Research Article

Magnetic Field and Gravity Effects on Peristaltic Transport of a Jeffrey Fluid in an Asymmetric Channel

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Received 12 January 2014; Accepted 19 February 2014; Published 13 April 2014

Academic Editor: Juntao Sun

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In this paper, the peristaltic flow of a Jeffrey fluid in an asymmetric channel has been investigated. Mathematical modeling is carried out by utilizing long wavelength and low Reynolds number assumptions. Closed form expressions for the pressure gradient, pressure rise, stream function, axial velocity, and shear stress on the channel wall have been computed numerically. Effects of the Hartmann number, the ratio of relaxation to retardation times, time-mean flow, phase angle, and the gravity field on the pressure gradient, pressure rise, stream function, axial velocity, and shear stress are discussed in detail and shown graphically. The results indicate that the effect of Hartmann number, ratio of relaxation to retardation times, time-mean flow, phase angle, and gravity field are very pronounced in the peristaltic transport phenomena. Comparison was made with the results obtained in the presence and absence of magnetic field and gravity field.

1. Introduction

Peristaltic pumping has been the object of scientific and engineering research in recent years. The word peristaltic comes from a Greek word “Peristaltikos” which means clamping and compressing. The peristaltic transport is travelling contraction wave along a tube-like structure, and it results physiologically from neuron-muscular properties of any tubular smooth muscle. Peristaltic motion of blood (or other fluid) in animal or human bodies have been considered by many authors. It is an important mechanism for transporting blood, where the cross section of the artery is contracted or expanded periodically by the propagation of progressive wave. It plays an indispensable role in transporting many physiological fluids in the body in various situations such as urine transport from the kidney to the bladder through the ureter, transport of spermatozoa in the ducts efferents of the male reproductive tract, and the movement of the ovum in the flipping tubes.

A variety of complex theological fluids can easily be transported from one place to another with a special type of pumping known as peristaltic pumping. This pumping principle is called peristalsis. The mechanism includes involuntary periodic contraction followed by relaxation or expansion of the ducts that the fluids move through; this leads to the rise of pressure gradient that eventually pushes the fluid forward.

The study of the peristaltic transport of a fluid in the presence of an external magnetic field and rotation is of great importance with regard to certain problems involving the movement of conductive physiological fluids, for example, blood and saline water. Pandey and Chaube [1] investigated an analytical study of the MHD flow of a micropolar fluid through a porous medium induced by sinusoidal peristaltic waves traveling down the channel wall. The magnetohydrodynamic flow of a micropolar fluid in a circular cylindrical tube has been investigated by Wang et al. [2]. Nadeem and Akram [3] studied the analytical and numerical treatment of peristaltic flows in viscous and non-Newtonian fluids. Vajravelu et al. [4] studied the influence of heat transfer on peristaltic transport of a Jeffrey fluid in a vertical porous stratum. Hayat et al. [5] discussed the influence of compliant
The aim of this paper is to study the effect of magnetic field and gravity field on peristaltic motion of Jeffrey type and is electrically conducting in asymmetric channel. Here the governing equations are nonlinear in nature; we used infinitely long wavelength assumption to obtain linearized system of coupled differential equations which are then solved analytically. Results have been discussed for pressure gradient, pressure rise, streamline and axial velocity to observe the Hartmann number, the ratio of relaxation to retardation times, time-mean flow, the phase angle, and the gravity field effect. The numerical result displayed by figures and the physical meaning is explained. The results and discussions presented in this study may be helpful to further understand MHD peristaltic motion for non-Newtonian fluids in an asymmetric channel.

2. Formulation of the Problem

Let us consider the peristaltic transport of an incompressible viscous fluid in a two-dimensional channel of width \( d_1 + d_2 \). The channel walls are inclined at angles \( \alpha \). The flow is induced by sinusoidal wave trains propagating with constant speed \( c \) along the channel walls.

