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Article

Wave Transport and the Effects of Magnetohydrodynamics on a Non-Newtonian Biological Fluid

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Abstract: In this article, the effect of hydromagnetic dynamics on blood circulation within a non-Newtonian fluid characterised by specific mathematical properties was investigated. The wavelength and flow regime were modelled using an analysis of ordinary differential equations, leading to the derivation of a closed-form solution. Following the application of the theories, results were obtained showing that the magnetic field increases the temperature distribution, leading to a decrease in pressure. The coefficients leading to a decrease in temperature distribution were also studied; The increase in the number of particles in the cycle is caused by the effect of the magnetic field, whilst the increase in the slip coefficient and porosity leads to an increase in the volume of the cycle.

Keywords: wave transport , dimensionless variables , hydromagnetic dynamics , blood circulation , magnetic field.

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Introduction

It is widely acknowledged that numerous physiological fluids display non-Newtonian characteristics[1-6]. To tackle diagnostic issues in human circulation, various fluid models have been proposed. Both practical uses and scientific interest have spurred extensive research into peristaltic motion within ducts, a process where fluid is moved by sequential waves of contraction or expansion along tubular structures. This type of transport is evident in biological systems, such as the movement of ova in the fallopian tube, the act of swallowing in the esophagus, lymphatic flow in lymph vessels, vasomotion in small blood vessels, and sperm transport in the male reproductive system. Following Latham's experimental research on peristaltic transport [7], a multitude of theoretical studies [8-11] have been carried out based on simplifying assumptions like small amplitude ratios, low Reynolds numbers, and long wavelengths. Peristaltic pumping has garnered considerable interest in both scientific and engineering fields. The term "peristaltic," which originates from the Greek word Peristaltikos meaning clasping or compressing, describes a traveling wave of contraction along a tubular structure. Physiologically, this motion is a result of the neuromuscular activity of smooth muscles in ducts. The peristaltic transport of blood and other biological fluids has been thoroughly investigated, as it represents a crucial mechanism in circulation where arterial cross sections experience periodic contraction and expansion due to progressive waves.

Peristalsis is characterized as a series of contraction and relaxation waves that affect the walls of a flexible conduit, facilitating the movement of the fluid contained within. Research on peristaltic flow generated by traveling waves along channel walls has extensive applications in both science and engineering. This natural transport mechanism is observed in various living organisms, including ureters, intestines, and small blood vessels. In addition to its physiological roles, peristaltic transport has been repurposed for industrial applications, such as the handling of sanitary fluids, blood pumps in medical devices, and the transfer of corrosive liquids where direct machinery contact is to be avoided. Recently, significant attention has been directed towards the peristaltic flow of non-Newtonian fluids, driven by the lack of a universal constitutive relation that can effectively characterize all fluid behaviors across different flow conditions. Mekhemier [12] investigated how an induced magnetic field affects the peristaltic motion of couple stress fluids. Ebaid [13] examined the peristaltic transport of Newtonian fluids under slip conditions while considering magnetic effects. Haroun [14] explored the flow of third-order fluids in asymmetric channels and later expanded his research to include fourth-grade fluids in inclined asymmetric geometries [15]. Rao and Mishra [16] analyzed peristaltic transport within porous tubes for power law fluids. Kothandapani and Srinivas [17] looked into the magnetohydrodynamic (MHD) effects on Jeffrey fluid in asymmetric channels and subsequently studied Newtonian fluids in inclined porous channels [18]. Hayat et al. [19] addressed the issues of slip and variable viscosity in MHD peristaltic flows.

