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An Investigation of Blood Flow through Parallel Plate Channel in the Presence of Inclined Magnetic Field with Heat and Mass Transfer

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Abstract

A Mathematical model for MHD flow of blood between a parallel plate channel with the effect of heat transfer and mass transfer has been investigated. An inclined magnetic field has been applied to the parallel plates filed with porous substance. The partial differential equations which are governing the flow field have been resolved numerically by applying non-dimensional parameters. The effect of inclination of magnetic field on the parallel plate channel has been analyzed, furthermore the effect of Prandtl number, thermal radiation, heat source parameter, chemical reaction parameter on the flow of blood has been studied in detail. The numerical results are analyzed and are represented graphically in the form of velocity profile, temperature profile and concentration profile. Moreover, the velocity of blood, temperature profile and concentration profile is adapting a wavy pattern as the various parameters vary.

Keywords: Blood flow, Inclined magnetic field, Parallel plate channel, Heat and mass transfer

Introduction

In recent years, the study of heat and mass transfer of unsteady MHD blood through a parallel plate channel has gained considerable importance because of its bio-fluid applications. Heat and Mass transfer in hydro dynamical and biological systems is relevant in lots of diagnostic and coronary heart related issues that contains the changes in temperature. Ample of research work has been carried out to explore the actions of biological fluids in the existence of magnetic field. The flow of blood which is typically taken into contemplation to be electrically conducting fluid, the electromagnetic field acts on the blood which in turns opposes the movement of the blood flow and consequently the use of external magnetic field can put a great impact as a remedy for many kinds of sickness like heart and lungs related diseases and also in diseases related to accelerated blood movement such as high blood pressure and brain-hemorrhages. As, the current study is based on the impact of inclined magnetic field on the flow of blood with heat and mass transfer therefore it will be really helpful in the diagnostic of heart related diseases and also the diseases related to stiffness in the back bone.

The attribute of the flow of blood in the existence of magnetic field with the effect of heat transfer and mass transfer were studied by many researchers viz Vardanyan [1] gave the effect of magnetic field on blood flow. The effect of magnetic field on blood flow through an indented tube in the presence of erythrocytes was discussed by Halder [2]. Khalid and Vafai [3] investigated the role of porous media in modelling flow and heat transfer in biological tissues. Tzirtzilakis [4] explained a mathematical order for the blood flow in magnetic field. Heat transfer to MHD oscillatory flow in a channel filed with porous medium was studied by Makinde and Mhone [5]. The mixed convective heat and mass transfer in a non-Newtonian fluid in a peristaltic surface with temperature dependent viscosity was studied by Eldabe, El-Sayed*et al.* [6].

In the past few decades, the investigation pertaining to the aggregated effects of heat transfer and mass transfer in blood flow has got fairly enchanting to some scientists and investigators both from the conceptual and observational perspective. Some of the researchers such as Chaturvedi and Shrivastava *et al.* [7] explained the blood flow in presence of magnetic field through porous medium and its effect on heat transfer rate. Mathematical analysis of unsteady MHD blood flow through parallel plate channel with heat source was given by Eldesoky [8]. Abou-zeid, El-zahrani*et al.* [9] analyzed the Mathematical modeling for pulsatile flow of a non-Newtonian fluid with heat and mass transfer in a porous medium between 2 permeable parallel plates. Ali and Ahmad [10] gave an analytical solution of unsteady MHD blood flow and heat transfer through parallel plates when lower plate stretches exponentially.

Unsteady MHD flow and heat transfer of micropolar fluid in a porous medium between parallel plates was suggested by Ojjela and Kumar [11]. Malapati and Dasari [12] investigated the slip velocity distribution on MHD oscillatory heat and mass transfer flow of a viscous fluid in a parallel plate channel. The unsteady MHD blood flow through porous medium in a parallel plate channel was analyzed by Latha and Kumar [13]. The study of MHD Flow of Incompressible Fluid through Parallel Plates in Inclined Magnetic field having Porous Medium with Heat and Mass Transfer was carried out by Hanvey, Khare and Paul [14]. The heat transfer investigation of non-Newtonian fluid between 2 vertically infinite flat plates by numerical and analytical solutions was studied by Pourmehran, Rahimi*et al.* [15]. Mathematical analysis of unsteady MHD blood flow through parallel plate channel with heat source was carried out by Suresh and Sekar [16]. Lavanya [17] made an analytical study on MHD rotating flow through a porous medium with heat and mass transfer. Sharma and Gaur [18] investigated the radiation effect on MHD blood flow through a tapered porous stenosed artery with thermal and mass diffusion. MHD oscillatory flow of non-Newtonian fluid through porous medium in the presence of radiation and chemical diffusion with hall effects was investigated by Sakthikala and Lavanya [19]. The effects of radiative heat and magnetic field on blood flow in an inclined tapered stenosed porous artery was studied by Abubakar and Adeoye [20].

