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Mathematical Examination of MHD Slip Oscillatory Blood Flow Through an Artery in the Presence of a Magnetic Field

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ABSTRACT

In this study, we investigated the mathematical examination of MHD slip oscillatory blood flow through an artery in the presence of a magnetic field. The process involves the development of dimensional mathematical models representing the flow in the form of a partial differential equation and scaling the model using some quantities where the governing models were made dimensionless and some pertinent parameters, such as the Hartman number and Womersley number, were obtained. The dimensionless governing model was perturbed and reduced to ODE. Method: The perturbed ODE was solved using the Laplace Method (LM), where the function representing the flow was obtained, and we performed numerical simulation using Wolfram Mathematica, version 12. The results reveal that the Hartman number and Womersley numbers influence the blood flow, flow rate, and shear stress, respectively. In conclusion, we have been able to derive a mathematical model that represents the problem, solve it analytically using the Laplace method, and carry out numerical simulation.

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Background of the Study

Blood is a type of Newtonian fluid made up of 45% formed elements and 55% plasma fluid that circulates through the blood vessels in the body, and pumped by the pulsatile oscillation of the heart. The formed element portion of blood is made up of the blood cells (which come in both red and white cells), and cell fragments called platelets, while the plasma is the main component of blood and consists mostly of water, with proteins, ions, nutrients, and wastes mixed in. Red blood cells are responsible for carrying oxygen and carbon dioxide. Platelets are responsible for blood clotting, Bunonyo et al. [1]. There are other authors and researchers who have studied the flow of blood through blood the various blood channels, these include: Dhange et al studied the flow of blood in a stenosed artery with post-stenotic dilatation and a force field with the help of mathematical algorithm [2]. It was observed that the narrowing of an artery is could be caused by arteriosclerotic deposition or other aberrant tissue growth, and it was concluded that, as the growth spreads into the artery's lumen, blood flow becomes grossly impeded. According Sriram et al. who talked about the haematocrit dispersion in asymmetrically bifurcating vascular network topology, including vessel branching [3]. Jones et al. studied the pressure losses in the haemodialysis graft vascular circuit [4]. In their studies, they formulated a mathematical model of this circuit, and pressure losses that were measured in an in vitro experimental apparatus and compared with losses predicted. Elhanafy et al. investigated the haematocrit variation effect on blood flow in an arterial segment with variable stenosis degree numerically in a three-dimensional axisymmetric segment with stenosis under steady conditions [5]. Studied two-phase blood flow through a stenosed curved artery with haematocrit and temperature-dependent viscosity. The two-phase blood flow model was considered to analyse the fluid flow and heat transfer in a curved tube with time-variant stenosis. Studied the theoretical models for regulation of blood flow. The investigation showed how blood flow rate in the normal microcirculation is regulated to meet the metabolic demands of the tissues, which vary widely with position and with time, but is relatively unaffected by changes of arterial pressure over a considerable range. Kumar et al. investigated a mathematical model for blood flow through a narrow catheterized artery [6]. The investigation analyses the effect of the stenosis height, shape, catheter radius, and slip velocity on axial velocity, shear stress, and effective viscosity. Onitilo et al. illustrated the effects of haematocrit on blood flow through a stenosed human carotid artery [7]. The study discovered that the resistance increases as the level of haematocrit increases. Branigan et al. carried out a research on the mean arterial pressure nonlinearity in an elastic circulatory system subjected to different haematocrit [8]. A mathematical model was used to evaluate the equilibrium intraluminal average blood pressure in an elastic, auto-regulated arteriole-like blood vessel. However, in this study, we would develop mathematical model that represents the MHD blood circulation through a slip-oscillatory micro channel in the present of magnetic field. The study aims at solving the mathematical model analytical using Laplace method (LM), perform sensitivity analysis on the model by varying some of the key pertinent parameters to study their impacts and draw up conclusion from the investigation.

Mathematical Formulation

This section involves the derivation of mathematical model that represent the physical situation, with the help of some realistic assumptions, thereafter proffer analytical solution of the problem, perform numerical simulation and write technical report based on the observations.

