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Impact of inclined magnetic field and rotation on peristaltic flow of viscoelastic fluid with variable viscosity

Mohammed Salim Ramadhan *
Department of Mathematics
College of Education
Mustansiriyah University
Baghdad
Iraq

Khalid Khaleefah Jassim †
Department of Surveying Techniques
Institute of Technology
Middle Technical University
Baghdad
Iraq

Abstract

This study focuses on how a slanted magnetic field and rotation affect viscoelastic fluid it moves peristaltically via porous media in a tapered asymmetric slanted channel with a variable viscosity and the mixed convection heat transfer is investigated. Under the presumption of a long wavelength and a short Reynold number, the equations of continuity, momentum, and energy have been developed. The flow is examined while moving at the wave's velocity in a wave frame of reference. The series of analytical solutions for the temperature, velocity, and stream function can be obtained using the perturbation technique. Using the Mathematica package, the effect of several fascinating parameters on temperature, axial velocity, and stream function in a flow system has been produced and described through graphical representation.

Subject Classification: *76X05, 83C50.*

Keywords: *Peristaltic flow, Reynolds number, Rotation, Stream function, Variable viscosity, Viscoplastic fluid.*

* *E-mail:* **m7md_salim@uomustansiriyah.edu.iq (Corresponding Author)**
† *E-mail:* **khalid.khaleefah@mtu.edu.iq**

1. Introduction

When transporting a variety of complex rheological fluids across different locations is straightforward, peristaltic pumping is the method of choice. Peristaltic pumping is the name given to this principle. The small intestine's movements, which are essential to the digestive system's correct operation, are caused by peristalsis. For this reason, they are in charge of bringing food to the surface for nutrient absorption, mixing it with digestive juices, breaking it down into smaller pieces, and moving food down the gastrointestinal tract. Blood flow, food mixing, and the extraction of crude oil from petroleum products are a few examples [1]-[3].

Understanding the peristaltic flows of hydrodynamic fluids under various assumptions, like low Reynolds number and long wave length and tiny wave amplitude, etc., has been the main subject of many experimental and theoretical studies. Despite the large body of research on this subject, only a few current studies are included in the studies [4]–[11]. The investigation of heat and fluid movement in porous media is crucial for numerous other scientific and engineering domains, including biological material drying and biomedical research. Natural porous media include things such as wood, beach sand, rye bread, stand stone, human lung, the bile duct, gall bladders with stones, and tiny blood veins. Many researchers, such as [12]-[15], report their findings in the peristaltic flows of viscoplastic fluid via a porous media.

Ahmed, et al [16] discussed Peristaltic pumping of convective nanofluid with magnetic field and thermal radiation in a porous channel. Al-Khafajy, Labban [17] obtains Temperature and Concentration Effects on Oscillatory Flow for Variable Viscosity Carreau Fluid through an Inclined Porous Channel. Abdelhafez et al. [18] developed Influence of an inclined magnetic field and heat and mass transfer on the peristaltic flow of blood in an asymmetric channel. Inclined MHD Effects in Tapered Asymmetric Porous Channel with Peristalsis: Applications in Biomedicine. by Tanveer, Anum, and Sharak [19]. Khudair and Dwail [20] analyzed Studying the Magnetohydrodynamics for Williamson Fluid with Varying Temperature and Concentration in an Inclined Channel with Variable Viscosity. Farooq, et al. [21] studied Magnetohydrodynamic peristalsis of variable viscosity Jeffrey fluid with heat and mass transfer. Atlas, Javed, and Imran [22] have been study the effects of heat and mass transfer on the peristaltic motion of Sutterby fluid in an inclined channel [23].