In the present paper, blood is regarded as viscous, conducting and an incompressible fluid. It has been examined that unsteady hydro-magnetic flow of blood passing through a porous medium which is placed in an inclined magnetic field in the presence of heat transfer and mass transfer has gained much importance as it can be applied in the electromagnetic therapy which in turn can be a treatment for cancer. In this paper the continuity equation, the momentum equation, and the equations which are controlling the flow are being riddled out by using dimensionless numbers and a graphical investigation has been carried out.

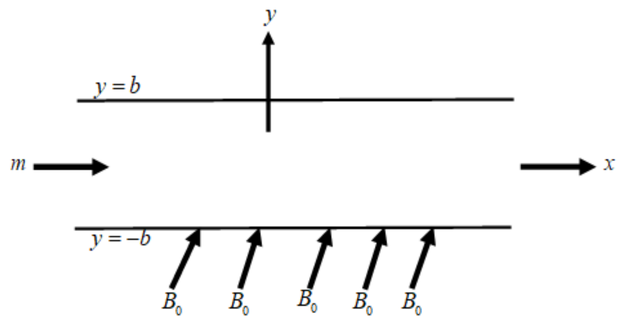

Figure 1 Geometry of the problem.

Formulation of the problem

Let us consider the unsteady, electrically conducting, incompressible, viscous and MHD blood flow past between 2 vertical parallel plates through a porous medium. In this model, the effect of inclined magnetic field on the flow of blood is being considered. Let u and v be the velocity components in x-axis and y-axis respectively at time t. The equations governing the flow field given by R Latha and B Kumar (2017) are:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+\frac{1}{\rho}\frac{\partial p}{\partial x}=\frac{\mu}{\rho}\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B_0^2\sin^2\alpha u}{\rho}-\frac{\nu u}{k}+g\beta(T-T_0)+g\beta'(C-C_0) \tag{2}$$

$$\frac{\partial T}{\partial t}=\frac{K'}{\rho C_p}\frac{\partial^2 T}{\partial y^2}+\frac{Q}{\rho C_p}(T-T_0)-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} \tag{3}$$

$$\frac{\partial C}{\partial t}=D\frac{\partial^2 C}{\partial y^2}-K_r(C-C_0) \tag{4}$$

The radiation heat flux q stated by Rosseland's approximation is:

$$q = \frac{-4\sigma'\partial T^4}{3k'\partial r} \quad (5)$$

Where k' is the mean absorption coefficient and $\sigma'$is Stefan-Boltzmann constant, assuming that the variation in temperature is negligible, therefore the above Eq. (5) can be solved using Taylor series which is about the mean ($T_0$is the wall temperature) and after overlooking higher order expression the equation will take the form as:

$$T^4 \cong 4T_0^3 T - 3 \quad (6)$$

Hence using Taylor's expansion in Eq. (5) which gives the heat flux as:

$$q = \frac{-4\sigma'\partial(4T_0^3 T - 3T_0^4)}{3k'\partial r}$$

Now Eq. (3) becomes

$$\frac{\partial T}{\partial t} = \frac{1}{Pr}\frac{\partial^2 T}{\partial y^2} + \frac{QTb^2}{kPr} + \frac{16\sigma' T_0^3}{3kk'Pr}\frac{\partial^2 T}{\partial y^2}$$