Assumptions

Before going into the derivation of mathematical model representing the physical problem, let's consider the following assumptions.

- The wall velocity is oscillatory with a slip velocity
- The fluid is considered homogenous, conducting, viscous, incompressible and Newtonian
- The tube wall is rigid and circular
- The motion is laminar, axisymmetric and parallel to the tube axis
- Pressure gradient is periodic function that drives the fluid due to the pumping action of the heart
- Gravitation has no effect on the fluid.
- The magnetic field is applied perpendicular to the flowing fluid

Model Derivation

Following Jain et al. and the above-mentioned assumptions, the governing equations are [9]:

The Continuity Equation

$$\frac{\partial(rv)}{\partial r}+\frac{\partial(rw)}{\partial z}=0 \qquad (3.1)$$

The Momentum Equation

$$\rho\frac{\partial w}{\partial t}=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial r^2}+\frac{1}{r}\frac{\partial w}{\partial r}\right)-\sigma\mu_e^2\beta_0^2 w \qquad (3.2)$$

The Corresponding Boundary Conditions are:

$$\left.\begin{aligned} w&=w_1e^{-i\omega t}, \text{at } r=h\\ w&=0, \quad \text{at } r=0\end{aligned}\right\} \qquad (3.3)$$

The Pressure Gradient and Velocity Blood flow can be taken as

$$\left.\begin{aligned}\frac{\partial p}{\partial z}&=-P_0e^{-i\omega t}\\ w&=w_0e^{-i\omega t}\end{aligned}\right\} \qquad (3.4)$$

Differentiating the Velocity in Equation (3.3) with Respect to *t*, we have:

$$\frac{\partial w}{\partial t}=i\omega w_0e^{-i\omega t} \qquad (3.5)$$

Differentiating the Velocity in Equation (3.3) with Respect to *r*, We have:

$$\frac{\partial}{\partial r} \quad \frac{\partial}{\partial r} \quad \text{int} \qquad (3.6)$$

Differentiating Equation (3.5), We have:

$$\frac{\partial^2 w}{\partial r^2}=\frac{\partial^2 w_0}{\partial r^2}e^{-\text{int}} \qquad (3.7)$$

By Substituting Equations (3.4) - (3.7) into Equation (3.2), We have

$$\rho i\omega w_0e^{-i\omega t}=P_0e^{-i\omega t}+\mu\left(\frac{\partial^2 w_0}{\partial r^2}+\frac{1}{r}\frac{\partial w_0}{\partial r}\right)e^{-i\omega t}+\sigma\mu_e^2B_0^2w_0e^{-i\omega t} \qquad (3.8)$$

By Eliminating $e^{-i\omega t}$ from Equation (3.8), We have

$$\rho i\omega w_0=P_0+\mu\left(\frac{\partial^2 w_0}{\partial r^2}+\frac{1}{r}\frac{\partial w_0}{\partial r}\right)+\sigma\mu_e^2B_0^2w_0 \qquad (3.9)$$

By Simplifying Equation (3.9), We have

$$i\frac{\rho\omega}{\mu}w_0=\frac{P_0}{\mu}+\frac{\partial^2 w_0}{\partial r^2}+\frac{1}{r}\frac{\partial w_0}{\partial r}+\frac{\sigma\mu_e^2B_0^2}{\mu}w_0 \qquad (3.10)$$

From Equation (3.10), let $\alpha_1=i\frac{\rho\omega}{\mu}, P_1=-\frac{P_0}{\mu}$ and

$$H=\mu_eB_0\sqrt{\frac{\sigma}{\mu}} \qquad (3.11)$$

Substituting Equations (3.11) into (3.10), it Yields

$$\alpha_1w_0=P_1+\frac{\partial^2 w_0}{\partial r^2}+\frac{1}{r}\frac{\partial w_0}{\partial r}+Hw_0 \qquad (3.12)$$

