

$$\begin{gathered} x=\frac{x'}{\lambda}, y=\frac{y'}{\lambda}, h_1(x)=\frac{h_1'(x')}{d_1}, h_2(x)=\frac{h_2'(x')}{d_2}, \\ u=\frac{u'}{c}, v=\frac{\lambda v'}{d_1 c}, p=\frac{d_1{}^2 p'(x')}{\lambda\mu c}, t=\frac{ct'}{\lambda}, \end{gathered} \tag{7}$$

Using the transformation (6) and dimensionless equations (7) into governing Equations (3) to (5) becomes

$$\mathrm{Re}\,\delta\{(u+1)\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\}=-\frac{\partial p}{\partial x}+(\delta^2\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2})-\frac{1}{\gamma^2}(\delta^4\frac{\partial^4 u}{\partial x^4}+\frac{\partial^4 u}{\partial y^4})-\frac{H^2(u+1)}{(1+m^2)}+\frac{\mathrm{Re}}{Fr}\sin\alpha \tag{8}$$

$$\begin{gathered} \mathrm{Re}\,\delta^3\{(u+1)\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\}=-\frac{\partial p}{\partial y}+\delta^2(\delta^2\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2})-\delta^2\gamma(\delta^4\frac{\partial^4 v}{\partial x^4}+\frac{\partial^4 v}{\partial y^4})- \\ \frac{H^2}{1+m^2}\delta^2 v-\frac{\mathrm{Re}\,\delta}{Fr}\cos\alpha \end{gathered} \tag{9}$$

where $\mathrm{Re}=\frac{\mu c d_1}{\mu}$ is the Renolds number, $\delta=\frac{d_1}{\lambda}$ is the wave number,

$H=B_o d_1\sqrt{\frac{\sigma}{\mu}}$ is the Hartmann number, $\gamma=\frac{\eta}{\mu d_1{}^2}$ is the couple stress parameter and

$Fr = \dfrac{c^2}{gd_1}$ is the Froude number.

Under the assumption of long wave length (λ) that is δ<<1 and low Reynolds number *Re*<<1 (cf.Shapiro[2]), the equations (8) and (9) reduces to

$$-\frac{\partial p}{\partial x} + \frac{\partial^2 u}{\partial y^2} - \frac{1}{\gamma^2}\frac{\partial^4 u}{\partial y^4} - \frac{H^2(u+1)}{1+m^2} + \frac{\mathrm{Re}}{Fr}\sin\alpha = 0 \tag{10}$$

$$\frac{\partial p}{\partial y} = 0 \tag{11}$$

The volumetric flow rate in the fixed frame is given by

$$Q = \int_{h2'}^{h_1'} U'(X',Y',t')dY' \tag{12}$$

where h_1' and h_2' are functions of *X'* and *t'*.
The rate of volume flow in the wave frame is found to be

$$q = \int_{h2'}^{h_1'} u'(x',y')dy' \tag{13}$$

where h_1' and h_2' are functions of *x'* alone.
Using transformation $U' = u' + c$ in equation (12) and using (13) we have

$$Q = q + c(h_1' - h_2') \tag{14}$$

The time mean flow rate over a period T at a fixed position X' is defined to be

$$Q' = \frac{1}{T}\int_0^1 Qdt \tag{15}$$

Use equation (14) into equation (15) we have

$$Q' = q + cd_1 + cd_2 \tag{16}$$

The non dimensional form of equation (16) will be

$$\theta = F + 1 + d \tag{17}$$

where

$\theta = \dfrac{Q'}{cd_1}, F = \dfrac{q}{cd_1}$ and $d = \dfrac{d_2}{d_1}$.

The boundary conditions for the present problem can be written as:

Slip boundary condition: $u = -\beta\dfrac{\partial u}{\partial y}$ at y=h$_1(x)$, and $u = +\beta\dfrac{\partial u}{\partial y}$ at y=h$_2(x)$

Vanishing of couple stress:

$$\frac{\partial^2 u}{\partial y^2} = 0, \text{ at } y = h_1(x) \text{ and } y = h_2(x) \tag{18}$$

Solving equation (10) by using the boundary conditions (18) we have the axial velocity "u" is obtained as

$$u = c_1 \cosh(m_1 y) + c_2 \sinh(m_1 y) + c_3 \cosh(m_2 y) + c_4 \sinh(m_2 y) + \frac{\frac{\mathrm{Re}}{Fr}\sin\alpha - \frac{H^2}{1+m^2} - \frac{\partial p}{\partial x}}{\frac{\gamma^2 H^2}{1+m^2}} \tag{19}$$

where the constants c_i $(i = 1\ to\ 4)$ in equation (19) can be calculated by simple algebraic calculations.