2. The mathematical formulation of the problem

We investigate the flow via a porous media of viscoplastic magnetohydrodynamic (MHD) fluid in a tapering asymmetric channel with a width of (2d). The X and Y axes are parallel to the flow and vertical to it, respectively. The movement has been brought about by the transmission of channel walls. The equations below present the upper and lower wall geometry equations respectively:

$$\bar{H}_1(\bar{X},\bar{t}) = \bar{d} + \bar{m}\bar{X} + \bar{a}\cos[\tfrac{2\pi}{\lambda}(\bar{X} - c\bar{t})] \tag{1}$$

$$\bar{H}_2(\bar{X},\bar{t}) = -\bar{d} - \bar{m}\bar{X} - \bar{b}\cos[\tfrac{2\pi}{\lambda}(\bar{X} - c\bar{t}) + \phi] \tag{2}$$

Where d refers to the channel's mean half-width, a refers to the amplitudes wave of upper wall, λ refers to the length of the wave, c refers to a phase speed, t refers to the time, b is an amplitudes wave of lower wall, m is a non-uniform parameter and the phase difference denoted by ϕ. The parameters $\bar{a}, \bar{b}$ and $\bar{d}$ must be satisfying the condition $(\bar{a}^2 + \bar{b}^2 + 2\bar{a}\bar{b} \leq (2\bar{d})^2)$.

The differential equations govern the continuity, momentum, and energy equations of a fluid in an asymmetric inclined channel. These equations can be expressed as follows:

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

$$\rho\left(\frac{\partial \bar{U}}{\partial \bar{t}} + \bar{U}\frac{\partial \bar{U}}{\partial \bar{X}} + \bar{V}\frac{\partial \bar{U}}{\partial \bar{Y}}\right) = -\frac{\partial \bar{P}}{\partial \bar{X}} + \rho\Omega\left(\Omega\bar{U} + 2\frac{\partial \bar{V}}{\partial \bar{t}}\right) + \frac{\partial \bar{S}_{\bar{X}\bar{X}}}{\partial \bar{X}} + \frac{\partial \bar{S}_{\bar{X}\bar{Y}}}{\partial \bar{Y}} + \rho g \sin\Gamma - \sigma {B_0}^2\cos\beta\,(\bar{U}\cos\beta - \bar{V}\sin\beta) - \frac{\bar{\mu}(\bar{y})}{\bar{K}_0}(\bar{U} - c) \tag{4}$$

$$\rho\left(\frac{\partial \bar{V}}{\partial \bar{t}} + \bar{U}\frac{\partial \bar{V}}{\partial \bar{X}} + \bar{V}\frac{\partial \bar{V}}{\partial \bar{Y}}\right) = -\frac{\partial \bar{P}}{\partial \bar{Y}} + \rho\Omega\left(\Omega\bar{V} + 2\frac{\partial \bar{U}}{\partial \bar{t}}\right) + \frac{\partial \bar{S}_{\bar{Y}\bar{Y}}}{\partial \bar{Y}} + \frac{\partial \bar{S}_{\bar{X}\bar{Y}}}{\partial \bar{X}} - \rho g\cos\Gamma + \sigma {B_0}^2\sin\beta\,(\bar{U}\cos\beta - \bar{V}\sin\beta) - \frac{\bar{\mu}(\bar{y})}{\bar{K}_0}\bar{V} \tag{5}$$

$$\rho C_P\left(\frac{\partial \bar{T}}{\partial \bar{t}} + \bar{U}\frac{\partial \bar{T}}{\partial \bar{X}} + \bar{V}\frac{\partial \bar{T}}{\partial \bar{Y}}\right) = Z\left(\frac{\partial^2 \bar{T}}{\partial \bar{X}^2} + \frac{\partial^2 \bar{T}}{\partial \bar{Y}^2}\right) + \omega\,(\nabla\bar{V}) + \sigma B_0^2(\bar{U}\cos\beta - \bar{V}\sin\beta)^2 \tag{6}$$

