Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Peristaltic Transport of Bingham Fluid through Nonuniform Channel with Convective Conditions and Lorentz Forces

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ARTICLE INFO

Article history:
Received 26 August 2022
Received in revised form 9 January 2023
Accepted 15 January 2023
Available online 3 February 2023

Keywords:
Variable viscosity; Biot number; variable thermal conductivity; permeable walls; partial velocity slip parameter

ABSTRACT

In this study, the impacts of changing the liquid characteristics of the Bingham fluid are highlighted under MHD peristaltic transport. Conditions for convective and porous boundary conditions are taken into consideration. By using proper similarity transformations, the governing equations become dimensionless. For temperature, velocity, and streamlines, the series solution is found. The MATLAB 2019b programming offers a graphical depiction of relevant metrics on physiological flow parameters. The findings demonstrate that lowering the velocity and temperature profiles occurs when the magnetic parameter is increased. Furthermore, the effect of changing viscosity increases the trapped bolus size by a small amount. Once again, the results of the present investigation have significance for our knowledge of the complex rheological mechanisms governing blood flow via small arteries.

1. Introduction

As seen in the human gastrointestinal system, peristalsis allows fluid to flow through a duct as a result of waves formed along the wall. The smooth muscle's contraction and relaxation propels the ball of the foot, which is commonly referred to as a bolus. Latham [1] coined the term "peristaltic waves" in physiological and mechanical studies. Peristaltic transport was studied by Ramachandra and Usha [2] under various physiological conditions. Hamid *et al.,* [3] used a long wavelength as well as a small Reynolds number to study the non-linear peristaltic motion of a micropolar fluid. Eldesoky *et al.,* [4] looked at how dynamic wall characteristics, relaxation time, and border slip circumstances affected the viscous non-Newtonian Maxwell fluid flow during peristalsis.

MHD generators, aerospace engineering, the geothermal industry, nuclear reactors, astrophysics, engineering, medicine, and petroleum operations all make extensive use of Magnetohydrodynamic fluid flow. Researchers have been interested in flow-through channels in the MHD sector due to their many uses in medical engineering and the human organ system. The broad usage of magnetic particle flow during peristalsis, as shown in magnetic blood pumping, medication targeting, casting process,

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https://doi.org/10.37934/arfmts.103.1.7586

bleeding reduction during surgery, and magnetotherapy, among other uses, has lately attracted a lot of researchers. Reddy [5] analysed the velocity slip of MHD porous peristaltic transport impact in mass and heat transfer, motivated by the application of MHD on biological fluids. To examine the consequences of joule heat and the velocity slip of MHD peristaltic transport under chemical reaction, Reddy and Kattamreddy [6] took into consideration the permeable channel. Avid *et al.*, [7] analyse the magnetic effects of peristaltic flow in a curved complex wavy channel. Hayat [8] investigated the Johnson-Segalman fluid through an inclined channel with MHD peristalsis while taking convective boundary conditions into account. Divya *et al.,* [9] study the Jeffrey liquid motion in a porous MHD conduit in peristalsis. The inclined channel has compliant walls with concentration slip and convective boundary conditions. To investigate the effects of different flow properties and slip circumstances under peristalsis, Manjunath *et al.*,[10] investigated the Jeffrey liquid flow in an axisymmetric conduit with compliant walls and the MHD impact.

Although constant thermo-physical features including thermal conductivity and variable viscosity have been used to study the peristaltic process, isotropic fluids can't use these properties as their fundamentals. As the temperature and viscosity fluctuate in blood, they become more significant. As a result, it is important to consider these effects. Temperature diversity can cause differences in the characteristics, particularly variable viscosity and thermal conductivity. The physical characteristics of the fluid are altered by the temperature and heat instability induced for lubricating fluids by the inner contacts, and cannot be recovered. The increasing usage of transportation is caused by the rise in temperature. Numerous conventional and biological fluids may be used because of variable liquid characteristics. Samreen *et al.*,[11] studied nanofluids. In a peristaltic channel with convective boundary parameters, porosity, and varying liquid characteristics, Hanumesh [12] analyse the Rabinowitsch fluid flow. For analysing the mass and heat transfer impact, Manjunatha [13] analyse the movement of a Jeffery fluid through a porous non-uniform conduit with varying parameters. To continue the study of mass and heat transferring properties of MHD peristaltic movement, Hanumesh *et al.*, [14] investigated flow in a complaint channel with porosity in varied thermal conductivity and convective parameters. According to Khan *et al.,* [15], the peristaltic process of magneto-Carreaunanofluid with irreversible heat transfer is affected by varying thermal viscosity and conductivity.