In order to write the governing equations in dimensionless form, some non-dimension variables are being introduced:

$$x' = \frac{x}{b}, y' = \frac{y}{b}, u' = \frac{u}{\frac{m}{2\rho b}}, v' = \frac{v}{\frac{m}{2\rho b}}, t' = \frac{t}{\frac{\rho b^2}{\mu}}, p'(x,t) = \frac{\frac{dp}{dx}}{\frac{\mu m}{2\rho^2 b^3}}, \theta' = \frac{\theta}{\frac{\mu m}{2\rho^2 b^3}}, \ C' = \frac{C}{\frac{\mu m}{2\rho b^3}}, Ha^2 = \frac{\sigma B_0^2 b^2}{\mu}$$

$$,N = \frac{Qb^2}{K}, \ Pr = \frac{\mu C_p}{K}, Cr = \frac{K_r b^2}{v}, Sc = \frac{v}{D}, R = \frac{16\sigma' T_0^3}{3kk'} \quad (7)$$

The Eqs. (1) to (4) are solved using dimensionless parameter in (7), we obtain the equations after dropping the primes:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (8)$$

$$\frac{\partial u}{\partial t} + p = \frac{\partial^2 u}{\partial y^2} - M^2 u - \frac{b^2 u}{k} + g\beta\theta + g\beta' C \quad (9)$$

$$\frac{\partial \theta}{\partial t} = \frac{(1+R)}{Pr}\frac{\partial^2 \theta}{\partial y^2} + \frac{N\theta}{Pr} \quad (10)$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} - CC_r \quad (11)$$

Where$M^2 = M'^2 \sin\alpha, M' = Ha = \sqrt{\frac{\sigma}{\mu}} B_0 b$.

Arising out of Eq. (10), we can observe θ (temperature) has the 1st derivative with respect to t (time). We get the result of the Partial differential equation by variable separable techniques and the expression for temperature distribution can be given as:

$\left(\frac{\partial \theta}{\partial t}\right)_{\theta_1} = -\boldsymbol{\lambda^2}$**,** where $\theta = \theta_1(t)$, $\theta_1 = exp^{-\lambda^2 t}$

The boundary conditions are:

$$u = exp^{-\lambda^2 t}, \theta = exp^{-\lambda^2 t}, C = exp^{-\lambda^2 t} \text{ at } y = -1$$
$$u = 0\ , \ \theta = 0, \quad C = 0 \text{ at } y = 1 \quad (12)$$

Hence the solution of equations fromEqs. (8) to (11) can be given as:

$$u(y,t) = A(y)exp^{-\lambda^2 t} \quad (13)$$
$$v(y,t) = B(y)exp^{-\lambda^2 t} \quad (14)$$
$$\theta(y,t) = S(y)exp^{-\lambda^2 t} \quad (15)$$

$$C(y,t) = T(y)exp^{-\lambda^2 t} \tag{16}$$

Now substituting Eqs. (13) to (16) in Eqs. (8) to (12), we get the following equations:

$$\frac{\partial^2 A}{\partial y^2} + A\zeta = P - g\beta S - g\beta' T \tag{17}$$

Where $\zeta = \sqrt{\lambda^2 - M^2 - \frac{b^2}{k}}$ and $P = \frac{p}{exp^{-\lambda^2 t}}$

Since the flow is along the x-axis therefore;

$$B = C \text{ (a constant)} \tag{18}$$

$$\frac{\partial^2 S}{\partial y^2} + \left(\frac{N+\lambda^2 Pr}{1+R}\right) S(y) = 0 \tag{19}$$

$$\frac{\partial^2 T}{\partial y^2} + Sc(\lambda^2 - Cr)T(y) = 0 \tag{20}$$

The boundary conditions may be given as:

$$A = 1,\ S = 1,\ T = 1 \text{ at } y = -1$$
$$A = 0,\ S = 0,\ T = 0 \text{ at } y = 1 \tag{21}$$

Hence, solutions of the 2 equations; Eqs. (19) and (20) can be given as:

$$S(y) = s_1 \cos(\eta y) + s_2 \sin(\eta y) \tag{22}$$

$$T(y) = t_1 \cos(\varphi y) + t_2 \sin(\varphi y) \tag{23}$$

Where $\eta = \sqrt{\left(\frac{N+\lambda^2 Pr}{1+R}\right)}$, $\varphi = \sqrt{Sc(\lambda^2 - Cr)}$

Using the boundary conditions given in the Eq. (21), we have:

$s_1 = \frac{1}{2\cos\eta}$ and $s_2 = \frac{-1}{2\sin\eta}$

$t_1 = \frac{1}{2\cos\varphi}$ and $t_2 = \frac{-1}{2\sin\varphi}$

Now equating the values of the constants in the Eqs. (22) and (23), we have:

$$S(y) = \frac{1}{2\cos\eta}\cos(\eta y) - \frac{1}{2\sin\eta}\sin(\eta y) \tag{24}$$

$$T(y) = \frac{1}{2\cos\varphi}\cos(\varphi y) - \frac{1}{2\sin\varphi}\sin(\varphi y) \tag{25}$$

The temperature and concentration profile can be discussed from Eqs. (15), (16), (24) and (25)

$$\theta(y,t) = \left(\frac{1}{2\cos\eta}\cos(\eta y) - \frac{1}{2\sin\eta}\sin(\eta y)\right) exp^{-\lambda^2 t} \tag{26}$$

$$C(y,t) = \left(\frac{1}{2\cos\varphi}\cos(\varphi y)\frac{1}{2\sin\varphi}\sin(\varphi y)\right) exp^{-\lambda^2 t} \tag{27}$$

Now using Eqs. (24) and (25) in Eq. (17), we have:

$$A''(y) + A(y)\left(\lambda^2 - M^2 - \frac{b^2}{k}\right) = P - g\beta\left(\frac{1}{2\cos\eta}\cos(\eta y) - \frac{1}{2\sin\eta}\sin(\eta y)\right) - g\beta'\left(\frac{1}{2\cos\varphi}\cos(\varphi y) - \frac{1}{2\sin\varphi}\sin(\varphi y)\right) \tag{28}$$

Hence the homogeneous solution of Eq. (28) can be given as:

$$A_h = A_1 \cos(\zeta y) + A_2 \sin(\zeta y) \tag{29}$$

Utilizing the boundary condition in Eq. (21), we have:

$$A_1 = \frac{1 - 2A_3 + 2A_4 \cos\eta + 2A_6 \cos\varphi}{2\cos\zeta}$$
$$A_2 = \frac{1 + 2A_5 \sin\eta + 2\,A_7 \sin\varphi}{-2\sin\zeta}$$

Now the particular solution for Eq. (28) can be given as:

$$A_p = A_3 - A_4\cos(\eta y) + A_5\sin(\eta y) - A_6\cos(\varphi y) + A_7\sin(\varphi y) \tag{30}$$

The general solution of A can be given by Eqs. (29) and (30), therefore we have:

$$A = A_1\cos(\zeta y) + A_2\sin(\zeta y) + A_3 - A_4\cos(\eta y) + A_5\sin(\eta y) - A_6\cos(\varphi y) + A_7\sin(\varphi y) \tag{31}$$

Hence from Eqs. (13) and (31), we get the axial flow transport as:

$$u(y,t) = (A_1\cos(\zeta y) + A_2\sin(\zeta y) + A_3 - A_4\cos(\eta y) + A_5\sin(\eta y) - A_6\cos(\varphi y) + A_7\sin(\varphi y))e^{-\lambda^2 t} \tag{32}$$

Where

$$A_3 = \frac{P}{\zeta^2}, A_4 = \frac{g\beta}{2\cos\eta(\zeta^2-\eta^2)},$$
$$A_5 = \frac{g\beta}{2\sin\eta(\zeta^2-\eta^2)}, A_6 = \frac{g\beta'}{2\cos\varphi(\zeta^2-\varphi^2)}, A_7 = \frac{g\beta'}{2\sin\varphi(\zeta^2-\varphi^2)}$$

Arising out of Eqs. (14) and (18), we get the axial velocity as:

$$v(y,t) = Cexp^{-\lambda^2 t} \tag{33}$$

Where the value of C can be taken as 1 as it is an arbitrary constant.

The expressions representing the profile for temperature, profile for concentration, profile for axial flow transport and profile for normal velocity are given by Eqs. (26), (27), (32) and (33), respectively.

Results and discussion

The investigation on the flow of blood has been accomplished and the impact of inclined magnetic field, heat source parameter, thermal radiation, Prandtl number and Schmidt number on the axial velocity of the blood flow has been examined. The results have been investigated and represented graphically using MATLAB R2018B.