The geometry of the wall surfaces is

\[
\begin{align*}
\vec{h}_1 (\vec{X}, \vec{t}) &= d_1 + a_1 \cos \left( \frac{2\pi}{\lambda} (\vec{X} - c\vec{t}) \right) \text{ at upper wall}, \\
\vec{h}_2 (\vec{X}, \vec{t}) &= -d_2 - b_1 \cos \left( \frac{2\pi}{\lambda} (\vec{X} - c\vec{t}) + \phi \right) \text{ at lower wall},
\end{align*}
\]

where \( a_1 \) and \( b_1 \) are the types of amplitude of the waves, \( \lambda \) is the wavelength, \( c \) is the wave speed, \( \phi \) (\( 0 \leq \phi \leq \pi \)) is the phase difference, \( \phi = 0 \) corresponds to symmetric channel with waves out of phase, and \( \phi = \pi \) indicates that the waves are in phase, and further \( a_1, b_1, d_1, d_2, \) and \( \phi \) satisfy the condition

\[
a_1^2 + b_1^2 + 2a_1b_1 \cos \phi \leq (d_1 + d_2)^2. \tag{2}
\]

The Cauchy (\( \vec{T} \)) and extra (\( \vec{S} \)) stress tensors take the following form

\[
\begin{align*}
\vec{T} &= -\vec{p}\vec{I} + \vec{S}, \\
\vec{S} &= \frac{\mu}{1 + \lambda_1} \left( \vec{y} + \lambda_2 \vec{y} \right),
\end{align*}
\]