Non-Newtonian behaviour is seen in a typical Bingham plastic and has a linear shear stress-deformation rate. These fluids can transfer shear stress even in the absence of a velocity gradient. Under low stress, the fluid acts like a solid body; under high stress, it becomes viscous. Compared to Newtonian fluids, Bingham has a thicker covering. Clay, toothpaste, printing ink, paint, and edibles such as margarine, mayonnaise, yogurt, melted chocolate, and ketchup are traditional examples of Bingham fluids. When the yield stress in the core layer exceeds the applied shear stress, Bingham liquids behave like a solid medium. This implies that a solid plug is moving within the channel. Bingham fluids are useful in several situations, including the shallow flow of mud and soil, pulmonary mucus, avalanches, waxy crude oils, and ceramics. Through the use of the increased magnetic field, Akram *et al.,* [16] investigate how the Bingham fluid flow behaves in terms of heat and mass transfer. The Soret and Dufour properties of Bingham plastic movement in the existence of a magnetic field were examined by Hayat *et al.*, [17]. Using an inclined porous channel, Lakshminarayana [18] observed the results of Joule heat on the behaviour of fluid during peristaltic pumping. Bingham liquid transfer using the peristaltic mechanism is investigated by Manjunath *et al.,* [19] in a convectively heated tube with pores and varied liquid characteristics. Recently, Tanveer *et al.*,[20] analysed how electro osmosis affected the peristaltic nanofluid flow using the Bingham liquid. Several researchers has calculated to the peristaltic transport medium with nonNewtonian fluids and nanofluids via different geometry [21-39].

Based on the aforementioned research, a flow behaviour model of a Bingham fluid in a peristaltic channel with a compliant wall is designed to examine the implications of changing liquid parameters. In addition, the partial velocity slip and non-uniform geometry under the MHD effect are investigated. In the lubrication technique, the governing equations are resolved by MATLAB programming.

2. Problem Formulation

Taking into account the two-dimensional Bingham fluid flow that conducts electricity in a non-uniform channel via solid walls. This fluid is transmitted at a constant velocity c through the wave-like movements that the peristaltic action causes. The channel about the axis is symmetric. This liquid is exposed toB_1a transverse magnetic field, and since we approximate the Reynolds number to be low, the induced charge is minimal. In the process of moving into the magnetic field, two important physical effects occur. First, the stream is stimulated by$E$, an electric field. Due to the lack of sufficient charge thickness,$\nabla . E = 0$. By neglecting the induced magnetic field, the induced electric field is rendered irrelevant$\nabla \times E = 0$. The following impact is progressive, meaning that a Lorentz force $(J \times B_1)$ follows the liquid and modifies its motion, where$J$represents its current density. As a consequence, energy from the electromagnetic field is transferred to the fluid. The relativistic effects are neglected in the present study, and Ohm's law provides J as

$$J = \sigma(\overline{V} \times B_1) \tag{1}$$

The peristalsis-induced channel wall deformation is

$$\overline{h}(\overline{X}, \overline{t}) = l(\overline{X}) + b\text{Sin}\left[\frac{2\pi}{\lambda}\left(\overline{X} - c\overline{t}\right)\right], \tag{2}$$

Where width of the Nonuniform channel is given by $l(\overline{X})$, time by t, and wave amplitude by b. The formulas governing the flow are as given below [21-31]

$$\frac{\partial \overline{U}}{\partial \overline{X}} + \frac{\partial \overline{V}}{\partial \overline{Y}} = 0, \tag{3}$$

$$\rho\left(\frac{\partial \overline{U}}{\partial \overline{t}} + \overline{U}\frac{\partial \overline{U}}{\partial \overline{X}} + \overline{V}\frac{\partial \overline{U}}{\partial \overline{Y}}\right) = -\frac{\partial \overline{P}}{\partial \overline{X}} + \frac{\partial \overline{\tau}_{\overline{XX}}}{\partial \overline{X}} + \frac{\partial \overline{\tau}_{\overline{XY}}}{\partial \overline{Y}} - \sigma_1 B_0^2 \overline{U} + \rho g \text{Sin}\alpha, \tag{4}$$

