UNSTEADY MHD FLOW BETWEEN TWO HORIZONTAL PARALLEL SEMI-INFINITE POROUS PLATES

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ABSTRACT

This study investigated unsteady MHD flow of an incompressible fluid through horizontal semi-infinite porous plates. A variable magnetic field was applied normal to the flow. The flow was assumed to occur along the positive x direction between two parallel horizontal plates stationed at $y = \pm L$ planes. Effects of different flow parameters were investigated when the lower plate was impulsively started in the positive x direction at a uniform velocity while the upper plate was kept stationary. The coupled non-linear partial differential equations governing the flow were first non-dimensionalised then solved using the finite difference method. The results obtained were presented in tables and graphs. It was noted that an increase in magnetic field intensity causes a decrease in both the primary and secondary velocity profiles.

Key Words: MHD, Vorticity, Unsteady flow.

Introduction

An ideal fluid is one that is incompressible and flows steadily, irrotationally and with no viscosity. According to the non dissipative nature of ideal fluids, experimental results have shown that fluids such as air and water are not so ideal and that ideal fluids do not actually exist. Real fluids are either compressible or incompressible and their flow exhibits viscous effect. This means that whenever there is a velocity gradient across the real fluid's flow path, frictional forces arise between adjacent fluid particles due to the viscosity μ of the fluid. Real fluids obey the Newton's law of viscosity i.e.

$$\tau \propto \frac{du}{dy}$$

This means that the shear stress τ in a fluid is proportional to the velocity gradient, which is the rate of change of velocity across the fluid flow path. For a Newtonian fluid, we can express

$$\tau = \mu \frac{du}{dy} \qquad \textbf{(1)}$$

The constant of proportionality μ is known as the coefficient of viscosity. For some fluids sometimes known as exotic fluids, the value of μ changes with stress or velocity gradient. The viscosity of a pure Newtonian fluid depends only on temperature and pressure. When viscous fluids flow between stationary solid surfaces, the velocity of fluid particles in contact with the solid boundary is zero. At the solid wall boundary, a type of frictional force called skin friction exists. A boundary layer forms in the fluid flow region close to the solid wall. This is due to the no slip boundary condition. The thickness of the boundary layer will be dependent on the Reynolds number and the local flow properties.

Fluid flow can be classified as either steady or unsteady. The flow is said to be steady if the fluid flow variables such as velocity, applied magnetic field and temperature are independent of time. If on the other hand the flow variables are dependent on time the flow is said to be unsteady. Laminar fluid flow is the motion of the fluid particles in a very orderly manner with all particles moving in straight lines parallel to the boundary walls. The particles do not encounter disturbance on their path. Turbulence in fluid flow occurs when a flowing fluid suddenly encounters a disturbance such as a solid obstruction or a force. As a result the fluid particles move in a disorderly manner with different velocities and energy. The shape of the velocity curve (the velocity profile across any given section of the flow channel) depends upon whether the flow is laminar or turbulent. For turbulent flow in a pipe a fairly flat velocity distribution exists across the section of the flow field, with the result that the entire fluid flows at a given single value. If the flow is laminar the shape is parabolic with the maximum velocity at the centre being about twice the average velocity in the pipe.

As in ordinary hydrodynamics, the dynamics of the conducting fluid flowing in a transverse magnetic field obeys theorems expressing the conservation of mass, momentum and energy. These theorems are; matter can neither be created nor destroyed, momentum of a moving body is always conserved and energy can never be destroyed but can be converted from one form to another. These theorems treat the fluid as a continuum. This is justified if the mean flee path of the individual particles is much shorter than the flow. Although this assumption does not generally hold for plasmas, one can gain much insight into hydrodynamics from the continuum approximation. For incompressible fluids, the mean distance between fluid particles remains fairly constant and is not affected by an increase in pressure.

Magnetohydrodynamics (MHD) is a branch of science which concerns the study of the flow of an electrically conducting fluid in the presence of a magnetic field. The fluids can be ionized gases generally called plasmas or liquid metals. The central point of MHD theory is that magnetic field can induce a current in a moving conductive fluid which ends up creating pondermotive forces on the fluid particles and also change the magnetic field itself. When a conducting fluid moves through the magnetic lines of force the positive and negative charges are each accelerated in such a way that their average motion gives rise to an electric current $j = \sigma(q \times B)$. In accordance with the dynamo rule, the voltage drop or electric field which causes this current is at right angles to the direction of fluid motion and the magnetic field lines; (Verma, 1968).

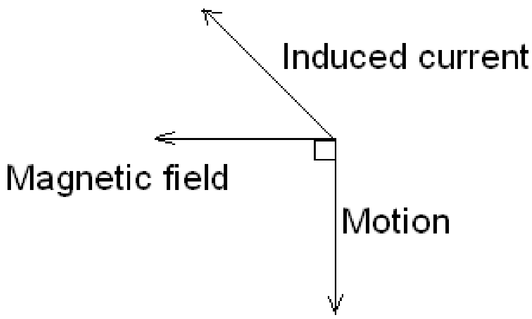

Figure 1: Dynamo rule

In the case of a fluid conductor flowing in presence of a transverse magnetic field, the ordinary laws of hydrodynamics can easily be extended to cover the effect of magnetic and electric fields. This is done by adding magnetic force (Lorentz force) to the momentum conservation equation. To incorporate exhaustively the effects of magnetic and electric fields, the electric heating and work are added to the energy conservation equation. The Lorentz force is in a direction perpendicular to both J and B and is proportional to the magnitude of both J and B and is given by the cross product of J and B i.e.

$$F_e = J \times B \quad \textbf{(2)}$$

In MHD this force acts on the fluid particles.