Similarly the expression for $\frac{dp}{dx}$ can be derived from equation (10) and hence the non dimensional expression for pressure rise per wave length Δp can be obtained as,

$$\Delta p = \int_0^1 \frac{dp}{dx} dx$$

3. Results and discussions

The analytical solutions for axial velocity, pressure gradient and pressure rise per wave length have been discussed in the previous sections. In the present study for numerical results, it is necessary to assign the following default physical parameter values and are adopted as [3, 12]:

$\phi = 0$, $\alpha = \frac{\pi}{4}$, $H = 1$, $\gamma = 3$, $\beta = 1$, $Fr = 0.3$, $\frac{dp}{dx} = 0.5$, $m = 1$, $\mathrm{Re} = 0.71$, $a = b = 0.5$,
, $x = 0$,. $d = 1$

These values kept as common in the entire study except for the varied values as displayed in figures 2 to 22.

Pressure rise per wave length (Δp):

Figures 2 to 8 give the variation in pressure rise per wave length (Δp) versus volumetric flow rate (θ) for different values of parameters β, γ, *Fr*, α, *H*, *m*. Figure 2 shows the effect of 'β' on pressure rise. The pressure rise gradually decreases with increase of volumetric flow rate 'θ', where as the pressure rise increases with the increase of slip parameter 'β'. The pressure rise increases with the increase of couple stress parameter γ in the pumping region ($\Delta p > 0$) and decreases in the co-pumping region ($\Delta p < 0$). From the figure 3, it is observed that the convergence of γ value is obtained at
θ = 2.

Figure 4 displays the effect of Froude number (*Fr*) on Δp. The pressure rise per wave length decreases when *Fr* increases. This happens due to the presence of the term *Fr* in the denominator of equation (10). The Δp increases with increase of inclination (α) and is observed from the figure 5 that there is equal interval of increase for every 15^0 inclination.

Figure 6 represents the effect of Hartmann number (*H)* on Δp. The pressure rise per wave length is proportional to *H* in the pumping region($\Delta p > 0$), and is inversely proportional to the co-pumping region, ie, a negative pumping is observed. It is also observed that Δp decreases with increase of Hall parameter value (m), as shown in the figure 7, at $\theta \geq 2$.

Figure 8 indicates the effect of phase difference (φ) on Δp. The pressure rise per wavelength is higher for higher phase difference but when θ approaches higher value the role of phase difference on Δp get decreases.

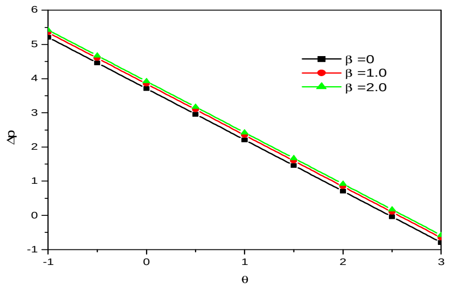

Figure 2: Variation in Pressure rise Δp with θ for different values of β.

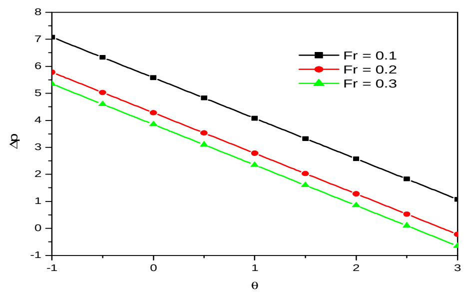

Figure 4: Variation in Pressure rise Δp with θ for different values of *Fr*.

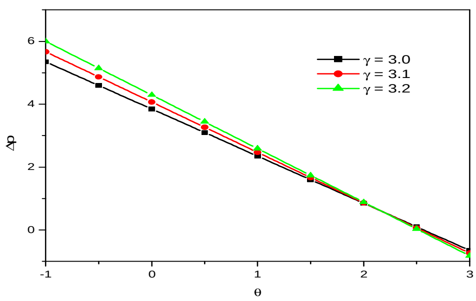

Figure 3: Variation in Pressure rise Δp with θ for different values of γ.