where \( \vec{p} \) is the pressure, \( \vec{I} \) is the identity tensor, \( \lambda_1 \) is the ratio of relaxation to retardation times, \( \lambda_2 \) is the retardation time, and \( \vec{y} \) is the shear rate.
In laboratory frame, the following set of pertinent field equations governing the flow are
\[
\rho \left[ \frac{\partial \vec{U}}{\partial t} + \vec{U} \cdot \nabla \vec{U} + \vec{V} \frac{\partial \vec{U}}{\partial \vec{Y}} \right] = - \frac{\partial \vec{P}}{\partial \vec{X}} + \frac{\partial}{\partial \vec{X}} \left( \vec{S}_{\vec{X} \vec{X}} \right) + \frac{\partial}{\partial \vec{Y}} \left( \vec{S}_{\vec{X} \vec{Y}} \right) + \frac{\partial}{\partial \vec{Y}} \left( \vec{S}_{\vec{Y} \vec{Y}} \right) - \rho g \sin \alpha,
\]
and the continuity equation takes the form
\[
\frac{\partial \vec{U}}{\partial \vec{X}} + \frac{\partial \vec{V}}{\partial \vec{Y}} = 0,
\]
where \(\vec{U}\) and \(\vec{V}\) are the velocity components in the laboratory frame \((\vec{X}, \vec{Y})\). However, the flow becomes steady in a wave frame \((\vec{x}, \vec{y})\) moving away from the laboratory frame with speed \(c\) in the direction of propagation of the wave. Taking \(u\) and \(v\) the velocity components in \(x\) and \(y\) directions, the transformation from the laboratory frame to the wave frame is given by
\[
\begin{align*}
\vec{x} &= \vec{X} - ct, \\
\vec{y} &= \vec{Y}, \\
\vec{u} &= \vec{U} - c,
\end{align*}
\]
Using (6), (7a), and (7b) into (3)-(4) and eliminating pressure by cross differentiation, we get
\[
\delta \Re \left[ \left( \frac{\partial^2 \psi}{\partial \vec{y}^2} - \delta^2 \frac{\partial^2 \psi}{\partial \vec{x}^2} \right) \nabla^2 \psi \right] = \left[ \left( \frac{\partial^2}{\partial \vec{y}^2} - \delta^2 \frac{\partial^2}{\partial \vec{x}^2} \right) s_{xy} \right]
+ \delta \left[ \frac{\partial^2}{\partial \vec{x} \partial \vec{y}} \left( s_{xx} - s_{xy} \right) \right]
+ M^2 \frac{\partial^2 \psi}{\partial \vec{y}^2} \frac{gd_1}{c^2} \sin \alpha
\]
in which
\[
\begin{align*}
s_{xx} &= \frac{2\delta}{1 + \lambda_1} \left[ 1 + \frac{\delta \lambda_1 c}{d_1} \left( \frac{\partial \psi}{\partial \vec{y}} \frac{\partial \psi}{\partial \vec{x}} + \frac{\partial \psi}{\partial \vec{x}} \frac{\partial \psi}{\partial \vec{y}} \right) \right] \frac{\partial^2 \psi}{\partial \vec{x} \partial \vec{y}}, \\
s_{xy} &= \frac{1}{1 + \lambda_1} \left[ 1 + \frac{\delta \lambda_1 c}{d_1} \left( \frac{\partial \psi}{\partial \vec{y}} \frac{\partial \psi}{\partial \vec{x}} - \frac{\partial \psi}{\partial \vec{x}} \frac{\partial \psi}{\partial \vec{y}} \right) \right] \frac{\partial^2 \psi}{\partial \vec{x} \partial \vec{y}}, \\
s_{yy} &= -\frac{2\delta}{1 + \lambda_1} \left[ 1 + \frac{\delta \lambda_1 c}{d_1} \left( \frac{\partial \psi}{\partial \vec{y}} \frac{\partial \psi}{\partial \vec{x}} - \frac{\partial \psi}{\partial \vec{x}} \frac{\partial \psi}{\partial \vec{y}} \right) \right] \frac{\partial^2 \psi}{\partial \vec{x} \partial \vec{y}}
\end{align*}
\]
where
\[
\nabla^2 = \delta^2 \frac{\partial^2 \psi}{\partial \vec{x}^2} + \frac{\partial^2 \psi}{\partial \vec{y}^2}, \quad \delta = \frac{2\pi d_1}{\lambda}, \quad \Re = \frac{\rho cd_1}{\mu} \text{ is the Reynolds number,}
\]
\[
M = \sqrt{\frac{\sigma}{\beta}} B_0 d_1 \text{ is the Hartmann number.}
\]
Using the long wavelength approximation and neglecting the wave number \(\delta\) along with low Reynolds number in our analysis, the field equations (8) and (10) now give
\[
\begin{align*}
\frac{\partial^2 \psi}{\partial \vec{x}^2} \left[ \frac{1}{1 + \lambda_1} \frac{\partial^2 \psi}{\partial \vec{y}^2} \right] + M^2 \frac{\partial^2 \psi}{\partial \vec{y}^2} + \frac{gd_1}{c^2} \sin \alpha &= 0.
\end{align*}
\]
The boundary conditions for the stream functions in the wave frame are
\[
\psi = \frac{q}{2}, \quad h_1 = 1 + a \cos \left[ \frac{x}{\lambda} \right],
\]
\[
\psi = -\frac{q}{2} \quad \text{at } y = h_2 \left( x \right) = -d - b \cos \left[ \frac{2\pi}{\lambda} \left( x + \phi \right) \right],
\]
where \(q\) is the flux in the wave frame and \(a, b, \phi, \text{ and } d\) satisfy the relation
\[
a^2 + b^2 + 2ab \cos \phi \leq (1 + d)^2.
\]
3. Solution of the Problem

The solution of (12) satisfying the corresponding boundary conditions (13) is

\[ \psi = \frac{(h_1 + h_2) \left[ Nq + 2 \tanh \left( \frac{N(h_1 - h_2)}{2} \right) \right]}{2N(h_2 - h_1) + 4 \tanh \left( \frac{N(h_1 - h_2)}{2} \right)} + \frac{Nq + 2 \tanh \left( \frac{N(h_1 - h_2)}{2} \right)}{N(h_1 - h_2) - 2 \tanh \left( \frac{N(h_1 - h_2)}{2} \right)} \]

\[ + \left( (q + h_1 - h_2) \sech \left( \frac{N(h_1 - h_2)}{2} \right) \right) \]

\[ \times \sinh \left( \frac{N(h_1 - h_2)}{2} \right) \]

\[ \times \left( N(h_1 - h_2) - 2 \tanh \left( \frac{N(h_1 - h_2)}{2} \right) \right)^{-1} \]

\[ \times \cosh (Ny) \]
Asymmetric

\( \Theta = -4, -3, -2, -1 \)

\( g = 1, 5, 10, 20 \)

Figure 3: Variation of \( \frac{dp}{dx} \) with influence of \( \Theta \) and \( g \) respect to \( x \).