Literature Review

The problem of unsteady MHD convection heat and mass transfer past a semi- infinite vertical permeable moving plate with heat absorption has been studied by several researchers who include Chamkha,A.K. (2004) and Attia, H.A. (1999) who researched on transient MHD flow and heat transfer between two parallel plates with temperature dependent viscosity. Nithiarasu et., al (2001) presented their numerical work on natural convection in porous medium fluid interface problems where they used the finite difference method to solve the governing generalized porous medium equations. Chandra, B S (2005) studied a steady MHD flow of an electrically conducting fluid between two parallel infinite plates when the upper plate is made to move with constant velocity while the lower plate is stationary. Smokentsev et., al (2006) studied modeling quasi-two dimensional turbulence in MHD duct flows in a transverse uniform magnetic field where viscous and Ohmic losses occur in the boundary layers at the flow-confining walls perpendicular to the magnetic field (Hartman layers). Ramana, et. al (2007) studied the effect of Hall current on MHD flow and heat transfer along a porous flat plate with mass transfer. He applied numerical methods to obtain the solutions. Ganesh et. al (2007) studied unsteady magnetohydrodynamic Stokes flow of a viscous fluid between two parallel porous plates in a channel in the presence of a transverse magnetic field when the fluid is being withdrawn through both walls of the channel at the same rate. Singh, N P et., al (2007) studied two dimensional free convection and mass transfer flow of an incompressible, viscous and electrically conducting fluid past a continuously moving infinite vertical porous plate in the presence of heat source, thermal diffusion, large suction and under influence of a uniform magnetic field applied normal to the flow. The present research will be to investigate unsteady flow of an incompressible, viscous and electrically conducting fluid between two parallel semi-infinite porous plates when the lower plate is set impulsively in motion at constant velocity U while the upper plate remains stationary in the presence of a variable magnetic field and constant suction. The fluid is considered to flow in the X-direction between two parallel flat plates located at $y=\pm L$ and the variable transverse magnetic field is applied in Y-direction. The fluid will be assumed to be Newtonian. Semi- infinite implies that the flow field is unbounded in one direction; the z direction.

Mathematical Formulations

The flow geometry describing this system is presented in figure 2. The velocity, temperature and magnetic field initial and boundary conditions for this flow problem can be stated in summary as follows;

- $t<0$, $u(x, y, 0) = 0$, $w(x, y, 0) = 0$, $T(x, y, 0) = T_\infty$
- $t\geq 0$, $u(x, -L, t) = U$, $w(x, -L, t) = 0$, $T(x, -L, t) = T_\infty$
- $t\geq 0$, $u(x, L, t) = 0$, $w(x, L, t) = 0$, $T(x, L, t) = T_w$
- $t\geq 0$, $u(X, y, t) = 0$, $w(X, y, t) = 0$, $T(X, y, t) = T_\infty$