Methodology

This study presents an analytical investigation of hydromagnetic blood flow in a non-Newtonian fluid model. The governing equations describing conservation of mass, momentum, and energy were formulated based on the assumptions of incompressible flow through a porous channel under the influence of an external magnetic field. Appropriate constitutive relations were employed to characterize the non-Newtonian behavior of blood. The governing equations were transformed into dimensionless form using suitable dimensionless variables. The long-wavelength and low-Reynolds-number approximations were then applied to simplify the mathematical model, reducing the governing partial differential equations to a system of ordinary differential equations. Analytical techniques were subsequently used to obtain closed-form solutions for the velocity, temperature, pressure gradient, and pressure rise. A parametric analysis was performed to evaluate the influence of key physical parameters, including the magnetic field parameter, slip coefficient, porosity parameter, and particle concentration, on the flow characteristics. The effects of these parameters on the velocity profile, temperature distribution, pressure gradient, pressure rise, and volumetric flow rate were analyzed and interpreted to assess the hydromagnetic behavior of blood circulation.

Study Theory and Problem Approach

The subject of the study has been defined as the wave transport of viscous, incompressible fluids within two-dimensional channels of width 2a, where the channel walls are inclined at an angle, the flows are generated by a sinusoidal wave and propagate at a constant speed along the boundaries, and the geometry of the surfaces can be described in [20].

$$\bar{H}_1 = \bar{\eta}_1(\bar{X}, \bar{t}) = 0 \quad \text{at upper wall,} \tag{1}$$

$$\bar{H}_2 = \bar{\eta}_2(\bar{X}, \bar{t}) = a + b\cos\left[2\pi\left(\frac{\bar{X}}{\lambda} - \frac{\bar{t}}{T^*}\right)\right] \quad \text{at lower wall,} \tag{2}$$

The Cauchy $\bar{T}$ (The total stress tensor) and $\bar{S}$ is the extra stress tensors take the following form:

$$\bar{T} = -\bar{p}\bar{I} + \bar{\tau}, \tag{3}$$

$\bar{\tau} = \frac{\mu}{1+\lambda_1}(\dot{\gamma} + \lambda_2 \ddot{\gamma})$ (4)

Here, a and b denote the amplitudes of the waves, while λ represents the wavelength. The wave speed is given by $c = \frac{\lambda}{T^*}$, where T^* is the wave pressure parameter. The isotropic pressure contribution is expressed as $\bar{p}\bar{I}$, with $\bar{p}$ denoting the pressure and $\bar{I}$ the identity tensor. The parameter λ_1 corresponds to the ratio of relaxation to retardation times, and λ_2 is the retardation time. The shear rate is represented by $\dot{\gamma}$, and $\ddot{\gamma}$ denotes its second time derivative. Based on these definitions, the governing equations for fluid motion in a porous medium under the influence of a magnetic field can be formulated as follows:

$$\frac{\partial \bar{U}}{\partial \bar{X}} + \frac{\partial \bar{V}}{\partial \bar{Y}} = 0, \quad (5)$$

$$\frac{\partial \bar{U}}{\partial \bar{t}} = -\left[\bar{U}\frac{\partial \bar{U}}{\partial \bar{X}} + \bar{V}\frac{\partial \bar{U}}{\partial \bar{Y}}\right] - \frac{1}{\rho}\frac{\partial \bar{P}}{\partial \bar{X}} + \frac{1}{\rho}\left(\frac{\partial}{\partial \bar{X}}(\bar{\tau}_{\overline{XX}}) + \frac{\partial}{\partial \bar{Y}}(\bar{\tau}_{\overline{XY}})\right) - \left(\frac{\sigma\beta_0^2}{\rho}\right)\bar{U}, \quad (6)$$

$$\frac{\partial \bar{V}}{\partial \bar{t}} = -\left[\bar{U}\frac{\partial \bar{V}}{\partial \bar{X}} + \bar{V}\frac{\partial \bar{V}}{\partial \bar{Y}}\right] - \frac{1}{\rho}\frac{\partial \bar{P}}{\partial \bar{Y}} + \frac{1}{\rho}\left(\frac{\partial}{\partial \bar{X}}(\bar{\tau}_{\overline{YX}}) + \frac{\partial}{\partial \bar{Y}}(\bar{\tau}_{\overline{YY}})\right) - \left(\frac{\sigma\beta_0^2}{\rho}\right)\bar{V}, \quad (7)$$