Where C_P represent the heat at a constant pressure, B_0 represent applied magnetics field, $\bar{\mu}(\bar{y})$ represents the variable viscosity of the fluid, Z represents the thermal conductivity, Ω is the rotation, σ is the electrical conductivity, ρ is the density of the fluid, g refers to acceleration due to gravity, ϵ represents the thermal expansion coefficient, β is inclination angle of the magnetic field, Γ is an inclination angle of channel, g is gravitational acceleration, K_0 is the permeability parameter, $\bar{P}$ is the pressure, $\bar{T}$ is the temperature, The components of the extra stress tensor are $\bar{S}_{\bar{X}\bar{X}}$, $\bar{S}_{\bar{Y}\bar{Y}}$ and $\bar{S}_{\bar{X}\bar{Y}}$, and $\nabla = [\frac{\partial}{\partial X}, \frac{\partial}{\partial Y}]$. ω which is defined as follows for Bingham plastic:

$$\omega = -\bar{P}I + \bar{S},\ S = 2\bar{\mu}(\bar{y})\,\Upsilon + 2\tau_0\hat{\Upsilon} \tag{7}$$

Where τ_0 is the yield stress, Υ is deformation rate and $\hat{\Upsilon}$ is tensor are known as:

$$\Upsilon = \frac{1}{2}(\nabla\bar{V} + (\nabla\bar{V})^T),\ \ \hat{\Upsilon} = \frac{\Upsilon}{\sqrt{2\,tr\,\Upsilon^2}} \tag{8}$$

So, the energy equation (6) can be written as follow:

$$\rho C_P\left(\frac{\partial \bar{T}}{\partial \bar{t}} + \bar{U}\frac{\partial \bar{T}}{\partial \bar{X}} + \bar{V}\frac{\partial \bar{T}}{\partial \bar{Y}}\right) = Z\left(\frac{\partial^2 \bar{T}}{\partial \bar{X}^2} + \frac{\partial^2 \bar{T}}{\partial \bar{Y}^2}\right) + \bar{S}_{\bar{X}\bar{X}}\left(\frac{\partial \bar{U}}{\partial \bar{X}}\right) + \bar{S}_{\bar{X}\bar{Y}}\left(\frac{\partial \bar{U}}{\partial \bar{Y}}\right) +$$

$$\bar{S}_{\bar{X}\bar{Y}}\left(\frac{\partial \bar{V}}{\partial \bar{X}}\right)+\bar{S}_{\bar{Y}\bar{Y}}\left(\frac{\partial \bar{V}}{\partial \bar{Y}}\right)+\sigma B_0^2(\bar{U}\cos\beta-\bar{V}\sin\beta)^2 \tag{9}$$

In laboratory frame, the extra stress tensor components are expressed as follows:

$$\bar{S}_{\bar{X}\bar{X}}=2\,\bar{\mu}(\bar{y})\Upsilon_{\bar{X}\bar{X}}+\frac{2\tau_0}{\sqrt{2\,tr\,\Upsilon^2}}\,\Upsilon_{\bar{X}\bar{X}}\,,\ \bar{S}_{\bar{X}\bar{Y}}=2\,\bar{\mu}(\bar{y})\Upsilon_{\bar{X}\bar{Y}}+\frac{2\tau_0}{\sqrt{2\,tr\,\Upsilon^2}}\,\Upsilon_{\bar{X}\bar{Y}},\quad \bar{S}_{\bar{Y}\bar{Y}}=2\,\bar{\mu}(\bar{y})\Upsilon_{\bar{Y}\bar{Y}}+\frac{2\tau_0}{\sqrt{2\,tr\,\Upsilon^2}}\,\Upsilon_{\bar{Y}\bar{Y}} \tag{10}$$

The velocity and temperature boundary conditions at the wall are provided by:

$$\bar{U}=0\,,\ \bar{T}=\bar{T}_0\ \text{ at } \bar{Y}=\bar{H}_1\,,\bar{U}=0\,,\ \bar{T}=\bar{T}_1\ \text{ at } \bar{Y}=\bar{H}_2 \tag{11}$$