$$\rho\left(\frac{\partial \overline{V}}{\partial \overline{t}} + \overline{U}\frac{\partial \overline{V}}{\partial \overline{X}} + \overline{V}\frac{\partial \overline{V}}{\partial \overline{Y}}\right) = -\frac{\partial \overline{P}}{\partial \overline{Y}} + \frac{\partial \overline{\tau}_{\overline{XX}}}{\partial \overline{X}} + \frac{\partial \overline{\tau}_{\overline{XY}}}{\partial \overline{Y}} - \rho g \text{Cos}\alpha, \tag{5}$$

$$\rho c_p\left(\frac{\partial \overline{T}}{\partial \overline{t}} + \overline{U}\frac{\partial \overline{T}}{\partial \overline{X}} + \overline{V}\frac{\partial \overline{T}}{\partial \overline{Y}}\right) = \frac{\partial}{\partial \overline{X}}\left(k(\overline{T})\frac{\partial \overline{T}}{\partial \overline{X}}\right) + \frac{\partial}{\partial \overline{Y}}\left(k(\overline{T})\frac{\partial \overline{T}}{\partial \overline{Y}}\right) + \overline{\tau}_{\overline{XX}}\frac{\partial \overline{U}}{\partial \overline{X}} + \overline{\tau}_{\overline{YY}}\frac{\partial \overline{V}}{\partial \overline{Y}} + \overline{\tau}_{\overline{XY}}\left(\frac{\partial \overline{V}}{\partial \overline{X}} + \frac{\partial \overline{U}}{\partial \overline{Y}}\right) = 0, \tag{6}$$

The elastic wall motion expression is represented as

$$L(P) = P - P_0, \tag{7}$$

where $P_0(=0)$ expresses the pressure exerted on outer wall as a result of muscle tension. The membrane stretching and viscous damping is the primary focuses of this L linear operator, which is expressed as

$$L = -\tau \frac{\partial^2}{\partial x^2} + m_1 \frac{\partial^2}{\partial t^2} + n_1 \frac{\partial}{\partial t}, \tag{8}$$

where viscous damping coefficient is represented by n_1, elastic tension byτ, and mass/unit area by m_1.

$$\frac{\partial p}{\partial x} = E_1 \frac{\partial^3 h}{\partial x^3} + E_2 \frac{\partial^3 h}{\partial t^2 \partial x} + E_3 \frac{\partial^3 h}{\partial t \partial x^2}. \tag{9}$$

when in $(\overline{x}, \overline{y})$ wave frame, $(\overline{u}, \overline{v})$ denotes velocity variables and $(\overline{x}, \overline{y})$ denotes coordinates then,

$$\overline{x} = \overline{X} - c\overline{t}, \overline{y} = \overline{Y}, \overline{u}(\overline{x}, \overline{y}) = \overline{U}(\overline{X}, \overline{Y}, \overline{t}) - c, \overline{v}(\overline{x}, \overline{y}) = \overline{V}(\overline{X}, \overline{Y}, \overline{t}), \overline{T}(\overline{x}, \overline{y}) = \overline{T}(\overline{X}, \overline{Y}, \overline{t}), \overline{p}(\overline{x}, \overline{y}) = \overline{P}(\overline{X}, \overline{Y}, \overline{t}). \tag{10}$$

Dimensionless values can be expressed as

$$x = \frac{\overline{x}}{\lambda}, y = \frac{\overline{y}}{l_2}, u = \frac{\overline{u}}{c}, v = \frac{\overline{v}}{c\delta}, c_p = \frac{l_2}{\lambda}, p' = \frac{p{l_2}^2}{\mu_0 \lambda c}, Re = \frac{l_2 c}{\vartheta}, \vartheta = \frac{\mu_0}{\rho}, M = \sqrt{\frac{\sigma_1}{\mu_0}} B_0 l_2,$$
$$\tau_{xx} = \frac{l_2 \overline{\tau}_{xx}}{\mu_0 c}, \varepsilon = \frac{b}{l_2}, t = \frac{\overline{t}c}{\lambda}, \tau_{xy} = \frac{l_2 \overline{\tau}_{xy}}{\mu_0 c}, \tau_{yy} = \frac{l_2 \overline{\tau}_{yy}}{\mu_0 c}, \psi' = \frac{\psi}{l_2 c}, Sc = \frac{\mu_0}{\rho M_A}, \mu_0 = \frac{\overline{\mu}_0}{\mu},$$
$$Pr = \frac{\mu_0 c_p}{k_0}, E_1 = \frac{-\tau {l_2}^3}{\mu_0 \lambda^3 c}, E_2 = \frac{m_1 {l_2}^3 c}{\mu_0 \lambda^3}, E_3 = \frac{n_1 {l_2}^3}{\mu_0 \lambda^3}, \theta = \frac{T - T_0}{T_0}, Ec = \frac{c^2}{c_p T_0},$$
$$l(\overline{x}) = l_2 + m_1(\overline{x}), F = \frac{\vartheta c}{g l_2^2}, h = \frac{\overline{h}}{l_2} = 1 + \frac{\lambda m_1 x}{l_2} + \varepsilon\, sin(\,2\pi(x - t)). \tag{11}$$