$$\frac{\partial \bar{T}}{\partial \bar{t}} = -\left[\bar{U}\frac{\partial \bar{T}}{\partial \bar{X}} + \bar{V}\frac{\partial \bar{T}}{\partial \bar{Y}}\right] + \frac{k}{\rho C_p}\left[\frac{\partial^2 \bar{T}}{\partial \bar{X}^2} + \frac{\partial^2 \bar{T}}{\partial \bar{Y}^2}\right] + \frac{1}{\rho C_\rho}\left(\bar{\tau}_{\overline{XX}}\frac{\partial \bar{U}}{\partial \bar{X}} + \bar{\tau}_{\overline{YY}}\frac{\partial \bar{V}}{\partial \bar{Y}} + \bar{\tau}_{\overline{XY}}\left(\frac{\partial \bar{U}}{\partial \bar{Y}} + \frac{\partial \bar{V}}{\partial \bar{X}}\right)\right) + \frac{Q_0}{\rho C_\rho}, \quad (8)$$

$$\frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} = 0, \quad (10)$$

$$\frac{\partial \bar{u}}{\partial \bar{t}} = -\left[\bar{u}\frac{\partial \bar{u}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{u}}{\partial \bar{y}}\right] - \frac{1}{\rho}\frac{\partial \bar{p}}{\partial \bar{x}} + \frac{1}{\rho}\left(\frac{\partial}{\partial \bar{x}}(\bar{\tau}_{\overline{xx}}) + \frac{\partial}{\partial \bar{y}}(\bar{\tau}_{\overline{xy}})\right) - \left(\frac{\sigma\beta_0^2}{\rho}\right)\bar{u}, \quad (11)$$

$$\frac{\partial \bar{v}}{\partial \bar{t}} = -\left[\bar{u}\frac{\partial \bar{v}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{v}}{\partial \bar{y}}\right] - \frac{1}{\rho}\frac{\partial \bar{p}}{\partial \bar{y}} + \frac{1}{\rho}\left(\frac{\partial}{\partial \bar{x}}(\bar{\tau}_{\overline{yx}}) + \frac{\partial}{\partial \bar{y}}(\bar{\tau}_{\overline{yy}})\right) - \left(\frac{\sigma\beta_0^2}{\rho}\right)\bar{v}, \quad (12)$$

$$\frac{\partial \bar{T}}{\partial \bar{t}} = -\left[\bar{u}\frac{\partial \bar{T}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{T}}{\partial \bar{y}}\right] + \frac{k}{\rho C_p}\left[\frac{\partial^2 \bar{T}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{T}}{\partial \bar{y}^2}\right] + \frac{1}{\rho C_\rho}\left(\bar{\tau}_{\overline{xx}}\frac{\partial \bar{u}}{\partial \bar{x}} + \bar{\tau}_{\overline{yy}}\frac{\partial \bar{v}}{\partial \bar{y}} + \bar{\tau}_{\overline{xy}}\left(\frac{\partial \bar{u}}{\partial \bar{y}} + \frac{\partial \bar{v}}{\partial \bar{x}}\right)\right) + \frac{Q_0}{\rho C_\rho}, \quad (13)$$

$$\bar{H}_1 = \bar{\eta}_1(\bar{x}, \bar{t}) = a \quad \text{at upper wall}, \quad (14)$$

$$\bar{H}_2 = \bar{\eta}_2(\bar{x}, \bar{t}) = a + b\cos\left[2\pi\left(\frac{\bar{x}}{\lambda} - \frac{\bar{t}}{T^*}\right)\right] \quad \text{at lower wall}, \quad (15)$$