In order to convert the motion from an unsteady to a steady peristaltic flow in equations (1,2,3,4,5,9,10,11) need to change the frame from a laboratory frame to a wave frame in the way that follows:

$$\bar{X}=\bar{x}+c\,\bar{t},\ \bar{Y}=\bar{y},\ \bar{U}(\bar{X},\bar{Y},\bar{t})=\bar{u}(\bar{x},\bar{y})+c,\ \bar{V}(\bar{X},\bar{Y},\bar{t})=\bar{v}(\bar{x},\bar{y})$$
$$\bar{P}(\bar{X},\bar{Y},\bar{t})=\bar{p}(\bar{x},\bar{y}),\ \bar{T}(\bar{X},\bar{Y},\bar{t})=\bar{T}(\bar{x},\bar{y}) \tag{12}$$

Where u and v represent the wave frame's velocity components, p is refers to the pressure wave frame. Develop a dimensionless variant of the outcomes equations by the below dimensionless variable.

$$x=\frac{\bar{x}}{\lambda},y=\frac{\bar{y}}{d},u=\frac{\bar{u}}{c}\,,v=\frac{\bar{v}}{\delta c}\,,p=\frac{\bar{p}d^2}{c\mu\lambda}\,,h_1=\frac{\bar{H}_1}{d}\,,h_2=\frac{\bar{H}_2}{d}\,,t=\frac{c\bar{t}}{\lambda}\,,\delta=\frac{d}{\lambda}\,,Re=\frac{\rho c d}{\mu}\,,a=\frac{\bar{a}}{d}\,,b=\frac{\bar{b}}{d}\,,S=\frac{d\bar{S}}{\mu c}\,,M^2=\frac{\sigma B_0^2 d^2}{\mu}\,,\theta=\frac{T-T_0}{T_1-T_0}\,,K_0=\frac{\bar{K}_0}{d^2}\,,BN=\frac{d\tau_0}{\mu c}\,,Pr=\frac{\mu C_p}{Z}\,,Ec=\frac{c^2}{C_P T_0}\,,BR=Pr.Ec\,,Fr=\frac{c^2}{gd}\,,m=\frac{\bar{m}\lambda}{d},\mu(y)=\frac{\bar{\mu}(\bar{y})}{\mu} \tag{13}$$

Where R is the Reynolds number, K_0 is the permeability parameter, Pr is the Prandtl number, δ is the wave number, Ec is the Eckert number, BR is the Brinkman, Fr is the Froude number, BN is the Bingham number, M is the Hartmann number and μ is the viscosity.

The governing equations ((3)-(4)-(5)-(9)) and wall equations (1) and (2) will take on the forms shown below by introducing the stream function ($u=\psi_y, v=-\psi_x$), assuming a long wavelength approximation, neglecting the small Reynolds number and wave number (δ<<1), as well as the boundary conditions.

$$h_1=1+mx+a\cos[2\pi x] \tag{14}$$

$$h_2=-1-mx-a\cos[2\pi x+\phi] \tag{15}$$

$$\frac{\partial P}{\partial x}=L\,\frac{\partial \psi}{\partial y}+\frac{\partial S_{xy}}{\partial y}-\mathrm{A}^2\frac{\partial \psi}{\partial y}+\frac{Re}{Fr}\sin\Gamma \tag{16}$$

$$\frac{\partial P}{\partial y}=0 \tag{17}$$

$$\frac{\partial^2 \theta}{\partial y^2}+BR\frac{\partial^2 \psi}{\partial y^2}S_{xy}+H^2\left(\frac{\partial \psi}{\partial y}\right)^2=0 \tag{18}$$

Where $L=\frac{\rho\Omega^2 d^2}{\mu}$, $\quad A^2=M^2\cos^2\beta+\frac{\mu(y)}{K_0}$, $\quad H^2=BR\,M^2\,\cos^2\beta$.