Impact on velocity profile due to various parameters

Figures 2-5 displays the axial velocity for different values of α, B_0, N and t at $\lambda = 1,\ p = 0.5,\ R = 0.5,\ Pr = 1,\ Sc = 1,\ Cr = 0.8, \beta = 0.5,\ \beta' = 0.5,\ g = 9.81$. As seen in **Figure 2**, the axial velocity takes a sinusoidal pattern due to the trigonometric functions present in the axial velocity equation. The velocity increases and attains a maximum position at $u = 1.569583,\ 1.525746, 1.545445, 1.596829$ for different values of angle of inclination of magnetic field, viz, $\alpha = 15, 30, 45, 60$ and then decreases in a converging manner. In **Figure 3**, the axial velocity takes a curvilinear pattern as the magnetic field intensity B_0 increases and attains a certain height at $u = 1.600533,\ 1.545235, 1.451673, 1.394343$ and then decreases gradually for different values of B_0 viz 1.0 , 2.5, 4.0 , 5.5. In **Figure 4**, the velocity adopts a pulsating pattern which is because of the trigonometric and exponential terms present in the velocity profile equation, hence the velocity becomes maximum at $u = 1.598994, 1.151955,\ 0.8038,\ 0.532657$ for $t = 1.00,\ 1.25,\ 1.50, 1.75$ and gradually the amplitude for the velocity profile decreases as the value of $'t'$ increases. In **Figure 5**, the velocity profile takes a wavy pattern and reaches a maximum point at $u = 1.598994,\ 1.707827, 1.830838$ and 1.970903 for the heat source parameter $N = 1.0, 1.1, 1.2, 1.3$ and uniformly decreases for increasing values of heat source parameter.

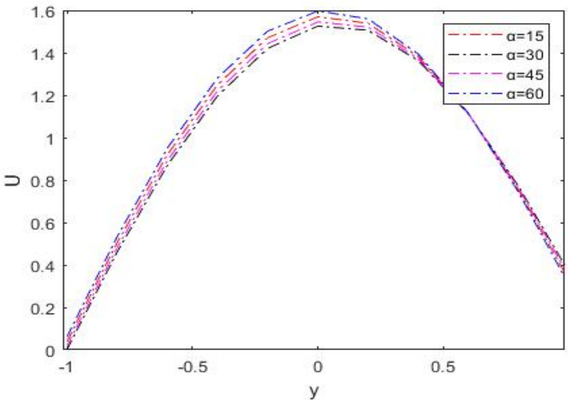

Figure 2 Axial velocity for various values of α where $\lambda = 1, B_0 = 2.5$.

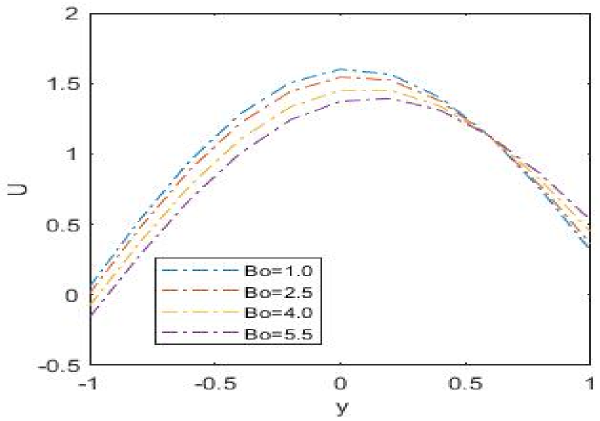

Figure 3 Axial velocity for various values of$B_0$where $\lambda = 1, \alpha = 20, N = 1$.

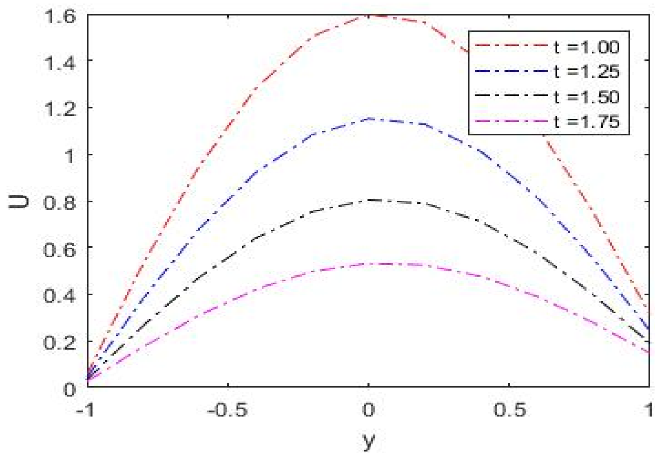

Figure 4 Axial velocity for various values of t where $B_0 = 1.5, N = 1$.