We will now use the dimensionless variables, which are:

$$\bar{y} = ay,\ \bar{x} = \frac{\lambda}{2\pi}x,\ \bar{u} = cu,\ \bar{v} = \delta cv, \bar{p} = \frac{c\lambda\mu}{2\pi a^2}p,\ \delta = \frac{2\pi a}{\lambda},\ \bar{t} = \frac{\lambda}{2\pi c}t,\ \bar{\tau} = \frac{\mu c}{a}\tau, \quad (16)$$

$$u = \frac{\partial\psi}{\partial y}, \quad v = -\frac{\partial\psi}{\partial x}, \quad (17)$$

$$\varepsilon = \frac{b}{a},\ \theta = \frac{\bar{T} - \bar{T}_0}{\bar{T}_0},\ \eta_2 = \frac{\bar{\eta}_2}{a} = 1 + \varepsilon\cos(x),\ \alpha^2 = \mathcal{M}^2(1 + \lambda_2), \quad (18)$$

$$Re(Reynolds\ no.) = \frac{\rho c a}{\mu},\quad \Pr(Prandtl\ no.) = \frac{\mu C_p}{k},\ \mathcal{M}^2 = \frac{\sigma a^2 \beta_0^2}{\mu}, \quad (19)$$

$$Br(Brinkman\ no.) = \frac{c^2\mu}{k T_0},\quad S(heat\ source/sink\ no.) = \frac{Q_0 a^2}{T_0 k}, Bi = \frac{h a}{k}, \quad (20)$$

$$\frac{\partial}{\partial x}\frac{\partial \psi}{\partial y} - \frac{\partial}{\partial y}\frac{\partial \psi}{\partial x} = 0,$$
(21)

$$Re\,\delta\frac{\partial u}{\partial t} = -Re\,\delta\left(\left[(u+1)\,\frac{\partial u}{\partial x} + v\,\frac{\partial u}{\partial y}\right]\right) - \frac{\partial p}{\partial x} + \delta\left(\frac{\partial}{\partial x}\,(\tau_{xx})\right) + \frac{\partial}{\partial y}\,\left(\tau_{xy}\right) - \mathcal{M}^2(u+1),$$
(22)

$$Re\,\delta^2\frac{\partial v}{\partial t} = -Re\,\delta^2\left(\left[(u+1)\frac{\partial v}{\partial x} + v\,\frac{\partial v}{\partial y}\right]\right) - \frac{\partial p}{\partial y} + \delta^2\left(\frac{\partial}{\partial x}\,(\tau_{xx})\right) + \delta\left(\frac{\partial}{\partial y}\,\left(\tau_{xy}\right)\right) - \delta^2\,\mathcal{M}^2 v,$$
(23)

$$Re\,\delta\,\Pr\left[\frac{\partial \theta}{\partial t} + \left[\,(u+1)\,\frac{\partial \theta}{\partial x} + \,v\,\frac{\partial \theta}{\partial y}\right]\right] = \left[\delta^2\,\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2}\right] + Br[\delta(\tau_{xx}\frac{\partial u}{\partial x}) + \delta(\tau_{yy}\frac{\partial v}{\partial y}) + \tau_{xy}\left(\frac{\partial u}{\partial y} + \delta^2\frac{\partial v}{\partial x}\right)] + \,S,$$
(24)

$$\tau_{xx} = \frac{2\,\delta}{1+\lambda_1}\left(1 + \frac{\delta\,c\,\lambda_2}{a}\left(\frac{\partial \psi}{\partial y}\frac{\partial}{\partial x} + \frac{\partial \psi}{\partial x}\frac{\partial}{\partial y}\right)\right)\frac{\partial^2 \psi}{\partial x \partial y},$$
(25)

$$\tau_{xy} = \frac{1}{1+\lambda_1}\left(1 + \frac{\delta\,c\,\lambda_2}{a}\left(\frac{\partial \psi}{\partial y}\frac{\partial}{\partial x} - \frac{\partial \psi}{\partial x}\frac{\partial}{\partial y}\right)\right)\left(\frac{\partial^2 \psi}{\partial y^2} - \delta^2\frac{\partial^2 \psi}{\partial x^2}\right) = \left(\frac{1}{1+\lambda_1}\right)\left(\frac{\partial^2 \psi}{\partial y^2}\right),$$
(26)

$$\tau_{yy} = \frac{2\,\delta}{1+\lambda_1}\left(1 + \frac{\delta\,c\,\lambda_2}{a}\left(\frac{\partial \psi}{\partial y}\frac{\partial}{\partial x} - \frac{\partial \psi}{\partial x}\frac{\partial}{\partial y}\right)\right)\frac{\partial^2 \psi}{\partial x \partial y},$$
(27)