Below is the Bingham plastic fluid's stress component:

$$S_{xy} = \mu(y)\frac{\partial^2\psi}{\partial y^2} + BN \tag{19}$$

The final equations obtain by derivative equation (16) with respect to (y) and substituting equation (19) in equations (16) and (18). As follow:

$$L\,\frac{\partial^2\psi}{\partial y^2} + \mu(y)\frac{\partial^4\psi}{\partial y^4} - \mathrm{A}^2\frac{\partial^2\psi}{\partial y^2} = 0 \tag{20}$$

$$\frac{\partial^2\theta}{\partial y^2} + BR\left[\mu(y)\left(\frac{\partial^2\psi}{\partial y^2}\right)^2 + BN\,\frac{\partial^2\psi}{\partial y^2}\right] + H^2\left(\frac{\partial\psi}{\partial y}\right)^2 = 0 \tag{21}$$

The viscosity change is explained by the Reynold's viscosity model as follow:

$$\mu(y) = e^{-\zeta y} \tag{22}$$

The previously mentioned equation can be written as follows using the Maclaurin series expansion:

$$\mu(y) = 1 - \zeta y\,, \qquad \zeta \ll 1 \tag{23}$$

In this instance, $\zeta = 0$ represents a case of constant viscosity. By substituting the equation (23) in equations (20) and (21) we have the result:

$$L\,\frac{\partial^2\psi}{\partial y^2} + \frac{\partial^4\psi}{\partial y^4} - \zeta y\,\frac{\partial^4\psi}{\partial y^4} - \mathrm{A}^2\frac{\partial^2\psi}{\partial y^2} = 0 \tag{24}$$

$$\frac{\partial^2\theta}{\partial y^2} + BR\left[(1-\zeta y)\left(\frac{\partial^2\psi}{\partial y^2}\right)^2 + BN\,\frac{\partial^2\psi}{\partial y^2}\right] + H^2\left(\frac{\partial\psi}{\partial y}\right)^2 = 0 \tag{25}$$

Where $\mathrm{A}^2 = M^2\cos^2\beta + \frac{1-\zeta y}{K_0}$

The boundary conditions for the temperature and velocity on the wall after make a dimensionless became as:

$$\frac{\partial\psi}{\partial y} = -1\,,\ \theta = 0 \quad \text{at} \quad y = h_1\,, \quad \frac{\partial\psi}{\partial y} = -1\,,\ \theta = 1 \quad \text{at} \quad y = h_2 \tag{26}$$

In a fixed frame, the instantaneous volume flow rate is provided by:

$$Q(\bar{X},\bar{t}) = \int_{H_2(\bar{X},\bar{t})}^{H_1(\bar{X},\bar{t})} \bar{U}(\bar{X},\bar{Y},\bar{t})\,d\bar{Y} \tag{27}$$

The dimensional of the volume flow rate in the wave frame is become:

$$q = \int_{\bar{H}_2(\bar{x})}^{\bar{H}_1(\bar{x})} \bar{u}(\bar{x},\bar{y})\ d\bar{y} \tag{28}$$

Substituting equation (12) in equation (27), we get:

$$Q = q + cH_1 - cH_2 \tag{29}$$

At a fixed point $\bar{X}$, the time-averaged flow during a period $\left(T_2 = \frac{\lambda}{c}\right)$ can be expressed as:

$$\bar{Q} = \frac{1}{T_2}\int_0^{T_2} Q\ d\bar{t} \tag{30}$$

Substituting equation (29) in (30) and integrating the result, the result is:

$$\bar{Q} = q - 2cd - 2cmx \tag{31}$$

When $= \frac{q}{cd}$, $\Theta = \frac{\bar{Q}}{cd}$, $W = (1 - mx)$ equation (31) reduce to:

$$\Theta = F - 2\,W \tag{32}$$

Where

$$F = \int_{h_2}^{h_1} \frac{\partial \psi}{\partial y}\, dy = \psi(h_1) - \psi(h_2) \tag{33}$$

Thus, the dimensionless stream function's boundary conditions will now have the following form.

$$\psi = \frac{F}{2}\,,\ \frac{\partial \psi}{\partial y} = -1\ ,\Theta = 0 \quad \text{at } y = h_1 \tag{34}$$

$$\psi = -\frac{F}{2}\,,\ \frac{\partial \psi}{\partial y} = -1\ ,\Theta = 1 \quad \text{at } y = h_2 \tag{35}$$