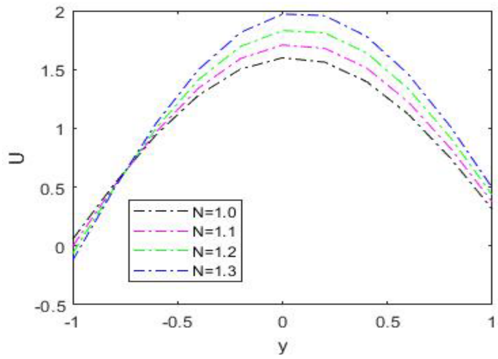

Figure 5 Axial velocity for different values of$N$ where $\lambda = 1, B_0 = 1.5$.

Impact on temperature profile due to various parameters

Figures 6-8 demonstrate the profile for temperature at different values of Pr, R and N at $\lambda = 1$, $p = 0.5$, $Sc = 1$, $Cr = 0.8$, $\beta = 0.5$, $\beta' = 0.5$, $g = 9.81$, $t = 1$. It can be seen from **Figure 6** that the temperature profile gives a wavy pattern for different values of thermal radiation R, as the value of R increases the temperature profile decreases gradually decreases and further converge at $y = 1$. Moreover, the highest numerical values of temperature are0.497011,0.43501,0.404403 and 0.386144 for different values of $R = 0.50,\ 0.75,\ 1.00, 1.25$. In **Figure 7**, the temperature profile starts from $\theta = 0.367879$ and then diverges for various values of Prandtl number and converges again at $y = 1$ giving a wavy patter to the temperature profile which is due to the exponential terms present in the temperature equation. The profile attains a maximum amplitude at $\theta = 0.52374,\ 0.554398,\ 0.594009, 0.639654$ for $Pr = 1.0$, 1.1, 1.2, 1.3. In **Figure 8**, the temperature profile shows a curvy pattern which diverges for various values of heat source parameter and then converges at $y = 1$. The amplitude of the temperature profile for $N = 1.75$ is the largest and then gradually decreases for $N = 1.50$ and then further decreases for $N = 1.25$ and 1.00.

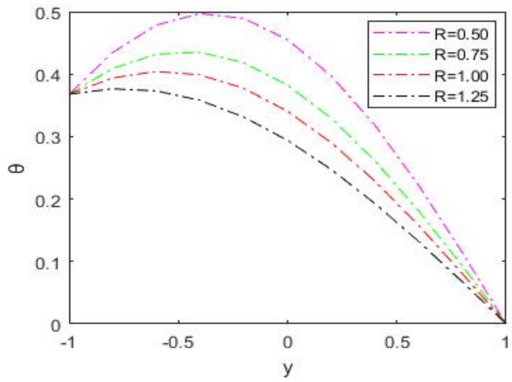

Figure 6 Temperature profile for different values of R where $N = 1,\ Pr = 1$.

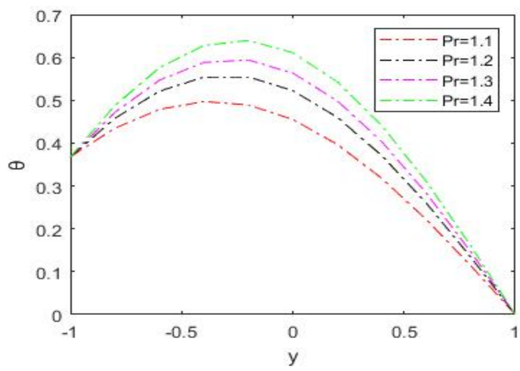

Figure 7 Temperature profile for variousvalues of Pr where $R = 0.5,\ N = 1$.

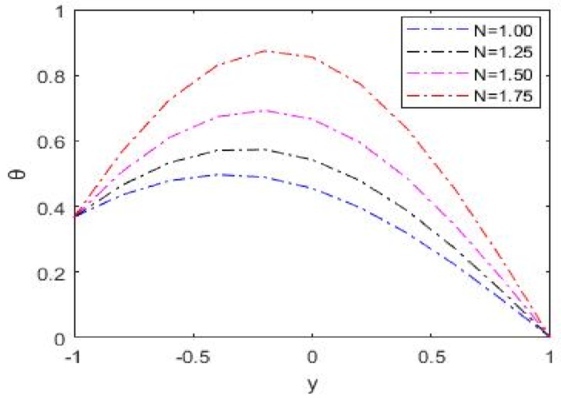

Figure 8 Temperature profile for various values of N where $Pr = 1,\ R = 0.5$.