Using Eq. (10) and Eq. (11) in Eq. 3 to Eq. 6 the nondimensional governing equations assume the following form, supposing small Reynolds numbers for long and wavelength

$$\frac{\partial p}{\partial x} = \frac{\partial \tau_{xy}}{\partial y} + \frac{\text{Sin}\alpha}{F} - M^2(u+1), \tag{12}$$

$$\frac{\partial p}{\partial y} = 0, \tag{13}$$

$$\frac{\partial}{\partial y}\left(k(\theta)\frac{\partial \theta}{\partial y}\right) + Br\tau_{xy}\left(\frac{\partial u}{\partial y}\right) = 0, \tag{14}$$

where τ_{xy} indicates the Bingham fluid's fundamental equation which can be expressed as

$$\tau_{xy} = \mu(y)\frac{\partial u}{\partial y} + \tau_0 \text{for} \tau \geq \tau_0, \tag{15}$$

$$\tau_{xy} = 0 \text{for} \tau \leq \tau_0, \tag{16}$$

where yield stress can be denoted by $\tau_0$and variable viscosity by $\mu(y)$.
The variable viscosity expressions can be written as

$$\mu(y) = 1 - \alpha_1 y \text{for} \alpha_1 << 1, \quad (17)$$

The thermal conductivity expressions can be written as

$$k(\theta) = 1 + \gamma\theta \text{for} \gamma << 1, \quad (8)$$

where the coefficient of viscosity can be given by α_1 and the thermal conductivity coefficient by γ.
Consequently, the dimensionless peripheral criteria are represented as

$$u + \frac{\sqrt{Da}}{\alpha}\frac{\partial u}{\partial y} = -1\,; \frac{\partial \theta}{\partial y} + Bi\theta = 0 \text{at} y = h = 1 + mx + \varepsilon\, sin[2\pi(x - t)], \quad (19)$$

$$\frac{\partial u}{\partial y} = \tau_0\,; \quad \frac{\partial \theta}{\partial y} = 0 \text{at} y = 0, \quad (20)$$

3. Method of Solution

Because of the nonlinear nature of the equations, it is difficult to address the issue and come up with a closed-form solution. To get this solution, the perturbation approach is used. To velocity and temperature, we utilize (α_1) and (γ) as perturbation parameters, correspondingly.

$$u = u_0 + \alpha_1 u_1 + \alpha_1^2 u_2 + O(\alpha_1^3), \quad (21)$$

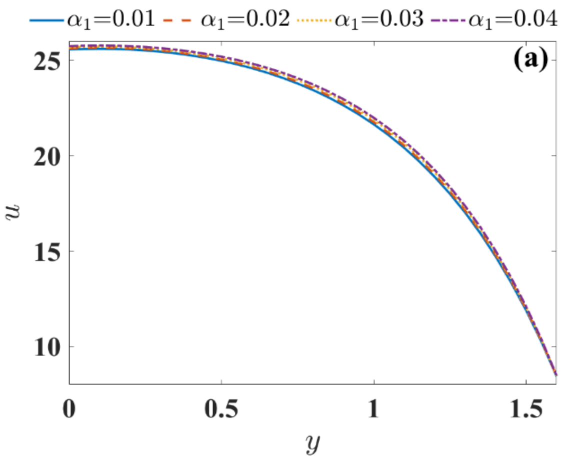
$$\theta = \theta_0 + \gamma\theta_1 + \gamma^2\theta_2 + O(\gamma^3), \quad (22)$$

The zeroth, first, and second orders of solutions for temperature and velocity have been solved using MATLAB 2019b programming. Additionally, a visual analysis of the influence of relevant factors of interest is provided.