3. Solution of the Problem

Solve the results equations by using the perturbation method that obtains below:

$$\psi = \psi_0 + \zeta\psi_1\ ,\ \theta = \theta_0 + \zeta\theta_1 \tag{36}$$

3.1. *Zeroth Order System*

$$L\,\frac{\partial^2 \psi_0}{\partial y^2} + \frac{\partial^4 \psi_0}{\partial y^4} - \mathrm{G}^2\,\frac{\partial^2 \psi_0}{\partial y^2} = 0 \tag{37}$$

$$\frac{\partial^2 \theta_0}{\partial y^2} + BR\left[\left(\frac{\partial^2 \psi_0}{\partial y^2}\right)^2 + BN\,\frac{\partial^2 \psi_0}{\partial y^2}\right] + H^2\left(\frac{\partial \psi_0}{\partial y}\right)^2 = 0 \tag{38}$$

Where $G^2 = M^2 \cos^2\beta + \frac{1}{K_0}$ .And the boundary conditions are:

$$\psi_0 = \frac{F}{2}\,,\ \frac{\partial \psi_0}{\partial y} = -1\ ,\theta_0 = 0 \quad \text{at } y = h_1 \tag{39}$$

$$\psi_0 = \frac{-F}{2}\,,\ \frac{\partial \psi_0}{\partial y} = -1\ ,\theta_0 = 1 \quad \text{at } y = h_2 \tag{40}$$

3.2. *First Order System*

$$L\,\frac{\partial^2 \psi_1}{\partial y^2} + \frac{\partial^4 \psi_1}{\partial y^4} - \mathrm{y}\frac{\partial^4 \psi_0}{\partial y^4} - G^2\frac{\partial^2 \psi_1}{\partial y^2} + \frac{y}{K_0}\frac{\partial^2 \psi_0}{\partial y^2} = 0 \tag{41}$$

$$\frac{\partial^2 \theta_1}{\partial y^2} + BR\left[2\frac{\partial^2 \psi_0}{\partial y^2}\frac{\partial^2 \psi_1}{\partial y^2} - y\left(\frac{\partial^2 \psi_0}{\partial y^2}\right)^2 + BN\,\frac{\partial^2 \psi_1}{\partial y^2}\right] + 2H^2\frac{\partial \psi_0}{\partial y}\,\frac{\partial \psi_1}{\partial y} = 0 \tag{42}$$

And the boundary conditions can be obtain as follow:

$$\psi_1 = 0\,,\ \frac{\partial \psi_1}{\partial y} = 0\ ,\theta_1 = 0 \quad \text{at } y = h_1, h_2 \tag{43}$$

4. Result and Discussion

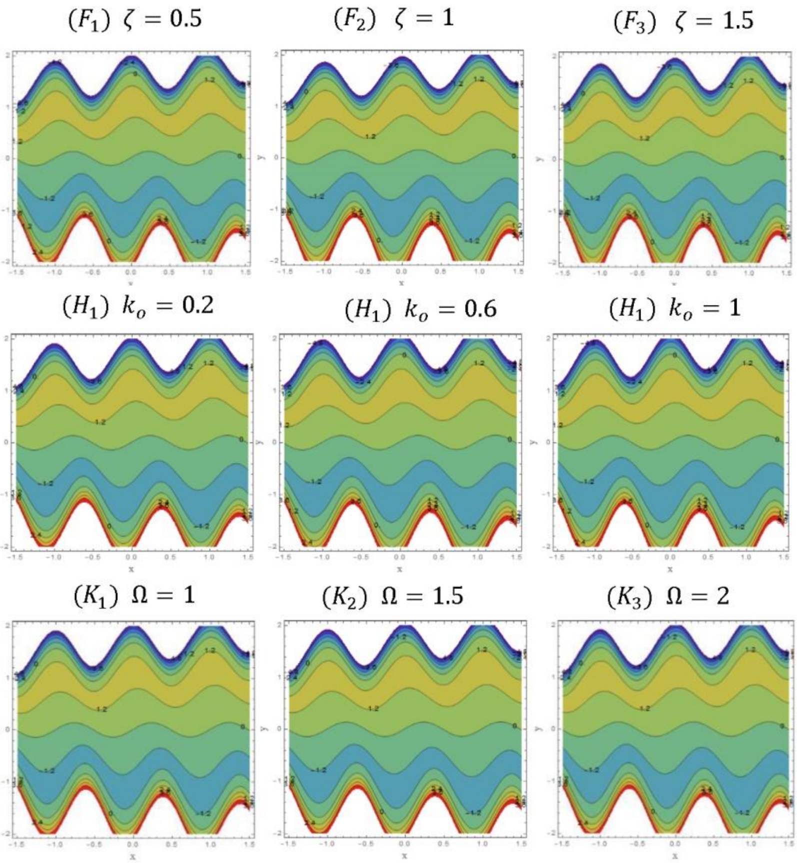
This section will examine how various parameters affect the temperature, velocity, and stream line, as indicated in figures (1-3). The default parameters value that used in this section is $\mathrm{Br} = 0.5, \mathrm{BN} = 2, \zeta = 0.3, \Theta = 0.8, k_0 =$