Re-Arrange Equation (3.12), We have,

$$\frac{\partial^2 w_0}{\partial r^2}+\frac{1}{r}\frac{\partial w_0}{\partial r}-(\alpha_1-H)w_0=P_1 \qquad (3.13)$$

Let $\beta^2=\alpha_1-H$ Then Equation (3.13) Becomes

$$\frac{d^2w_0}{dr^2}+\frac{1}{r}\frac{dw_0}{dr}-\beta^2w_0=P_1 \qquad (3.14)$$

Equation (3.14) can be Written as;

$$r\frac{d^2w_0}{dr^2}+\frac{dw_0}{dr}-\beta^2rw_0=rP_1 \qquad (3.15)$$

Equation (3.15) is a Bessel equation of order zero.

Method of Solution

In this section, we would be applying the Laplace method in solving equation (3.15), by firstly considering the Laplace of some functions as stated below.

$$L\left\{w_0(r)\right\} = w_0(s) = \int_0^\infty w_0(r) e^{-sr} dr \quad (3.16)$$

$$L\left\{rw_0\right\} = -\frac{dw_0}{ds} \quad (3.17)$$

$$L\left\{\frac{dw_0}{dr}\right\} = sw_0(s) - w_0(0) \quad (3.18)$$

$$L\left\{r\frac{d^2w_0}{dr^2}\right\} = -\frac{d}{ds}\left\{s^2w_0(s) - sw_0(0) - w_0(0)\right\} \quad (3.19)$$

$$L\left\{rP_1\right\} = \frac{P_1}{s^2} \quad (3.20)$$

Application of the Method of Solution

Applying Equation (3.16), Equation (3.15) Becomes:

$$L\left\{r\frac{d^2w_0}{dr^2}\right\} + L\left\{\frac{dw_0}{dr}\right\} - \beta^2 L\left\{rw_0\right\} = P_1 L\left\{r\right\} \quad (3.21)$$

Substituting Equations (3.17) - (3.20) into Equation (3.21), we have:

$$-\frac{d}{ds}\left\{s^2w_0(s) - sw_0(0) - w_0(0)\right\} + sw_0(s) - w_0(0) + \beta^2\frac{dw_0}{ds} = \frac{P_1}{s^2} \quad (3.22)$$

Simplifying Equation (3.22), We have:

$$-s^2\frac{dw_0}{ds} - 2sw_0(s) + s\frac{dw_0(0)}{ds} + w_0(0) + \frac{dw_0(0)}{ds} + sw_0$$

$$sw_0(s) - w_0(0) + \beta^2\frac{dw_0}{ds} = \frac{P_1}{s^2} \quad (3.23)$$

Simplifying Equation (3.23), We have:

$$-s^2\frac{dw_0}{ds} + \beta^2\frac{dw_0}{ds} - 2sw_0(s) + sw_0(s) + s\frac{dw_0(0)}{ds} + w$$

$$w_0(0) + \frac{dw_0(0)}{ds} - w_0(0) = \frac{P_1}{s^2} \quad (3.24)$$

Simplifying Equation (3.24), We have:

$$-\left(s^2-\beta^2\right)\frac{dw_0}{ds} - sw_0(s) + s\frac{dw_0(0)}{ds} + \frac{dw_0(0)}{ds} = \frac{P_1}{s^2} \quad (3.25)$$

If $\frac{dw_0(0)}{ds} = 0$, then Equation (3.25) Becomes:

$$-\left(s^2-\beta^2\right)\frac{dw_0}{ds} - sw_0(s) = \frac{P_1}{s^2} \quad (3.26)$$

Simplifying Equation (3.26), we have:

$$\frac{dw_0}{ds} + \frac{s}{\left(s^2-\beta^2\right)}w_0 = -\frac{P_1}{s^2\left(s^2-\beta^2\right)} \quad (3.27)$$