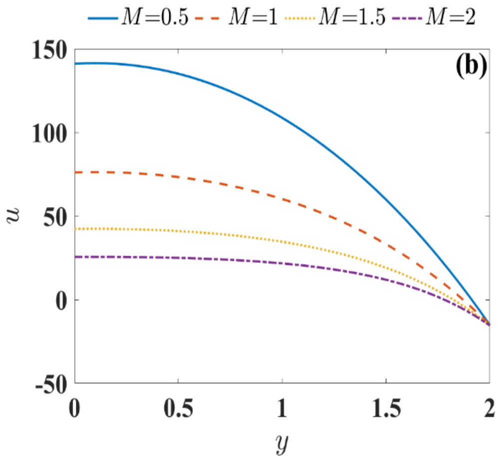
4. Results and Discussion

Using graphical representations, this section examines the effects of streamlines (ψ), velocity (u), and temperature (θ). Specifically, the impact nature on the magnetic parameter (M), wall parameters (E_1, E_2, E_3), variable viscosity (α_1), permeable parameter (Da), yield stress (τ_0), non-uniform parameter (m), partial slip parameter (β), Biotnumber (Bi),and angle of inclination (α) are studied.

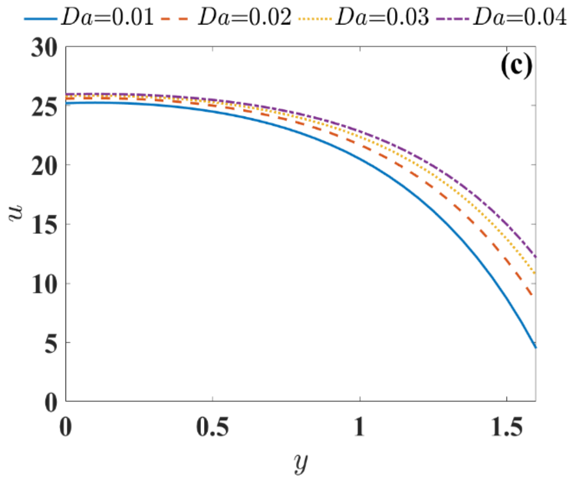
The results of the axial velocity in terms of various factors are mapped and depicted in Figure 1 to Figure 3. The flow velocity marginally rises when the variable viscosity coefficient changes, as demonstrated in Figure 1(a). Growing values gradually reduce viscosityα_1, which enhances fluid velocity. As seen in Figure 1(b), changing the magnetic parameter causes the velocity to decrease. The radially directed magnetic field motion slows the flow of fluid. The reflection of flow through porous walls can be utilized to highlight the blood flow within arteries. Figure 1(c) shows that the flow velocity gradually rises with the increased Darcy number. The velocity falls when the partial slip parameterβ is increased, as illustrated in Figure 1(d). The physical characteristics of the flexible wall are shown by the graphical representation of the elastic parameter effect E_1andE_2on the flow velocity. Figure 2(a)-(b), which demonstrate an incline in velocity with increasing elastic parameter values E_1andE_2 in the non-uniform channel, help to visualize them as they provide low resistance to the fluid movement. According to physical analysis, that dampness has little impact on speed which is supported by the fact that the flow velocity drops when the damping wall value E_3 is raised. Simultaneously, wall tension is preferred. Figure 3(a) demonstrates that decreasing the velocity while increasing the yield stress. The velocity of a fluid increases with non-uniform conditions, as illustrated in Figure 3(b). The impact of inclination angle elevation on the magnetic field is illustrated in Figure 3(c), which also implies that the velocity profile decreases along the channel's sides but rises in the middle.