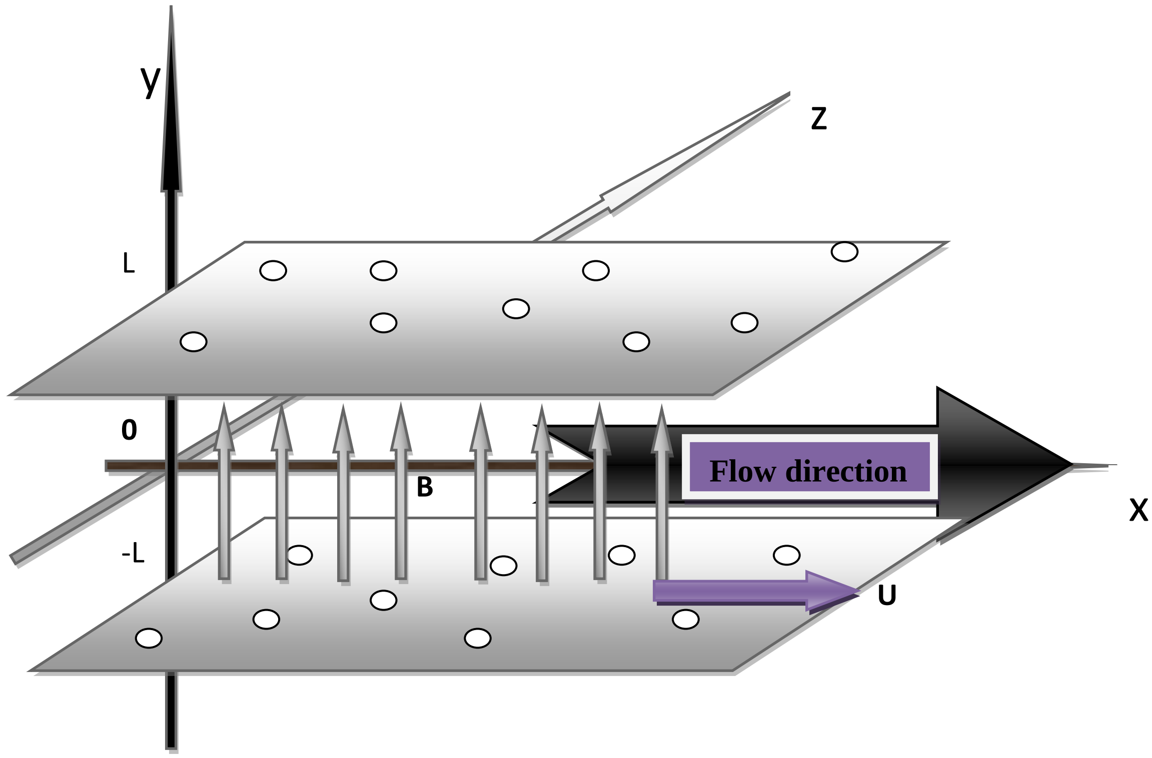

Figure 2: The flow geometry

The applied inhomogeneous magnetic field has the following boundary conditions:

- $t \geq 0$, $B_y = 0$ for $x<0$, $|B_y| = B_y \frac{\partial B_y}{\partial x}$ for $0 \leq x \leq X$

The flow set up is such that the rate at which the magnetic field intensity B_y changes in the defined length $0<x<X$ is constant, implying that the magnetic field gradient $\left(Fgrand = \frac{\partial B_y}{\partial x}\right)$ is constant. Vorticity is generated by the viscosity, and also by the interaction between the resultant electric field, ‘‘Curl B_y yields $\vec{J} = (0,0,j_z)$’’ and the applied magnetic field $\vec{B} = (0, B_y, 0)$ to produce an electromagnetic force (JxB). The governing equations for this research problem are:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + V\frac{\partial u}{\partial y} = \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \frac{1}{\rho \mu_e} B_y\left(\frac{\partial B_y}{\partial x}\right) \quad \textbf{(3)}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + V\frac{\partial w}{\partial y} = \nu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right) \quad \textbf{(4)}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial y}=\frac{K}{\rho C_p}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\frac{\mu}{\rho C_p}\left[\left(\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial w}{\partial y}\right)^2\right] \quad \textbf{(5)}$$

The final form of non-dimensional equations governing the primary and secondary velocity profiles are:

$$\frac{\partial u^*}{\partial t^*}+u^*\frac{\partial u^*}{\partial x^*}+V_0\frac{\partial u^*}{\partial y^*}=\frac{1}{R_e}\left(\frac{\partial^2 u^*}{\partial x^{*2}}+\frac{\partial^2 u^*}{\partial y^{*2}}\right)-R_h B_y^*\frac{\partial B_y^*}{\partial x^*} \quad \textbf{(6)}$$

$$\frac{\partial w^*}{\partial t^*}+u^*\frac{\partial w^*}{\partial x^*}+V_0\frac{\partial w^*}{\partial y^*}=\frac{1}{R_e}\left(\frac{\partial^2 w^*}{\partial x^{*2}}+\frac{\partial^2 w^*}{\partial y^{*2}}\right) \quad \textbf{(7)}$$

The final form of the energy equation is:

$$\frac{\partial \theta^*}{\partial t^*}+u^*\frac{\partial \theta}{\partial x^*}+V_0\frac{\partial \theta^*}{\partial y^*}=\frac{1}{P_r}\left(\frac{\partial^2 \theta}{\partial x^{*2}}+\frac{\partial^2 \theta}{\partial y^{*2}}\right)+E_c\left[\left(\frac{\partial u^*}{\partial y^*}\right)^2+\left(\frac{\partial w^*}{\partial y^*}\right)^2\right] \quad \textbf{(8)}$$

The non-dimensional form of the equations governing this problem can be stated in summary as:

- $$\frac{\partial u^*}{\partial t^*}+u^*\frac{\partial u^*}{\partial x^*}+V_0\frac{\partial u^*}{\partial y^*}=-\frac{\partial P^*}{\partial x^*}+\frac{1}{R_e}\left(\frac{\partial^2 u^*}{\partial x^{*2}}+\frac{\partial^2 u^*}{\partial y^{*2}}\right)-R_h B_y^*\frac{\partial B_y^*}{\partial x^*} \quad \textbf{(9)}$$
- $$\frac{\partial w^*}{\partial t^*}+u^*\frac{\partial w^*}{\partial x^*}+V_0\frac{\partial w^*}{\partial y^*}=-\frac{\partial P^*}{\partial z^*}+\frac{\mu}{\rho UL}\left(\frac{\partial^2 w^*}{\partial x^{*2}}+\frac{\partial^2 w^*}{\partial y^{*2}}\right) \quad \textbf{(10)}$$
- $$\frac{\partial \theta^*}{\partial t^*}+u^*\frac{\partial \theta}{\partial x^*}+V_0\frac{\partial \theta^*}{\partial y^*}=\frac{1}{P_r}\left(\frac{\partial^2 \theta}{\partial x^{*2}}+\frac{\partial^2 \theta}{\partial y^{*2}}\right)+E_c\left[\left(\frac{\partial u^*}{\partial y^*}\right)^2+\left(\frac{\partial w^*}{\partial y^*}\right)^2\right] \quad \textbf{(11)}$$

The fluid particles in contact with the solid boundaries are assumed to stick tightly and not to slide over the plates, i.e. the fluid satisfies the no-slip condition. This implies that their velocity in time t≥0 is equal to that of the plates. Halfway plates separation distance (L) is taken as the characteristic length. The non-dimensional initial and boundary conditions on velocity, temperature and magnetic field for this problem can be summarized as shown below.