The nondimensional expression for the pressure rise per wavelength \( \Delta p_\lambda \) and frictional forces on the lower (\( F^l_\lambda \)) and upper (\( F^u_\lambda \)) walls on the lower are defined as follows:

\[
\Delta p_\lambda = \int_0^{2\pi} \frac{dp}{dx} \, dx,
\]

\[
F^l_\lambda = \int_0^1 h_2^2 \left( -\frac{dp}{dx} \right) dx,
\]

\[
F^u_\lambda = \int_0^1 h_1^2 \left( -\frac{dp}{dx} \right) dx.
\]

The nondimensional expression of the shear stress at the upper wall of the channel is reduced to

\[
S_{xy} = \frac{1}{1 + \lambda_1} \frac{\partial^2 \psi}{\partial y^2}
\]

\[
= \frac{N^2 (q + h_1 - h_2) [N (h_1 - h_2)/2]}{(1 + \lambda_1) [N (h_1 - h_2) - 2 \tanh [N (h_1 - h_2)/2]]}
\]

\[
\times \left\{ \sinh \left[ \frac{N (h_1 - h_2)}{2} \right] \cosh Mh_1 - \cosh \left[ \frac{N (h_1 - h_2)}{2} \right] \sinh Mh_1 \right\}.
\]

4. Numerical Results and Discussion

In order to gain physical insight into the pressure gradient, pressure rise \( \Delta p_\lambda \), streamline \( \psi \), velocity \( u \), and shear stress \( S_{xy} \) have been discussed by assigning numerical values to the parameter encountered in the problem in which
the numerical results are displayed with the graphic illustrations. The variations are shown in Figures 1–7, respectively.

Figures 1, 2, and 3 show the variations of the axial pressure gradient $dP/dx$ with respect to the axial $x$ which it has oscillatory behavior in the whole range of the $x$-axis for different values of the Hartmann number $M$, the ratio of relaxation to retardation times $\lambda_1$, time-mean flow $\Theta$, the phase angle $\phi$, gravity field $g$, and the nondimensional amplitude of wave $b$ in asymmetric channel. In both figures, it is clear that the pressure gradient has a nonzero value only in a bounded region of space. The effect of the Hartmann number, the ratio of relaxation to retardation times, time-mean flow, rotation, gravity field, and the nondimensional amplitude of wave decreases and increases gradually. It is observed that the pressure gradient increases with increasing of the Hartmann number, gravity field, the phase angle, and the nondimensional amplitude of the wave, while it decreases with increasing of the time-mean flow and the ratio of relaxation to retardation times. It is noticed that the axial pressure gradient when compared to the case of asymmetric and symmetric channel takes a large values respect to the small values of $x$ and small values with an increasing of $x$.

Moreover, it can be noticed that, on the one hand, in the wider part of the channel $x \in [0, 2]$ and $[3, 5, 6]$, the pressure gradient is relatively small; that is, the flow can easily pass without imposition of a large pressure gradient. On the other
Figure 5: Variation of $\psi$ with influence of $M$, $\lambda_1$, $b$, $\phi$, and $\Theta$ with respect to $x$. 
hand, in a narrow part of the channel $x \in [2, 3.5]$, a much pressure gradient is required to maintain the flux to pass it especially near $x = 2.7$.

Figure 4 shows the variations of the pressure rise $\Delta p_1$ with respect to the time-mean flow $\Theta$ for different values of the Hartmann number $M$, the ratio of relaxation to retardation times $\lambda_1$, the phase difference $\phi$, and the nondimensional amplitude of wave $b$. In both figures, it is clear that the pressure rise has a nonzero value only in a bounded region of space. It is observed that the pressure rise increases with increasing of the Hartmann number and the nondimensional amplitude of the wave, while it decreases with increasing the time-mean flow, the ratio of relaxation to retardation times, and the phase difference. The graph is sectored so that the upper right-hand quadrant (I) denotes the region of the peristaltic pumping ($\Theta > 0, \Delta p_1 > 0$). Quadrant (II) is designated as an augmented flow when $\Theta > 0, \Delta p_1 < 0$. Quadrant (IV) such that $\Theta < 0, \Delta p_1 > 0$ is called retrograde or backward pumping.