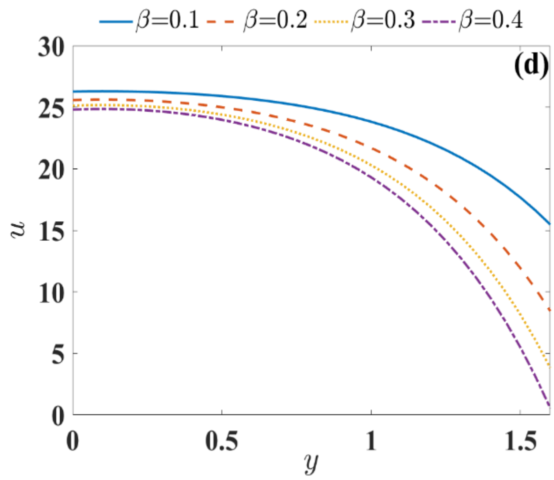
(a) variable viscosity



(b) magnetic



(c) permeable



(d) partial velocity slip

Fig. 1. Velocity graphs for distinctive parameter values

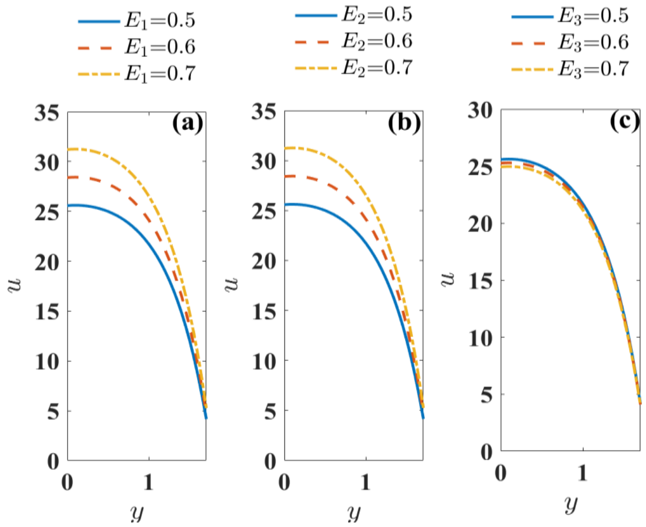


Fig. 2. Velocity plots *u(y)* for distinctive elastic parameter values

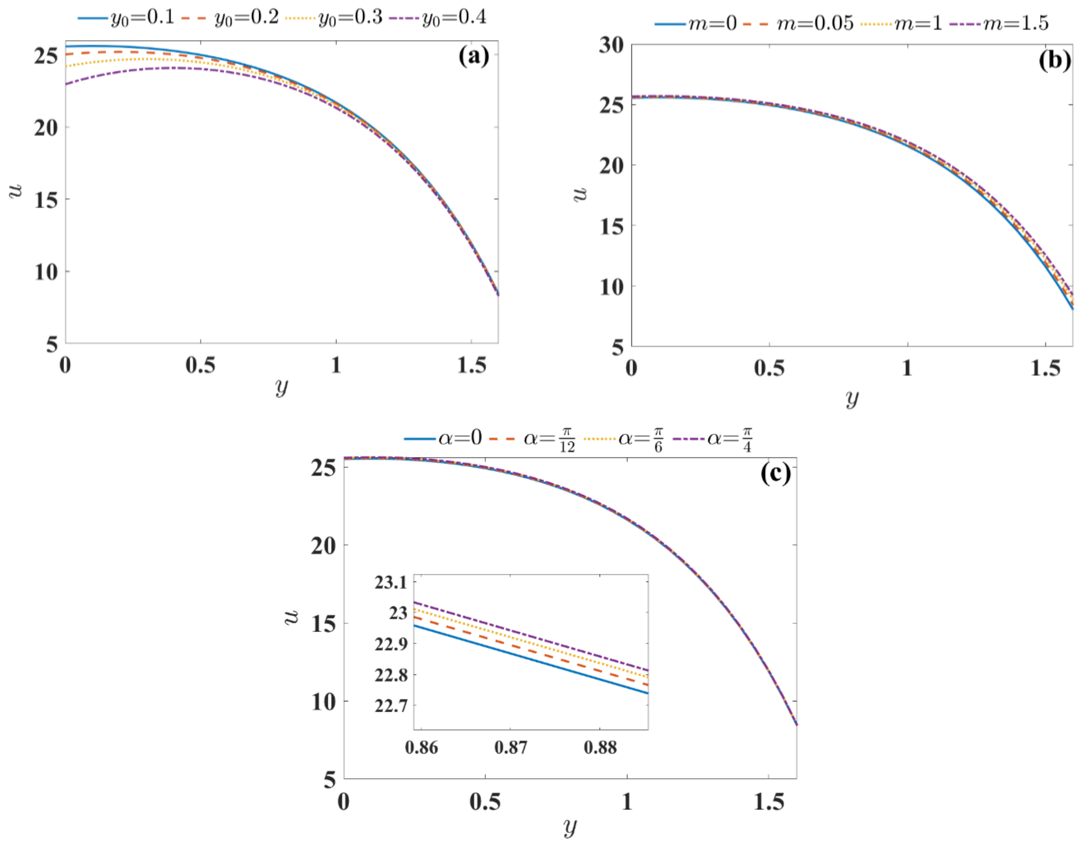


Fig. 3. Velocity graphs for distinctive parameter values i.e., (a) yield stress, (b) non-uniform (c) inclination angle