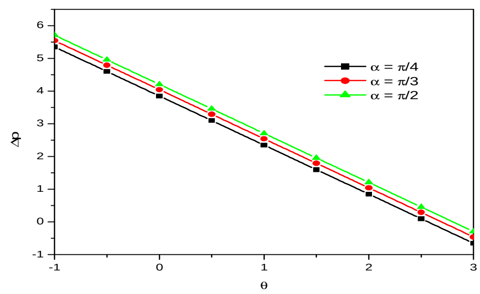

Figure 5: Variation in Pressure rise Δp with θ for different values of α.

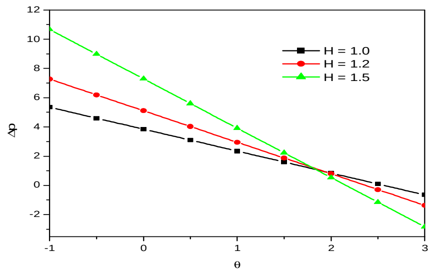

Figure 6: Variation in Pressure rise Δp with θ for different values of *H*.

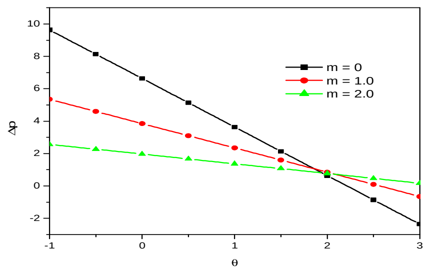

Figure 7: Variation in Pressure rise Δp with θ for different values of *m*.

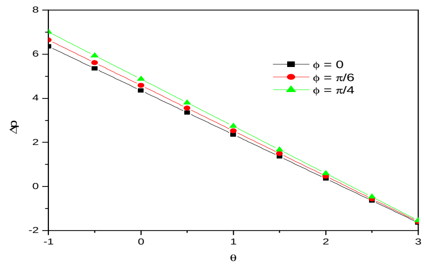

Figure 8: Variation in Pressure rise Δp with θ for different values of *φ*.

Pressure gradient $(\frac{dp}{dx})$:

The variation in pressure gradient , along the axial distance over one wave length for different values of physical parameters β, γ, *Fr*, α, *H*, *m* are ploted in figure 9 to 15. From these figures we note that through the region $x \in (0.2, 0.8)$, the channel path is narrowed and the flow cannot pass easily. Therefore it requires more pressure gradient to make it as normal flow. In the wider part of the channel $x \in (0, 0.2)$ and $x \in (0.8, 1.0)$ fluid can pass easily because of the lower pressure gradient. Figure 9 shows the effect of slip parameter (β) on pressure gradient. We observe that the value of slip parameter increases the magnitude of the axial pressure gradient also increases slightly. The pressure gradient also increases with increase of couple stress parameter γ and is illustrated in figure 10.

Figure 11 depicts the effect of Froude number (*Fr*) on pressure gradient. When Froude number increases, the pressure gradient also get increases in the wider region and decreases in the narrow region of the channel. Figure 12 presents the effect of pressure gradient on inclination (α); no remarkable change in pressure gradient is observed with change in α.

Figure 13 shows the effect of Hartmann number, *H* (magnetic parameter), on pressure gradient. Increase of Hartmann number follows the increase of pressure gradient. It shows that when strong magnetic field is applied to the flow field then higher pressure gradient is needed to pass the flow. This result suggests that fluid pressure can be controlled by the application of suitable magnetic field strength. This phenomenon is useful during critical surgery to control excessive bleeding. In figure 14, when the Hall parameter (m) increases, the pressure gradient decreases (positive, at $m<3$ and negative, at m>3). Figure 15 illustrates that a lesser amount of pressure gradient (dp/dx) is required to pass the flow through the channel when phase difference (φ) increases.

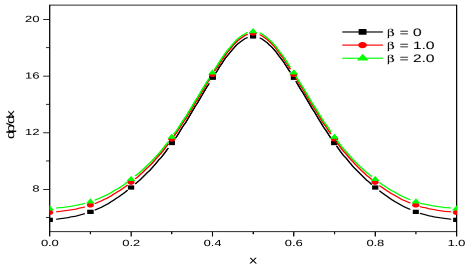

Figure 9: Variation in Pressure gradient *dp/dx* for different values of β.

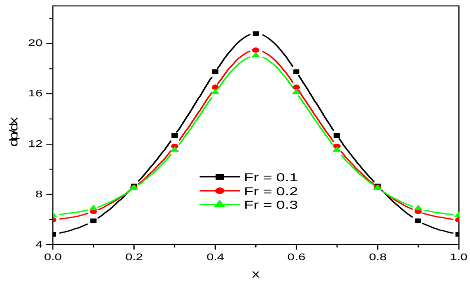

Figure 12: Variation in Pressure gradient *dp/dx* for different values of α.