Using the long wavelength approximation and neglecting the wave number δ along with low Reynolds number in our analysis [21], the field equations (21)- (27) now give:

$$\frac{\partial p}{\partial x} + \frac{\partial}{\partial y}\,\left(\tau_{xy}\right) - \mathcal{M}^2(u+1) = \frac{\partial p}{\partial x} + \frac{\partial}{\partial y}\left(\left(\frac{1}{1+\lambda_1}\right)\frac{\partial^2 \psi}{\partial y^2}\right) - \mathcal{M}^2(u+1) = 0,$$
(28)

$$\frac{\partial p}{\partial y} = 0,$$
(29)

$$\frac{\partial^2 \theta}{\partial y^2} + Br\,\tau_{xy}\left(\frac{\partial u}{\partial y}\right) + \,S = \frac{\partial^2 \theta}{\partial y^2} + Br\left(\left(\frac{1}{1+\lambda_1}\right)\left(\frac{\partial^2 \psi}{\partial y^2}\right)^2\right) + \,S = 0,$$
(30)

$$\frac{\partial p}{\partial x} - \left(\left(\frac{1}{1+\lambda_1}\right)\psi_{yyy}\right) + \mathcal{M}^2\left(\psi_y + 1\right) = 0,$$
(31)

$$\frac{\partial^2 \theta}{\partial y^2} + Br\,\tau_{xy}\left(\,\psi_{yy}\,\right) + \,S = \frac{\partial^2 \theta}{\partial y^2} + Br\left(\left(\frac{1}{1+\lambda_1}\right)\left(\psi_{yy}\,\right)^2\right) + \,S = 0,$$
(32)

The boundary conditions for flow functions in the wave frame are::

$$\psi = 1, \frac{\partial \psi}{\partial y} = -1 \qquad at \qquad \eta_1,$$
(33)

$$\psi = -1,\ \frac{\partial \psi}{\partial y} = -1 \qquad at \qquad \eta_2,$$
(34)

$$\psi_{yyyy} - \alpha^2\left(\psi_{yy}\right) = 0,$$
(35)

$$\theta_{yy} + Br\left(\left(\frac{\mathcal{M}}{\alpha}\right)^2\left(\psi_{yy}\,\right)^2\right) + \,S = 0,$$
(36)

$$\frac{\partial p}{\partial x} = \left(\left(\frac{1}{1+\lambda_1}\right)\psi_{yyy}\right) - \mathcal{M}^2(\psi_y + 1),$$
(37)

We can use the dimensionless equation to calculate the increase in pressure per wavelength, ΔP, as shown in the following figure::

$$\Delta P = \int_0^{2\pi}\left(\frac{dP}{dx}\right) dx,$$
(38)

Solution:

The solutions of Eqs. (35), (36) and (38) with the boundary conditions Eqs. (33) and (34) with help of Mathematica program are in the form:

$$\psi[y] = \frac{\frac{e^{y\alpha} c_1}{\alpha} + \frac{e^{-y\alpha} c_2}{\alpha}}{\alpha} + c_3 + y\, c_4,$$
(39)

$$\theta[y] = -\frac{\mathrm{Br}\, e^{-2\, y\, \alpha}\left(c_2{}^2 + c_1{}^2 e^{4\, y\, \alpha}\right)\mathcal{M}^2}{4\,\alpha^4} + c_5 + y c_6 - \frac{\left(2\,\mathrm{Br}\, c_1 c_2\, \mathcal{M}^2 + S\alpha^2\right)\mathrm{Log}\left[e^{2\, y\, \alpha}\right]^2}{8\,\alpha^4}, \quad (40)$$