$t^* < 0$	$u^*(x^*, y^*, 0) = 0$	$w^*(x^*, y^*, 0) = 0$	$\theta(x^*, y^*, 0) = 0$
$t^* \geq 0$	$u^*(x^*, 1, t^*) = 0$	$w^*(x^*, 1, t^*) = 0$	$\theta(x^*, 1, t^*) = 1$
	$u^*(x^*, -1, t^*) = 1$	$w^*(x^*, -1, t^*) = 0$	$\theta(x^*, -1, t^*) = 0$
	$u^*\left(\frac{X}{L}, y^*, t^*\right) = 0$	$w^*\left(\frac{X}{L}, y^*, t^*\right) = 0$	$\theta^*\left(\frac{X}{L}, y^*, t^*\right) = 0$

In the analysis it is assumed that electromagnetic interaction is initially zero; the magnetic field intensity $\left(B_y^*\right)$ is varied instantaneously from 2.0T to 4.0T, and the magnetic flux gradient $\left(\frac{\partial B_y^*}{\partial x^*}\right)$ similarly from 0.03 to 0.05. Referring to equation (9), the effect of isolated variation of these two terms corresponds to the effect of transverse variable magnetic field on the flow of the conducting fluid without loss of approximate generality. In the referred equation, the non-dimensionalised form of JxB has been simplified to $R_h B_y^* \frac{\partial B_y^*}{\partial x^*}$ where R_h is the magnetic pressure number. This approach renders the induction equation solved *a priori* as well as the Lorentz force term, thus at $t^* \geq 0$, $\left|B_y^*\right| = B_y^* \frac{\partial B_y^*}{\partial x^*}$ for $0 \leq x^* \leq X/L$ and $\left|B_y^*\right| = 0$ elsewhere.

The momentum equation can be expressed in finite difference form via time step k+1 yielding the primary velocity profile as

$$\frac{u^{*k+1}(i,j)-u^{*k}(i,j)}{\Delta t} + u^{*k}(i,j)\frac{u^{*k}(i+1,j)-u^{*k}(i,j)}{\Delta x} + V_0^* \frac{u^{*k}(i,j+1)-u^{*k}(i,j)}{\Delta y} =$$
$$\frac{1}{R_e}\left[\frac{u^{*k}(i+1,j)-2u^{*k}(i,j)+u^{*k}(i-1,j)}{(\Delta x)^2} + \frac{u^{*k}(i,j+1)-2u^{*k}(i,j)+u^{*k}(i,j-1)}{(\Delta y)^2}\right] - R_h B^{*k}(i,j) Fgrad$$

(12)

The secondary velocity profile is similarly expressed in finite difference form as

$$\frac{w^{*k+1}(i,j)-w^{*k}(i,j)}{\Delta t} + u^{*k}(i,j)\frac{w^{*k}(i+1,j)-w^{*k}(i,j)}{\Delta x} + V_0^* \frac{w^{*k}(i,j+1)-w^{*k}(i,j)}{\Delta y} =$$
$$\frac{1}{R_e}\left[\frac{w^{*k}(i+1,j)-2w^{*k}(i,j)+w^{*k}(i-1,j)}{(\Delta x)^2} + \frac{w^{*k}(i,j+1)-2w^{*k}(i,j)+w^{*k}(i,j-1)}{(\Delta y)^2}\right]$$

(13)

The pressure gradient terms $\left(\frac{\partial P^*}{\partial x^*}\right)$ and $\left(\frac{\partial P^*}{\partial z^*}\right)$ are considered to be constant (zero) since the flow is fully developed and *Fgrand* represents the magnetic flux gradient $\frac{\partial B_y^*}{\partial x^*}$. These two expressions are used to determine the velocity profiles by subjecting $u^{*k+1}(i,j)$ and $w^{*k+1}(i,j)$ respectively. The energy equation in finite difference form is expressed as

$$\frac{\theta^{*k+1}(i,j)-\theta^{*k}(i,j)}{\Delta t} + u^{*k}(i,j)\frac{\theta^{*k}(i+1,j)-\theta^{*k}(i,j)}{\Delta x} + V_0^* \frac{\theta^{*k}(i,j+1)-\theta^{*k}(i,j)}{\Delta y} = \frac{1}{P_r} +$$

$$\left[\frac{\theta^{*k}(i+1,j)-2\theta^{*k}(i,j)+\theta^{*k}(i-1,j)}{(\Delta x)^2}+\frac{\theta^{*k}(i,j+1)-2\theta^{*k}(i,j)+\theta^{*k}(i,j-1)}{(\Delta y)^2}\right]+E_c\left[\left(\frac{u^{*k}(i,j+1)-u^{*k}(i,j)}{\Delta y}\right)^2+\left(\frac{w^{*k}(i+1,j)-w^{*k}(i,j)}{\Delta y}\right)^2\right]$$

(14)

Method of Solution

The solution to this problem is obtained via an iterative strategy where the variable in question is expressed in terms of its local mesh point values at the previous time step. The values of velocity and temperature are computed via consecutive expressions of $u^{*k+1}(i,j)$, $w^{*k+1}(i,j)$ and $\theta^{k+1}(i,j)$, i.e.