Equation (3.27) can be Solved Using the Method of Integrating Factor Method, that is:

$$\text{IF} = e^{\int pds} \quad (3.28)$$

where $p = \frac{s}{\left(s^2-\beta^2\right)}$, then Equation (3.28) Becomes

$$\text{IF} = e^{\int \frac{s}{\left(s^2-\beta^2\right)}ds} \quad (3.29)$$

Thus, $\text{IF} = \sqrt{\left(s^2-\beta^2\right)}$ (3.30)

Now, multiply equation (3.27) by equation (3.30), We have:

$$\sqrt{\left(s^2-\beta^2\right)}\frac{dw_0}{ds} + \frac{s\sqrt{\left(s^2-\beta^2\right)}}{\left(s^2-\beta^2\right)}w_0 = -\frac{P_1\sqrt{\left(s^2-\beta^2\right)}}{s^2\left(s^2-\beta^2\right)} \quad (3.31)$$

Simplifying Equation (3.31), We have:

$$\frac{d}{ds}\left(w_0\sqrt{s^2-\beta^2}\right) = -\frac{P_1\sqrt{\left(s^2-\beta^2\right)}}{s^2\left(s^2-\beta^2\right)} \quad (3.32)$$

Simplifying Equation (3.32), We have:

$$\frac{d}{ds}\left(w_0\sqrt{s^2-\beta^2}\right) = -\frac{P_1}{s^2\sqrt{\left(s^2-\beta^2\right)}} \quad (3.33)$$

Simplifying Equation (3.33), We Obtained

$$d\left(w_0\sqrt{s^2-\beta^2}\right) = -\frac{P_1 ds}{s^2\sqrt{\left(s^2-\beta^2\right)}} \quad (3.34)$$

Integrating Equation (3.34), We Obtained

$$\underset{w}{w_0\sqrt{s^2-\beta^2}} = -P_1\int\frac{ds}{s^2\sqrt{\left(s^2-\beta^2\right)}} + c \quad (3.35)$$

Simplifying $\int\frac{ds}{s^2\sqrt{\left(s^2-\beta^2\right)}} = -\frac{\sqrt{\left(s^2-\beta^2\right)}}{\beta^2 s}$ (3.36)

Substitute Equation (3.36) into Equation (3.35), We Obtained:

$$w_0\sqrt{s^2-\beta^2} = P_1\frac{\sqrt{\left(s^2-\beta^2\right)}}{\beta^2 s} + c \quad (3.37)$$

Simplifying Equation (3.37), We Obtained:

$$w_0 = P_1\frac{\sqrt{\left(s^2-\beta^2\right)}}{\beta^2 s\sqrt{s^2-\beta^2}} + \frac{c}{\sqrt{s^2-\beta^2}} \quad (3.38)$$

Simplifying Equation (3.38), We Obtained:

$$w_0(s) = \frac{P_1}{\beta^2 s} + \frac{c}{\sqrt{s^2-\beta^2}} \quad (3.39)$$

But $w_0(r) = L^{-1}\{w_0(s)\}$ (3.40)

Applying Equation (3.40) on Equation (3.39), We have:

$$w_0(r) = \frac{P_1}{\beta^2} L^{-1}\left\{\frac{1}{s}\right\} + cL^{-1}\left\{\frac{1}{\sqrt{s^2-\beta^2}}\right\} \tag{3.41}$$

But $L^{-1}\left\{\frac{1}{s}\right\} = 1$ and $L^{-1}\left\{\frac{1}{\sqrt{s^2-\beta^2}}\right\} = I_0(\beta r)$ (3.42)

Substituting Equation (3.42) into Equation (3.41), We Obtained:

$$w_0(r) = \frac{P_1}{\beta^2} + cI_0(\beta r) \tag{3.43}$$

The Corresponding Boundary Conditions from Equation (3.3):

$$\left.\begin{array}{l} w_0 = w_1, \text{ at } r = h \\ w_0 = 0, \quad \text{at } r = 0 \end{array}\right\} \tag{3.44}$$