Figure 5 shows the variations of the streamlines $\psi$ with respect to the axial $x$ which has oscillatory behavior in the whole range of the $x$-axis for different values of the Hartmann number $M$, the ratio of relaxation to retardation times $\lambda_1$, time-mean flow $\Theta$, the phase difference $\phi$, and
Figure 7: Variation of $S_{xy}$ with influence of $M$, $\lambda_1$, $\Theta$, $g$, and $\phi$ with respect to $x$. 
the nondimensional amplitude of wave \( b \) in asymmetric channel. In both figures, it is clear that the streamlines have a nonzero value only in a bounded region of space. The effect of the Hartmann number, the ratio of relaxation to retardation times, time-mean flow, the phase angle, and the nondimensional amplitude of wave decreases and increases gradually. It is observed that the streamlines increase with the increasing of the phase angle, the Hartmann number, the time-mean flow, and the ratio of relaxation to retardation times. The streamlines near the channel walls do nearly strictly follow the wall waves, which are mainly engendered by the relative movement of the walls.

Figure 6 shows the variations of the axial velocity \( u \) with respect to the axial \( y \) which has oscillatory behavior in the whole range of the \( y \)-axis for different values of the Hartmann number \( M \), the ratio of relaxation to retardation times \( \lambda_1 \), time-mean flow \( \Theta \), and the phase angle \( \phi \) in asymmetric channel. In both figures, it is clear that the axial velocity has a nonzero value only in a bounded region of space. The effect of the Hartmann number, the ratio of relaxation to retardation times, time-mean flow, and the phase angle decreases and increases gradually. It is observed that the axial velocity increases with increasing of the time-mean flow, the Hartmann number, and the ratio of relaxation to retardation, while it decreases with increasing of the phase angle.

Figure 7 displays that the variations of the value of axial shear stress \( S_{xy} \) with respect to the axial \( x \) has oscillatory behavior may be due to peristalsis in the whole range of the \( x \)-axis for different values of the Hartmann number \( M \), the ratio of relaxation to retardation times \( \lambda_1 \), time-mean flow \( \Theta \), the phase angle \( \phi \), and the gravity field \( g \) in asymmetric channel. In both figures, it is clear that the value of shear stress has a nonzero value only in a bounded region of space. The effect of the Hartmann number, the ratio of relaxation to retardation times, time-mean flow, rotation, the phase difference, and the phase angle decreases and increases gradually. It is observed that the shear stress increases with increasing of the Hartmann number, gravity field, and the phase angle, while it decreases with increasing of the ratio of relaxation to retardation times and time-mean flow. Moreover the values of shear stress are larger in case of a Jeffery fluid when compared with Newtonian fluid.

5. Conclusion

Due to the complicated nature of the governing equations of the pertinent field equations governing the peristaltic transport of Jeffery fluid, the work done in this field is unfortunately limited in number. The method used in this study is quite successful in dealing with such problems. This method gives exact solutions in the peristaltic transport without any assumed restrictions on the actual physical quantities that appear in the governing equations of the problem considered. Important phenomena are observed in all these computations.

(i) It was found that, for large values of the Hartmann number \( M \), the ratio of relaxation to retardation times \( \lambda_1 \), time-mean flow \( \Theta \), the phase angle \( \phi \), and the gravity field \( g \) in asymmetric channel, the solution has been obtained in the context of the peristaltic transport of fluid.

(ii) By comparing Figures 1–7 for the peristaltic transport of fluid with figures without magnetic field and gravity field, it was found that it has the same behavior in the same field.

(iii) The results presented in this paper should prove useful for researchers in science and engineering, as well as for those working on the development of fluid mechanics. The study of the phenomenon of the Hartmann number, the ratio of relaxation to retardation times, time-mean flow, the phase angle, and the gravity field in asymmetric channel influence and operations is also used to improve the conditions of peristaltic motion.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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