$$u^{*k+1}(i,j)=\Delta t\left[-u^{*k}(i,j)\frac{u^{*k}(i+1,j)-u^{*k}(i,j)}{\Delta x}-V_0^*\frac{u^{*k}(i,j+1)-u^{*k}(i,j)}{\Delta y}+\frac{1}{R_e}\left(\frac{u^{*k}(i+1,j)-2u^{*k}(i,j)+u^{*k}(i-1,j)}{(\Delta x)^2}+\frac{u^{*k}(i,j+1)-2u^{*k}(i,j)+u^{*k}(i,j-1)}{(\Delta y)^2}\right)-R_hB^{*k}(i,j)Fgrad\right]+u^{*k}(i,j)$$

(15)

$$w^{*k+1}(i,j)=\Delta t\left[-u^{*k}(i,j)\frac{w^{*k}(i+1,j)-w^{*k}(i,j)}{\Delta x}-V_0^*\frac{w^{*k}(i,j+1)-w^{*k}(i,j)}{\Delta y}+\frac{1}{R_e}\left(\frac{w^{*k}(i+1,j)-2w^{*k}(i,j)+w^{*k}(i1,j)}{(\Delta x)^2}+\frac{w^{*k}(i,j+1)-2w^{*k}(i,j)+w^{*k}(i,j-1)}{(\Delta y)^2}\right)\right]+w^{*k}(i,j)$$

(16)

$$\theta^{*k+1}(i,j)=\Delta t\left\{-u^{*k}(i,j)\frac{\theta^{*k}(i+1,j)-\theta^{*k}(i,j)}{\Delta x}-V_0^*\frac{\theta^{*k}(i,j+1)-\theta^{*k}(i,j)}{\Delta y}+\frac{1}{P_r}\left(\frac{\theta^{*k}(i+1,j)-2\theta^{*k}(i,j)+\theta^{*k}(i-1,j)}{(\Delta x)^2}+\frac{\theta^{*k}(i,j+1)-2\theta^{*k}(i,j)+\theta^{*k}(i,j-1)}{(\Delta y)^2}\right)+E_c\left[\left(\frac{u^{*k}(i,j+1)-u^{*k}(i,j)}{\Delta y}\right)^2+\left(\frac{w^{*k}(i+1,j)-w^{*k}(i,j)}{\Delta y}\right)^2\right]\right\}+\theta^{*k}(i,j)$$

(17)

The computations are performed using small values of Δt, ie constant time steps of $\Delta t= 0.00625$. The range of i and j follows from constant step sizes $\Delta x\approx 0.05$ and $\Delta y\approx 0.05$ within a square mesh framework. Using the expressions $x^*=i\Delta x$ and $y^*=j\Delta y$, the range of j in terms of discrete units is transformed to $-20 \leq j \leq 20$ which is equivalent to $-1 \leq y^* \leq 1$. This follows from the deduction that for $y^* = -1,\ j = -1/0.05 = -20$. Similarly when $y^* = 1, j = 20$. This range is arbitrary and its equivalent whole unit grid steps over the entire mesh system are $0 \leq j \leq 40$. The unit grid steps along the direction of flow are similarly calculated and for a square mesh framework, $0 \leq i \leq 40$. The fluid exhibits free stream profiles in the region defined by i>40. Due to the sudden velocity given to the lower plate, the velocity at j=0 changes suddenly from zero at t≥0 to 1 while the velocity at the upper plate remains zero. The fluid exhibits free stream profiles in the region defined by i>40. In short, the discretised conditions become

Flow Conditions	**Primary velocity**	**Secondary velocity**	**Temperature**
$t < 0$	$u^{*0}(i,j) = 0$	$w^{*0}(i,j) = 0$	$\theta^0(i,j) = 0$
$t \geq 0$	$u^{*k}(i,40) = 0$	$w^{*k}(i,40) = 0$	$\theta^k(i,40) = 1$
	$u^{*k}(i,0) = 1$	$w^{*k}(i,0) = 0$	$\theta^k(i,0) = 0$
	$u^{*k}(40,j) = 0$	$w^{*k}(40,j) = 0$	$\theta^k(40,j) = 0$

This procedure ensures that the following conditions apply;

- The flow variables converge after the 300 iterations, i.e. for k+1=300. An immediate result for this value of k follows when further iterations do not make any significant change of the flow variable being iterated.
- The fluid exhibits free stream profiles in the region i>40 for all j and k, hence i=41=∞.
- The locations of the parallel plates at $y=\pm L$ are arbitrary.
- The iterations are obtained for different values of j=0,1,2,3,……….41. To cater for the inhomogeneous magnetic field, iterations are carried out for i=0,1,2,3,……….41.

To be able to cater for the inhomogeneous magnetic field, the variation of B_y and $\frac{\partial B_y}{\partial x}$ are considered. These two terms are as a result of the simplified Lorentz force J×B; ''the cross product of the induced current when the displacement current is neglected in line with Ampere's law and the applied transverse inhomogeneous magnetic field''. The results have been obtained for B_y=2.0-4.0 T, Fgrand=0.03-0.05 T^2m^{-1}, Rh=1.0-3.0, θ=0-1.0, Pr=0.71-0.74, Ec=0.5-0.7, V_0=0-0.5 and Re=1000-1500.