$0.2, M = 4, \rho = 0.8, \Omega = 0.3, d = 0.9, \mu = 2, a = 0.3, \emptyset = \frac{\pi}{4}, b = 0.4, m = 0.1, \beta = \frac{\pi}{3}$. The MATHEMATICA package is used in this part to plot the results.

The impact of $\zeta, k_o, \Omega, m, \beta$ can be seen in figure 1 respectively. We observe that when these parameters are changed, the trapped bolus's volume either increases or stays the same. We reveal that, the trapping bolus's size decrease with increasing the parameters m while it doesn't change with change the parameters β, k_o, ζ and Ω

The impact of the parameters $\mu, BN, \zeta, \beta, k_o, \Omega$ on the velocity profile obtained in the figure 2 respectively. The velocity doesn't change by changing BN, μ.while increases by increasing β,, k_o Also, The velocity rises at the upper wall and falls at the lower wall as ζ increases.

The effects of important parameters on the temperature are seen graphically in figure 3. We see that when these parameters are changed, the temperature changes either increases or decreases or stays the same; we explain these changes in detail in the conclusion section.



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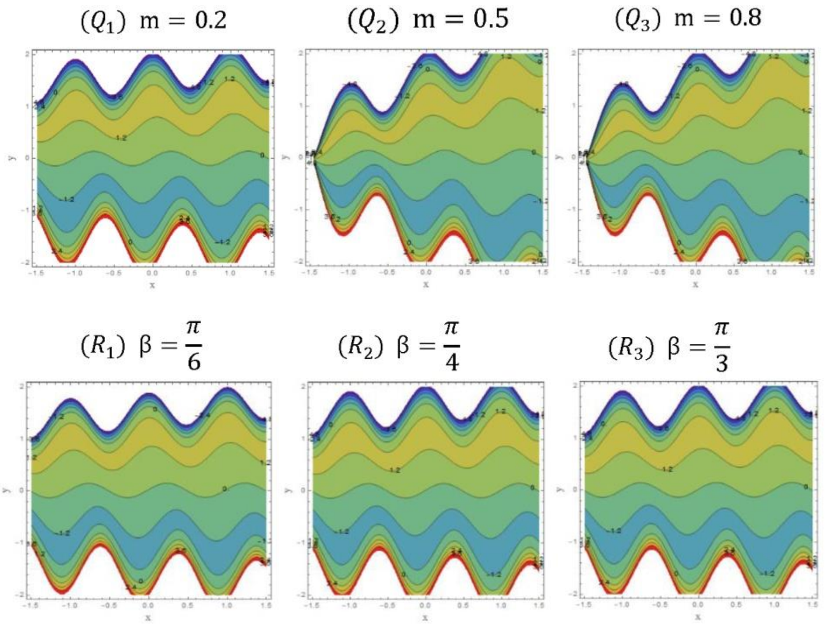