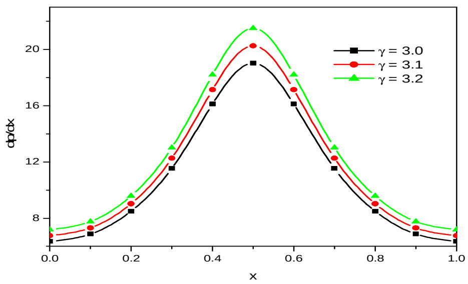

Figure 10: Variation in Pressure gradient *dp/dx* for different values of γ.

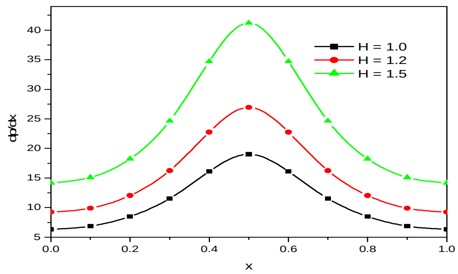

Figure 13: Variation in Pressure gradient *dp/dx* for different values of *H*.

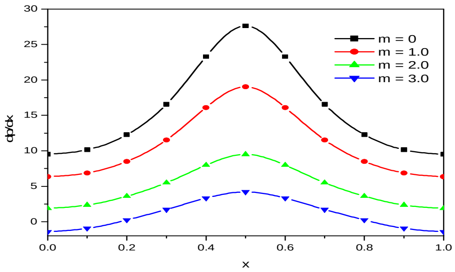

Figure 11: Variation in Pressure gradient *dp/dx* for different values of *Fr*.

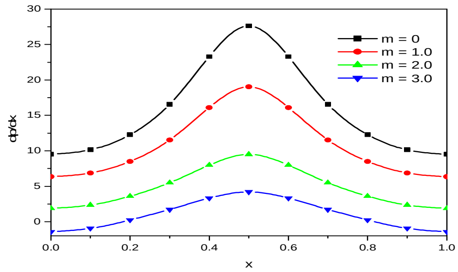

Figure 14: Variation in Pressure gradient *dp/dx* for different values of *m*.

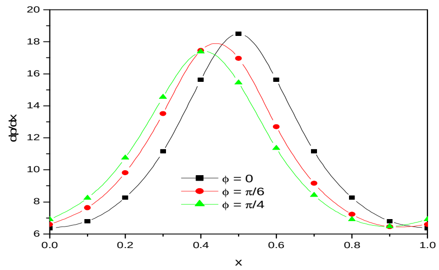

Figure 15: Variation in Pressure gradient *dp/dx* for different values of φ

Velocity profile (u)

Figures 16 to 22 give the distribution of axial velocity 'u' versus height of the channel 'y' for various parameters. Figure 16 shows the effect of slip parameter (β) on velocity profile. The velocity profile increases as slip parameter increases. However from figure 17, we observe that the velocity profile decreases as couple stress parameter (γ) increases. Figure 18 presents the effect of Froude number (*Fr*) on velocity profile. The velocity profile decreases with an increase of Froude number. Figure 19 represents that the velocity profile increases as α increases and it is obvious that when the angle of inclination of the channel increases the velocity of the fluid increases.

Figure 20 shows the effect of Hartmann number (*H*) on velocity profile. The velocity profile decreases as the values of Hartmann number increases, whereas it increases with the increasing values of Hall parameter (*m*) and is shown in figure 21.

From figure 22 we observe that at the lower half of the channel there is a shift in the velocity in the reverse direction to the phase value and the shift is found to be proportional to the φ value. But at the upper half of the channel the effect of phase on velocity get decreases and it gets nullified at the upper wall of the channel. It is quite interesting to confirm this result with standard fluid dynamics statement that the velocity goes on increasing from lower to upper layer of the fluid.

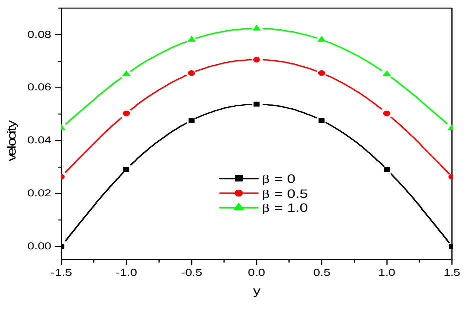

Figure 16: Variation in axial velocity for different values of β.