Results and discussions

The graphs below shows the primary velocity profiles, secondary velocity profiles as well as the temperature profiles. The various profiles are distinguished using different dash type line style curves which have been set apart by the use of different series code letters.

Pr = 0.71, Ec = 0.05

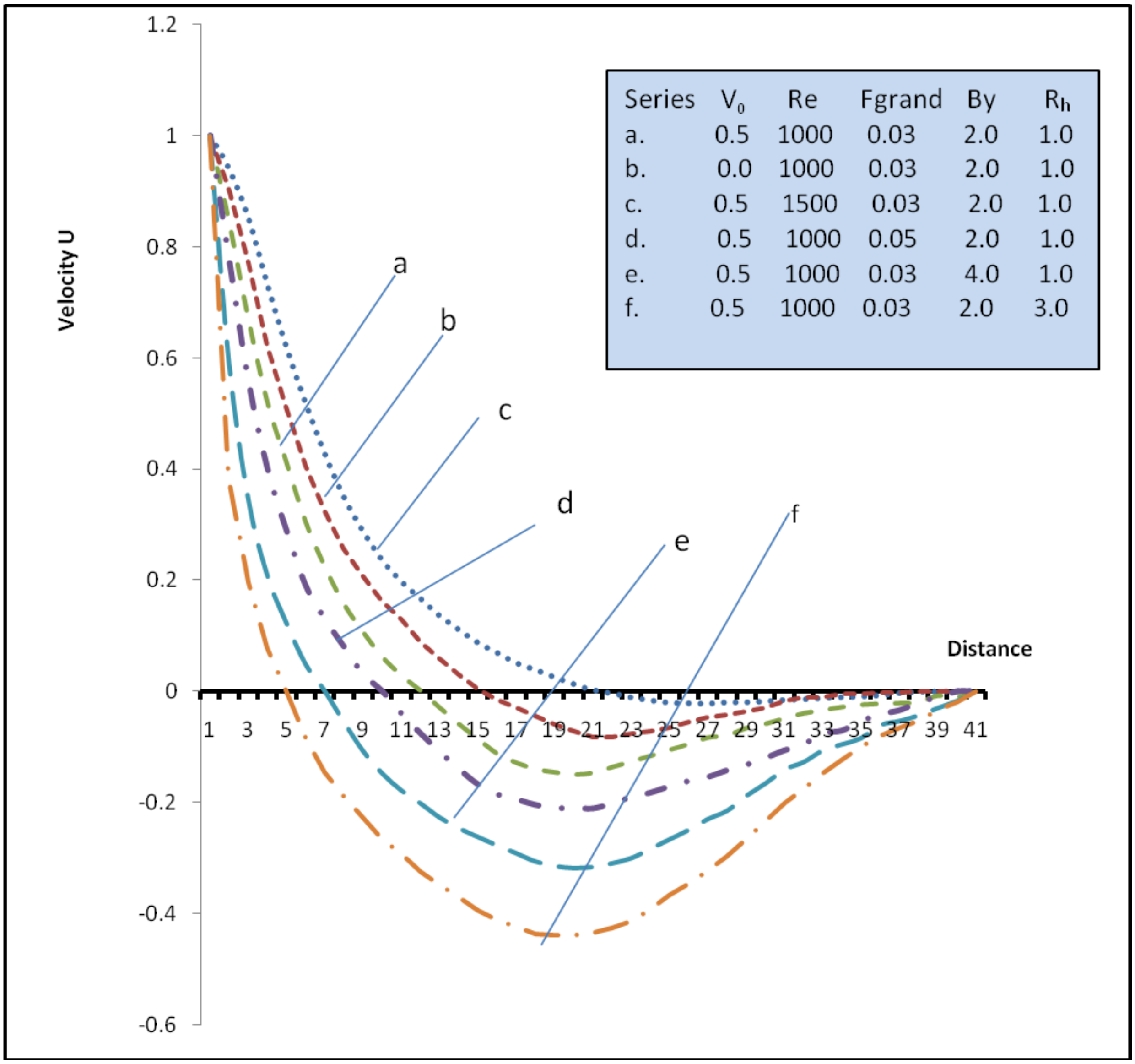

Figure 3: Primary Velocity Profiles

Pr=0.71, Ec=0.05

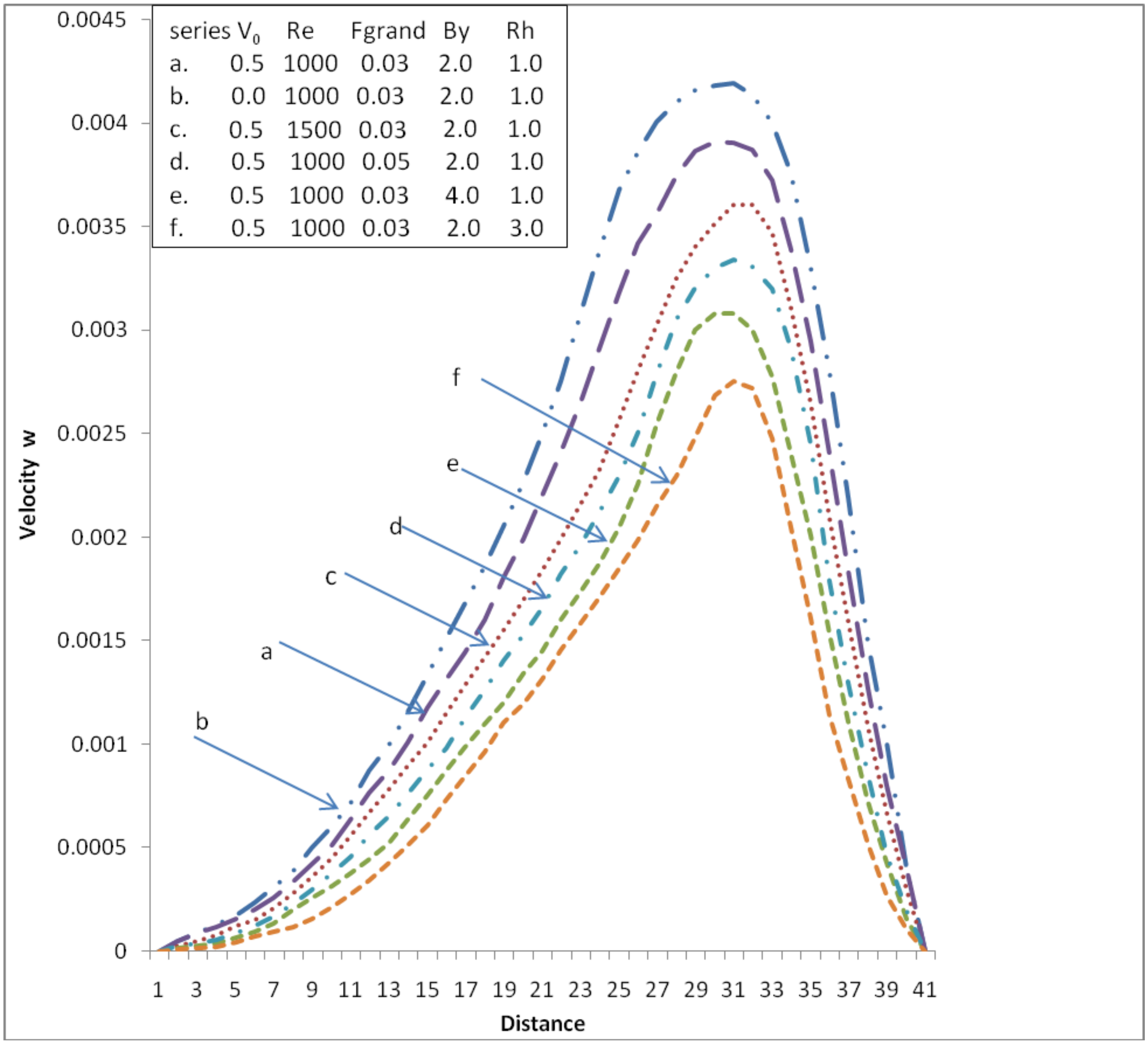

Figure 4: Secondary Velocity Profiles

Re=1000, Fgrand=0.03, R_h =3.0

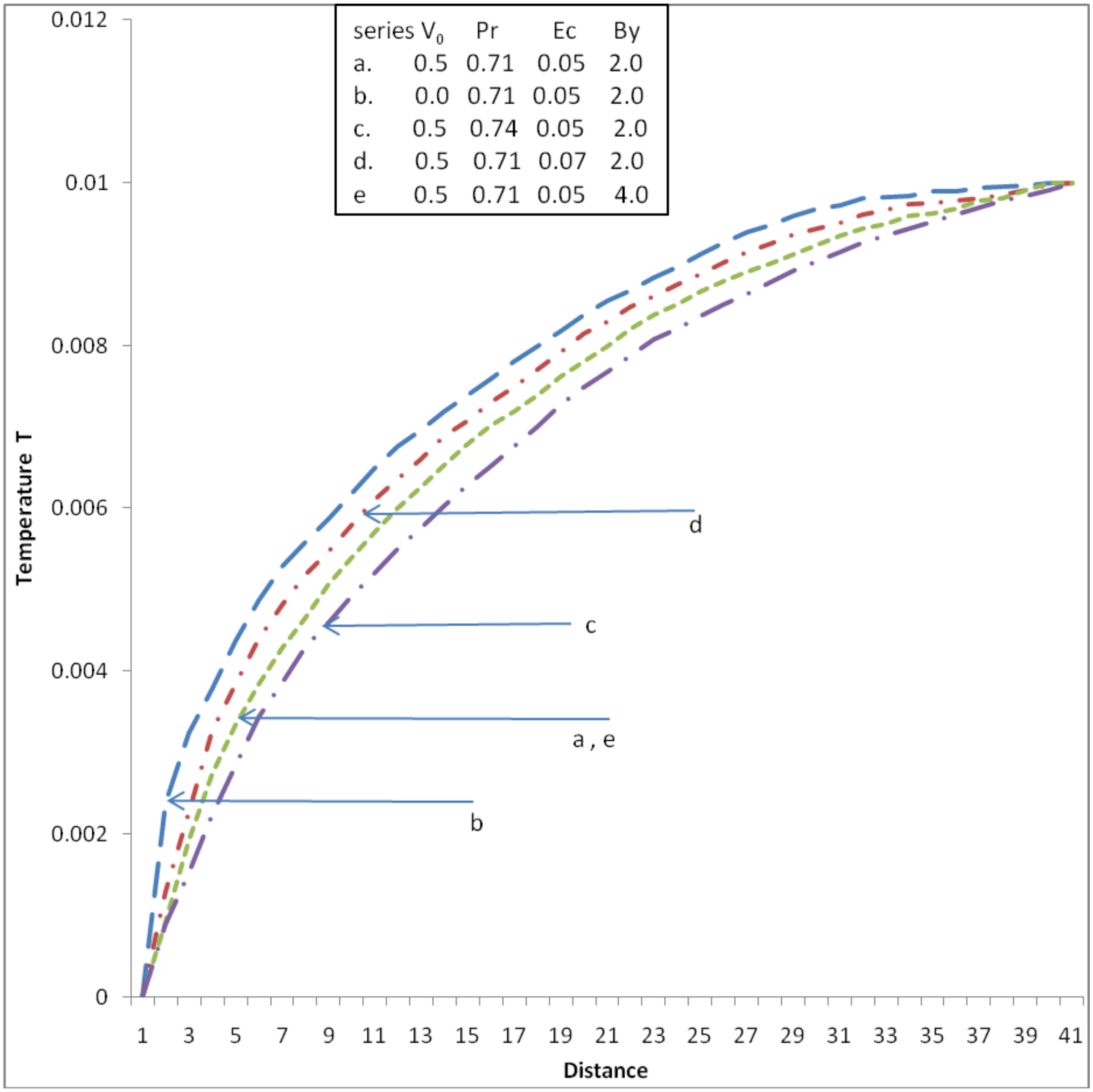

Figure 5: Temperature Profiles

Discussion of results

Primary Velocity Profiles

Figure (3) provides the primary velocity profiles obtained with respect to y when the Prandtl number (Pr) and Eckert number (Ec) are fixed and the other parameters varied. From this figure, it is clear that;

- Removal of suction i.e. $V_0=0.0$ leads to an increase primary velocity profiles.
- An increase in Reynolds number leads to an increase primary velocity profiles. Since this parameter acts to dampen the viscous effects, inertial forces tend to dominate over the viscous forces and the fluid tends to continue with its state of motion with negligible resistance of frictional forces.
- An increase in magnetic field gradient (*Fgrand*) leads to a decrease in primary velocity profiles. The interaction between the magnetic field gradient and the induced current in the fluid generates Lorentz force which opposes the flow thus slowing it down. The greater the flux gradient, the greater is this force implying greater opposition to the flow, yielding to reduced velocity profile.