The plot in Figure 4(a)–(d) demonstrates how different parameters respond to temperature. The decrease in velocity that occurs when the variable viscosity increases are seen in Figure 4(a). The temperature increases with increasing variable thermal conductivity values, according to the analysis of Figure 4(b). Figure 4(c) illustrated that the magnetic field's restricting properties cause the measure of temperature to decrease as the magnetic parameter's deviation increases. It is made clear in Figure

4(d) that raising the Biot number declines the temperature function because doing so reduces thermal conductivity and causes the temperature profile to drop.

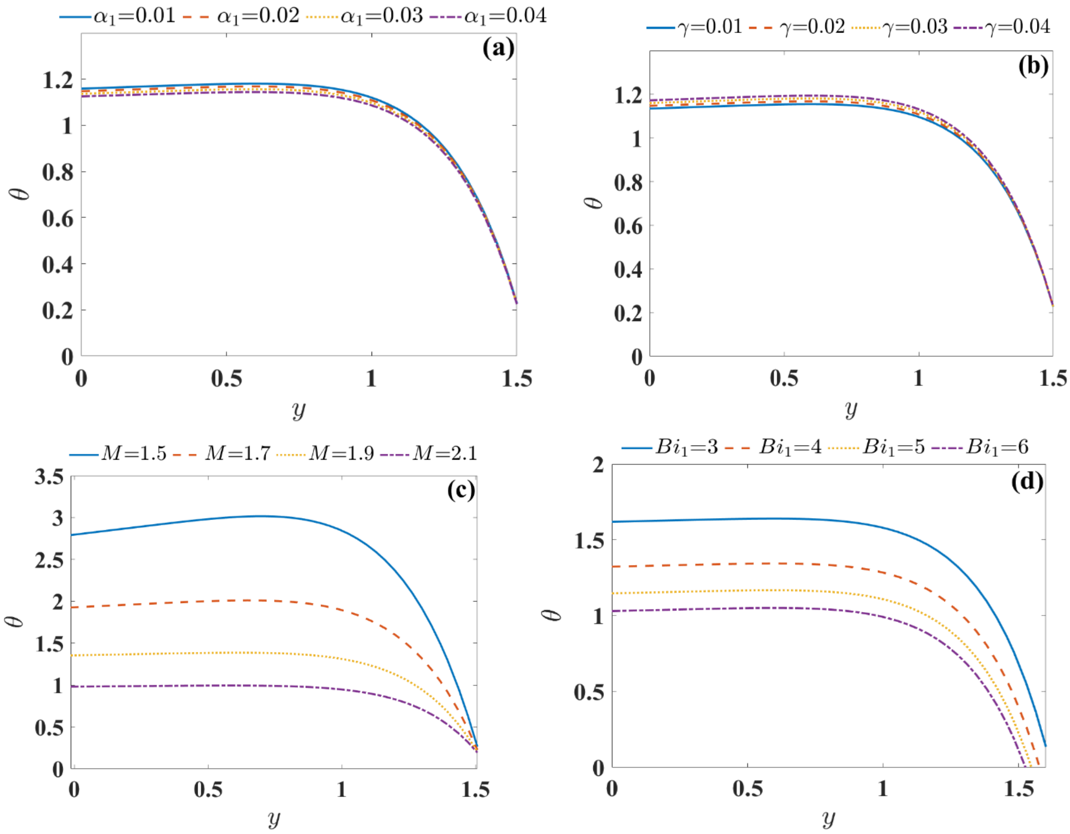


Fig. 4. Temperature graphs for distinctive values of (a) variable viscosity, (b) variable thermal conductivity, (c) magnetic parameters (d) Biot number

The streamlines are essential for comprehending how the bolus moves via biological organs. It particularly assists in comprehending chyme motion in the thrombus formation and gastrointestinal tract. The bolus size is slightly enhanced by the fluctuation in the variable viscosity, as depicted in Figure 5. Figure 6 demonstrated that the bolus diminishes when the magnetic parameter increases. With a change in the magnetic parameter and varied viscosity, the formation of bolus may thus be controlled.