Solving Equation (3.43) Using Equation (3.44), we have:

$$c = \frac{w_1}{I_0(\beta h)} - \frac{P_1}{\beta^2 I_0(\beta h)} \tag{3.45}$$

Substitute Equation (3.45) into Equation (3.43), which is:

$$w_0(r) = \frac{w_1 I_0(\beta r)}{I_0(\beta h)} + \frac{P_1}{\beta^2}\left(1 - \frac{I_0(\beta r)}{I_0(\beta h)}\right) \tag{3.46}$$

In order to get the Oscillatory Velocity, we Substitute Equations (3.46) into Equation (3.4), where we Obtained:

$$w = \left(\frac{w_1 I_0(\beta r)}{I_0(\beta h)} + \frac{P_1}{\beta^2}\left(1 - \frac{I_0(\beta r)}{I_0(\beta h)}\right)\right)e^{-i\omega t} \tag{3.47}$$

Shear Stress

$$\tau_{wall} = \left.\frac{\partial w}{\partial r}\right|_{r=h} = \frac{\beta I_1(\beta h)}{I_0(\beta h)}\left(w_1 - \frac{P_1}{\beta^2}\right)e^{-i\omega t} \tag{3.48}$$

Flow Rate

The flow Rate of Fluid at the wall can be Mathematically Stated as:

$$Q = \int_0^h r w(r,t)\,dr \tag{3.49}$$

Note that $\int r I_0(r)dr = rI_1(r)$ (3.50)

Substituting Equation (3.46) into Equation (3.49), we have

$$Q = e^{-i\omega t}\int_0^h r\left(\frac{w_1 I_0(\beta r)}{I_0(\beta h)} + \frac{P_1}{\beta^2}\left(1 - \frac{I_0(\beta r)}{I_0(\beta h)}\right)\right)dr \tag{3.51}$$

Simplifying Equation (3.51), We have:

$$Q = \frac{e^{-i\omega t} w_1}{I_0(\beta h)}\int_0^h rI_0(\beta r)\,dr + \frac{P_1 e^{-i\omega t}}{\beta^2}\int_0^h\left(r - \frac{rI_0(\beta r)}{I_0(\beta h)}\right)dr \tag{3.52}$$

Simplifying Equation (3.52), we have:

$$Q = \frac{w_1 e^{-i\omega t}}{I_0(\beta h)}\int_0^h rI_0(\beta r)\,dr + \frac{P_1 e^{-i\omega t}}{\beta^2}\int_0^h r\,dr - \frac{P_1 e^{-i\omega t}}{\beta^2 I_0(\beta h)}\int_0^h rI_0(\beta r)\,dr \tag{3.53}$$

Simplifying Equation (3.53) using Equation (3.50), we have:

$$Q = \frac{w_1 e^{-i\omega t} h I_1(\beta h)}{I_0(\beta h)} + \frac{P_1 e^{-i\omega t} h^2}{2\beta^2} - \frac{P_1 e^{-i\omega t} h I_1(\beta h)}{\beta^2 I_0(\beta h)} \tag{3.54}$$

Simplifying Equation (3.55), we have:

$$Q = \frac{w_1 e^{-i\omega t} h I_1(\beta h)}{I_0(\beta h)} + \frac{P_1 h e^{-i\omega t}}{\beta^2}\left(\frac{h}{2} - \frac{I_1(\beta h)}{I_0(\beta h)}\right) \tag{3.55}$$

where $I_0(\beta r) = \left(1 + \frac{\beta^2 r^2}{4} + \frac{\beta^4 r^4}{64} + \frac{\beta^6 r^6}{2304}\right)$ and $I_0(\beta) = \left(1 + \frac{\beta^2}{4} + \frac{\beta^4}{64} + \frac{\beta^6}{2304}\right)$

Results

In this section, we shall perform numerical simulation using Wolfram Mathematica, version 12, to test the sensitivity of the pertinent parameter such as Womersley number and Hartman number on the fluid velocity and flow rate. The simulated results are as follows:

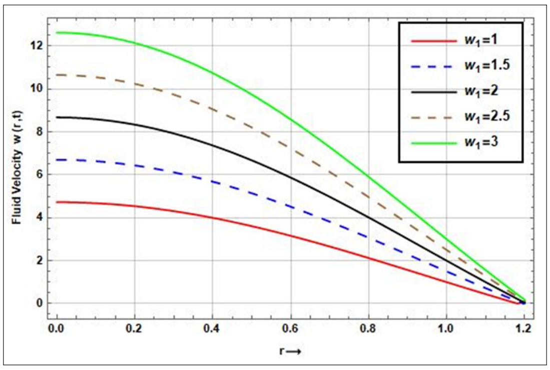

Figure 1: Effect of Variation of Slip Velocity on Flow Velocity

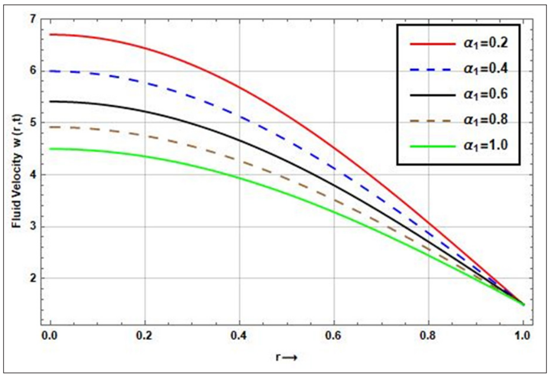

Figure 2: Effect of Variation of Womersley Number on Flow Velocity

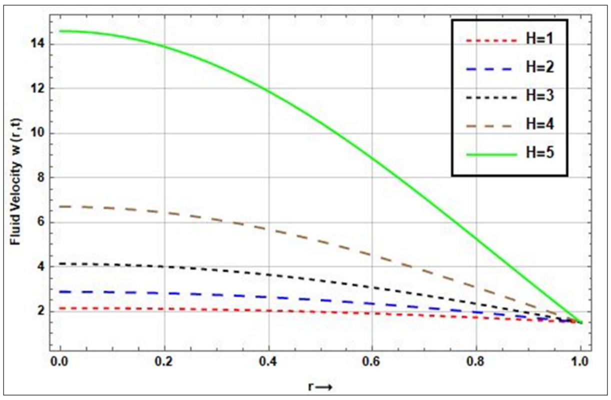

Figure 3: Effect of Variation of Hartman Number on Fluid Velocity

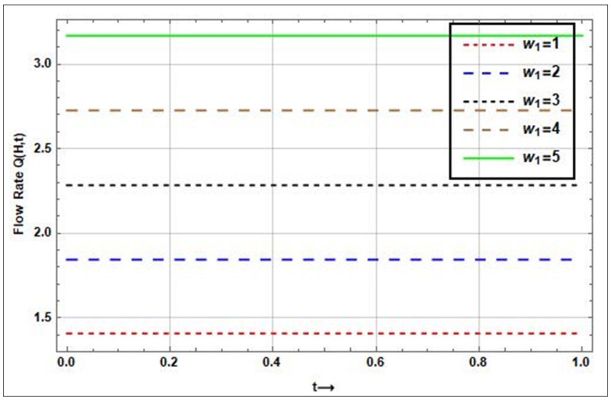

Figure 4: Effect of Variation of Wall Slip Velocity on Flow Rate

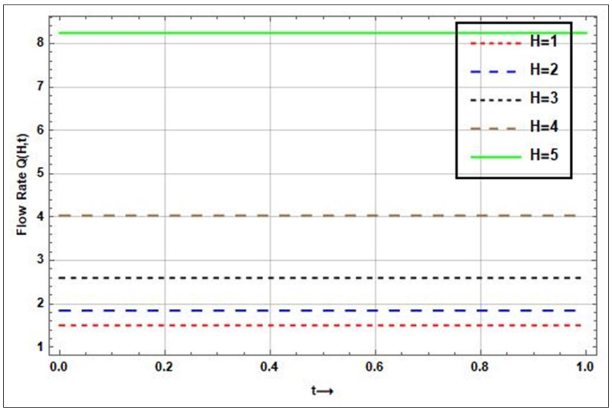

Figure 5: Effect of variation of Hartman Number on Flow Rate

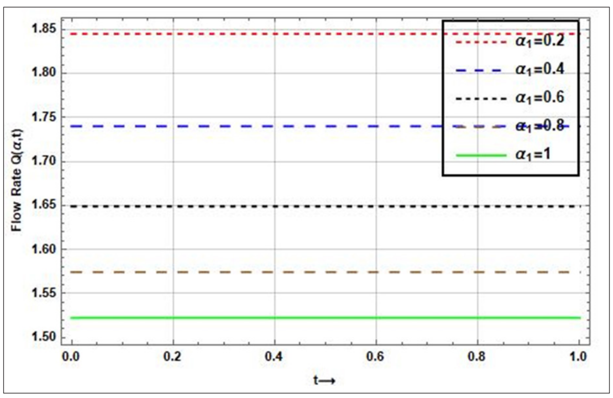

Figure 6: Effect of Variation of Womersley Number on the Flow Rate

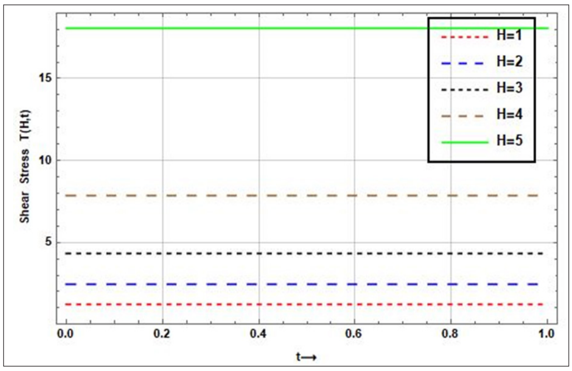

Figure 7: Effect of Variation of Hartman number on Shear Stress

Discussion

Figure 1 illustrates slip velocity impact on the flow momentum. Slip velocity means the blood does not stick at zero velocity. It is seen that increase in slip velocity increases the blood velocity because higher slip velocity implies less frictional resistance at the wall. Figure 2 Is of the view that the fluid velocity attained its maximum at the centre of the blood vessel for a Womersley number of 0.2, however, the velocity decreases as the boundary layer thickness increases from the initial state and increases to 0.34 when the boundary layer reached its peak. In addition, from the figure, it was observed that increasing values of Womersley number until its attaint its peak.

Figure 3 showed the impact of Hartman number on the flow momentum. The figure illustrates that the flow velocity decreases for an increase in Hartman number, and this is because the Lorentz force is generated as a result of the intersection of magnetic field and electrically conducting fluid. However, it can be observed that as the boundary layer