- An increase in magnetic field intensity (B_y) leads to a decrease in primary velocity profiles. The interaction between the magnetic field gradient and the induced current in the fluid generates Lorentz force which opposes the flow thus slowing it down. This is the effect of the inhomogeneous magnetic flux on the flow.
- An increase in magnetic pressure number (R_h) leads to a decrease in primary velocity profiles. This implies that an increase in magnetic pressure number yields an increase in magnetic pressure force. This force acts to oppose the flow and hence slowing it down.

Secondary Velocity Profiles

Figure (4) provides the secondary velocity profiles obtained with respect to y when the Prandtl number (Pr) and Eckert number (Ec) are fixed and the other parameters varied. From this figure, it is clear that;

- Removal of suction leads to an increase in the secondary velocity profiles.
- An increase in Reynolds number leads to a decrease in secondary velocity profiles.
- An increase in magnetic field intensity leads to a decrease in secondary velocity profiles.

- An increase in magnetic field gradient leads to a decrease in secondary velocity profiles.
- An increase in magnetic pressure number leads to a decrease in secondary velocity profiles**.**

Temperature Profiles

Figure (5) provides the secondary velocity profiles obtained with respect to y when the Reynolds number, magnetic flux gradient and magnetic pressure number are fixed and the other parameters varied. From this figure, it is clear that

- Removal of suction leads to an increase in the temperature profiles.
- An increase in Prandtl Number leads to a decrease in temperature profiles.
- Variation of magnetic field intensity does not affect the temperature profiles.