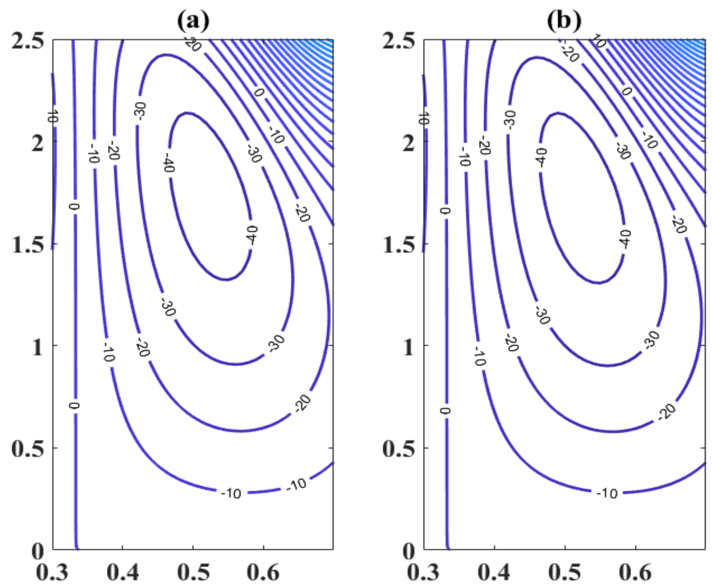


Fig. 5. Varying variable viscosity streamlines if (a) $\alpha_1 = 0.01$ (b) $\alpha_1 = 0.03$

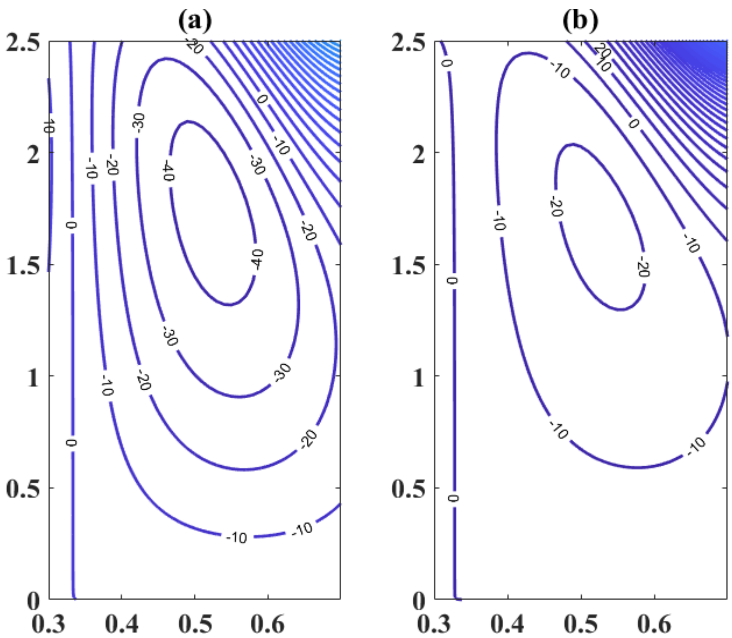


Fig. 6. Variable magnetic parameter streamlines if (a) $M = 1.5$ (b) $M = 2$

5. Conclusions

This investigation looks at how various liquid characteristics impact the MHD peristaltic Bingham fluid flow. The mass and heat transferring properties of a non-uniform channel with porous walls are investigated using the impacts of barrier and convective properties. The study's results also contribute to our understanding of how blood behaves in an external magnetic field. The following is a summary of these theoretical findings

i. Velocity rises in the presence of permeable parameters, variable viscosity, inclination angle, and non-uniform parameters. But the velocity is decreased by the magnetic parameter.
ii. The velocity decreases with increasing partial slip and yield stress parameters.
iii. Temperature increases with variable thermal conduction.
iv. The variable viscosity and Biot number increase together with a decline in the temperature function.
v. The magnetic parameter lowers the trapped bolus's size.

Acknowledgement
This research was not funded by any grant.

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