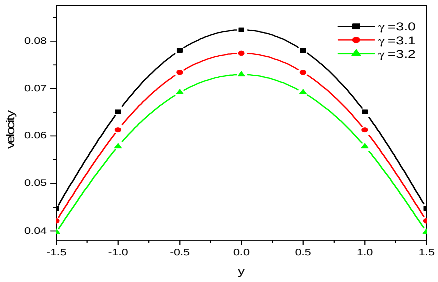

Figure 17. Variation in axial velocity for different values of γ.

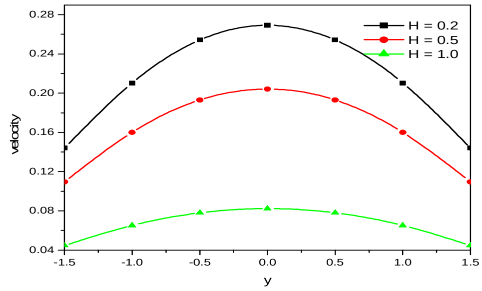

Figure 20. Variation in axial velocity for different values of *H*.

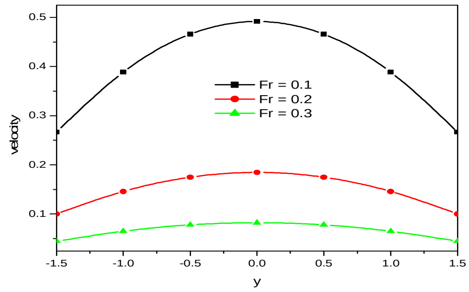

Figure 18: Variation in axial velocity for different values of *Fr*.

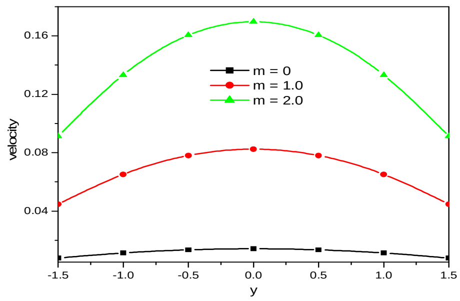

Figure 21: Variation in axial velocity for different values of *m*.

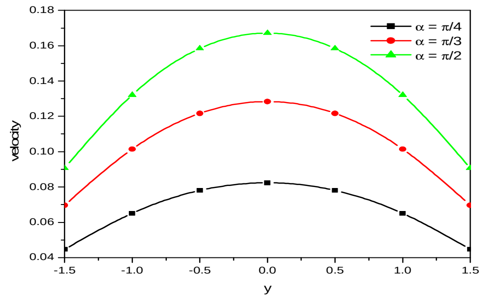

Figure 19: Variation in axial velocity for different values of α.

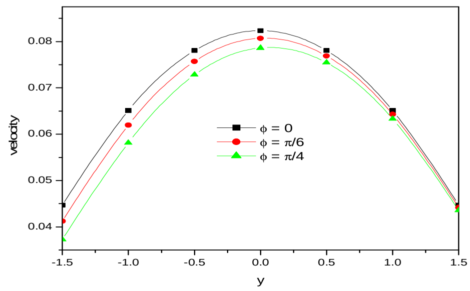

Figure 22: Variation in axial velocity for different values of φ.

4. Conclusions

The present study of MHD peristaltic flow of couple stress fluid in an inclined channel with Hall effects are taken into account. The main observations of this work are summarised as follows:

- The pressure rise per wave length 'Δp' increases in all pumping regions when slip parameter 'β' and angle of inclination 'α' increases, where as it decreases when Froude number '*Fr*' increases.
- The pressure rise per wave length 'Δp' decreases in the retrograde region and it increases in the co-pumping region when the Hall parameter '*m'* increases.
- The pressure gradient *dp/dx* increases in the narrow part of the channel and it decreases in the wider part of the channel with increasing values of β, α and *H.*
- The pressure gradient *dp/dx* decreases when Hall parameter *m* increases.
- A lesser amount of pressure gradient (dp/dx) is required to pass the flow through the channel when phase difference (φ) increases
- Increased values of slip parameter β, α and *m*, increases the velocity profile *u*.
- Velocity profile decreases when couple stress parameter γ, Fr and Hartmann number '*H'* increases.
- Our findings on the influence of magnetic parameter (Hartmann number, H) on the pressure gradient suggests that the pressure of a fluid such as blood, etc., can be controlled by applying suitable magnetic field, which may have a potential application in critical surgery for controlling excessive bleeding of blood.

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