increase, the velocity of the fluid decreases until it gets to the slipping wall velocity. Figure 4 depicts the effect of the change in wall slip velocity on flow rate. It can be seen that the increase in wall slip velocity increases, the fluid flow rate increases within the timeframe. However, it's interesting to note that the flow rate remained stable for any value of the wall slip velocity. Figure 5 illustrates the influence of Hartman number on the volumetric flow rate. It can be seen that the volumetric flow rate increases for an increase in Hartman number. However, it can be seen that the flow remained stable for the varying values of the Hartman number within the boundary layer.

Figure 6 showed the effect of Womersley number on the volumetric flow rate. This result illustrated that the volumetric flow rate increases for an increase in Womersley number and flow rate-maintained stability for each Womersley value within the boundary layer. Figure 7 depicts the effect of the change in Hartman number on shear stress within the boundary of the blood vessel. We observed that the shear stress increases for an increasing value of the Hartman number.

Conclusion

Finally, we were able to develop a mathematical model in partial differential equation form that represents blood flow through human arteries, scale it using dimensionless quantities, and provide an analytical solution. We went on to perform numerical simulations with Wolfram Mathematica version 12, varying the importance of relevant parameters such as the Hartman number, Womersley number, and wall slip velocity. However, the numerical simulation revealed that all relevant parameters have a significant effect on both the blood flow rate and the fluid's momentum.

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