- An increase in Eckert Number leads to an increase in temperature profiles. Hence the rate at which the fluid loses heat decreases as the Eckert Number is increased which can be attributed to the viscous dissipation as the Eckert number is increased.

Conclusion

The applied magnetic field is varied lengthwise in the direction of the flow hence resulting to a magnetic flux gradient. This inhomogeneous magnetic field yields an opposing force; the Lorentz force which is due to the interaction between the field and the induced current in the fluid. The equations governing the MHD flow in the analysis are non-linear and hence finite difference scheme is used in order to obtain the solutions. In this study, the flow problem involves fluids of Reynolds number in the range of 1000 to 2000, and thus is the case for unsteady problem. The velocity at the upper plate was fixed at zero and the lower plate was impulsively started at constant velocity in the direction o the main flow. The temperature at the lower plate was maintained constant and at the initial fluid temperature by cooling. There is significant effect on the velocity of the fluid by the inhomogeneous magnetic field. In conclusion, we can deduce the following from the study:

- Increase in magnetic field gradient causes a decrease in velocity profile in the direction of flow.
- An increase in magnetic field intensity causes a decrease in both the primary and secondary velocity profiles.
- The fluid is slowed down by an increase in magnetic pressure number.
- An increase in Prandtl number causes a decrease in temperature profiles.
- The fluids temperature flux increases with increase in Eckert number.

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