Figure 1
Represented Stream Function with Various Parameters

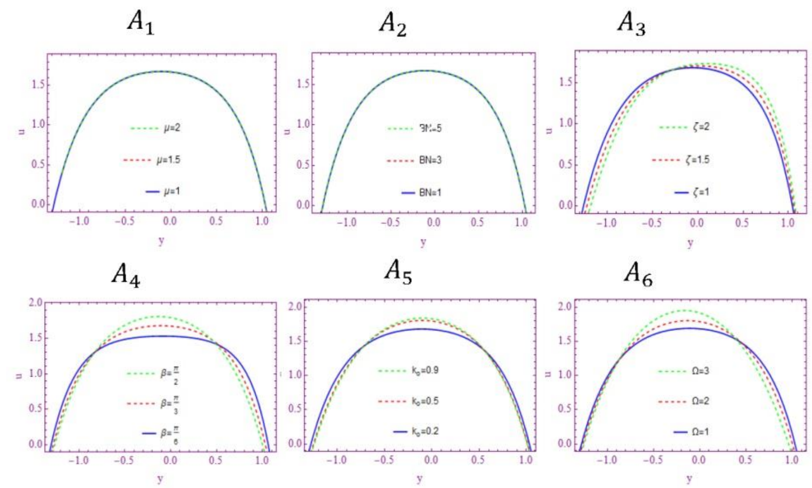

Figure 2
Velocity with a Variation of Parameters

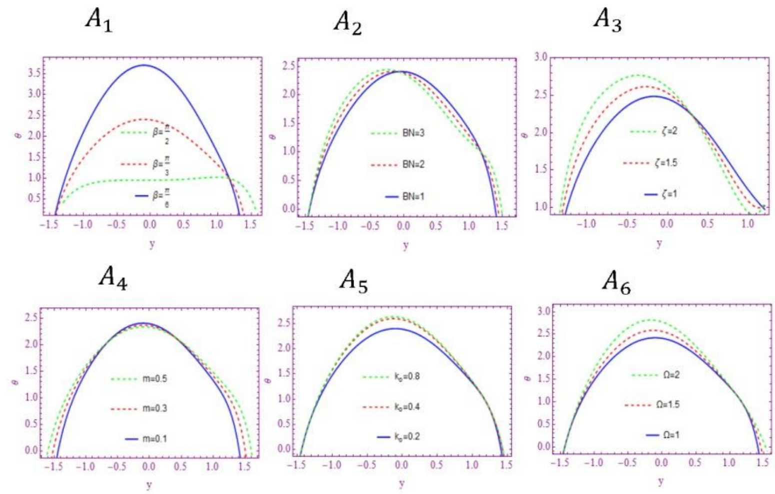

Figure 3
Represented Temperature with Various Parameters

5. Conclusion

This work discuss effects of rotation and inclined magnetic field on the mixed convection heat transfer that occurs when a viscoplastic fluid peristaltically moves via a porous media in an asymmetric inclined channel that is tapered with a variable viscosity. With the conditions of a low Reynolds number and long wavelength, we were able to find the problem's solution. Our results are examined for various values of important variables, such as the Bingham number, rotation, inclination angle of magnetic field, viscosity. Our main findings can be summed up as follows:

The trapping bolus size not change with changing the parameters β , k_o, ζ, Ω, And this size decreases from below wall and take a tapered shape by increasing *m*.

The velocity doesn't change by changing *BN*,μ.while increases by increasing β,Ω, k_o Also, When ζ increases the velocity rises at the top of the wall, and falls at the below wall. The temperature increases by increasing k_o. And decreases by increasing β. Whereas, the lower wall behaves in the opposite way as the higher wall thermally when increase *BN*. And by increasing *m* the temperature increases at the both wall side and decreases at the center. Also graphically we found that when increasing ζ the temperature will increased at the center and decreased at the upper wall.

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