Impact on concentration profile due to various parameters

Figures 9 and **10** gives the concentration profile for different values of Sc and Cr at $\lambda = 1,\ p = 0.5,\ \beta = 0.5,\ \beta' = 0.5,\ g = 9.81,\ t = 1,\ Pr = 1$ and $R = 0.5$. It can be seen in **Figure 9** that the profile for concentration drops down as Schmidt number (Sc) is increased. The graph reaches its maximum values of concentration i.e., 0.591935, 0.621248, 0.669152 and 0.753622 for $Sc = 1.00,\ 1.25$, 1.50 and 1.75. In **Figure 10**, the profile for concentration decreases as the chemical reaction parameter (Cr) is increased. The highest amplitude of concentration profile is attained at $Cr = 0.2$, moreover, the maximum values for concentration are 0.753622, 0.621248, 0.591935 and 0.574151for different values of $Cr = 0.2, 0.4, 0.6$ and 0.8.

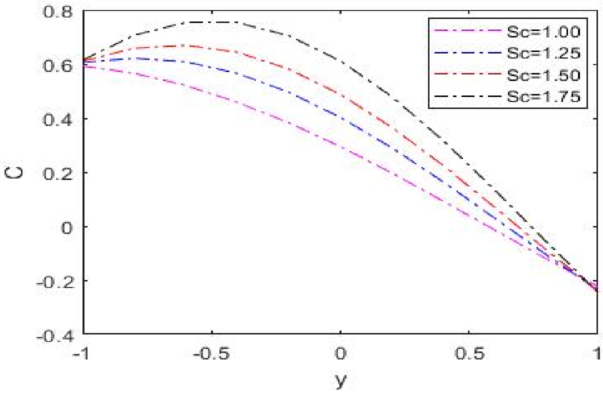

Figure 9 Concentration profile for different values of Sc where $t = 1,\ Cr = 0.2$.

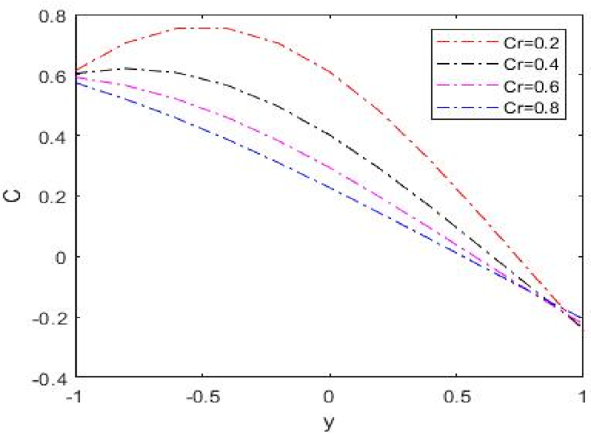

Figure 10 Concentration profile for different values of Cr where $t = 1,\ Sc = 2$.

Conclusions

A therotical exmination of unsteady blood flow through a restricted porous channel in the presence of inclined magnetic field subjected to heat source and radiation has been done. This study analyses the effect of Inclination of magetic field and heat source parameter on the flow of blood through parallel plate channel. The main interest of our study has been to access the behaviour of axial flow transport in the existance of inclined magnetic field as this investigation can be helpful in exploring the causes and development of arterial deseases. The conclusion for the computational results can be given as:

- The axial velocity takes a sinosoidal pattern with increasing values of angle of inclination of magnetic field α.
- The axial velocity shows a wavy pattern for both as the values of magnetic field intensity (B_0) and heat source parameter (N) increases.
- The axial velocity shows a decreasing pattern as the time (t) increases.
- The temperature profile takes a fluctation pattern and the graph first diverges and the converge at the same point for different values of radiation parameter (R), Prandtl number (Pr) and heat source parameter N.
- The concentration profile dimnisnes for different values of chemical reaction paramater (Cr) and Schmidt number (Sc).

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