$$\frac{\partial p}{\partial x} = -\mathcal{M}^2\left(1 + \frac{e^{y\alpha} c_1}{\alpha} - \frac{e^{-y\alpha} c_2}{\alpha} + c_4\right) + \frac{e^{y\alpha}\alpha c_1 - e^{-y\alpha}\alpha c_2}{1+\lambda_1},$$
(41)

$$\Delta P = -\frac{e^{-\alpha\lambda}\mathcal{M}^2\left(e^{2\alpha\lambda} c_1 + c_2 + e^{\alpha\lambda}\left(-c_1 - c_2 + \alpha^2\lambda(1+c_4)\right)\right)}{\alpha^2} - \frac{c_1 - e^{\alpha\lambda} c_1 + c_2 - e^{-\alpha\lambda} c_2}{1+\lambda_1},$$
(42)

Where, $c_1, c_2, c_3, c_4, c_5 and\ c_6$ are a constants that calculated later.

Results and Discussions:

In order to gain a physical understanding of the temperature θ, the pressure rise Δp and the streamline ψ, these factors were discussed by assigning numerical values to the parameters Br, M^2 and ε, To discuss the effect of Br on temperature in the presence of MHD, it should be noted that Br measures the extent to which the fluid's temperature is raised by viscous dissipation compared to thermal conduction, and that MHD induces a Lorentz force (J×B), which opposes motion and dampens velocity gradients; Consequently, a higher Br value indicates stronger viscous heating, but MHD tends to reduce velocity gradients, thereby mitigating the heating effect; Consequently, the temperature decreases as Br increases and rises as it decreases. Now, to examine the effect of the magnetic field on temperature, it turns out that the temperature increases as MHD (M^2) increases, and the opposite occurs as it decreases; that is, the temperature decreases if MHD decreases , The Brinkmann number is a key indicator of the extent to which viscous heating affects pressure. Higher values of 'Br' indicate a stronger correlation between temperature and pressure, leading to greater reductions in pressure and the potential for excessive temperature rise in engineering systems; where magnetohydrodynamic (MHD) dynamics affect fluid pressure by introducing electromagnetic forces that alter the momentum balance. An applied magnetic field tends to dampen velocity fluctuations, increase flow resistance, and alter pressure gradients, particularly in electrically conductive fluids such as plasma or molten metals. Higher Hartmann numbers (M^2) indicate stronger magnetic effects, greater reductions in pressure, and more consistent velocity profiles.

The effect of M^2 on the trapping process. An increase in M^2 from 0.1 to 0.3 results in rotation and relative displacement of the free vortices about the x-axis. Any further increase leads to an increase in this trapping process. Similarly, the effect of the capacity ratio, or the occlusion factor, on the mean flow rate ε. For narrow channels, ε has a strong influence on the mean flow rate; in a channel where ε = 0.3, the flow rate increases significantly as ε increases from 0.1 to 0.3. We conclude that ε may be an important parameter in the design of peristaltic systems.

Conclution:

This article explores the simultaneous impacts of hydromagnetic dynamics on blood circulation within a non-Newtonian fluid characterized by specific wall properties. The core issue of blood flow for this fluid is simplified by presuming a large wavelength and a creeping flow regime. An analytical solution is derived for the resulting ordinary differential equation, leading to a closed-form solution. The key findings of the current flow analysis are summarized as follows:

• The magnetic field causes an increase in heat distribution while decreasing pressure.

• The Lala coefficient results in a decrease in heat distribution and an increase in pressure.

• The wall stiffness and wall tension coefficient contribute to an increase in velocity distribution.

• An increase in the slip coefficient and porosity coefficient leads to a gradual rise in bolus volume.

• The magnetic field effects result in a higher number of retained boluses.

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