

# Unsteady Fluid Flow Between Two Moving Parallel Porous Plates in Presence of Inclined Applied Magnetic Field

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## Abstract

In this study, an unsteady fluid flow of a viscous, incompressible electrically conducting fluid between two moving parallel porous plates of infinite length in the  $x$  and  $z$  directions, subjected to a constant pressure gradient and a constant injection and suction, in presence of an inclined applied magnetic field whose lines are fixed relative to the moving plates, is investigated. The study is aimed at determining the profiles of velocity, temperature and the induced magnetic field, and the effects of various flow parameters, namely Magnetic parameter  $M$ , Reynold's number  $Re$ , Eckert number  $Ec$ , Prandtl number  $Pr$ , magnetic inclination  $\alpha$  and injection parameter  $S_0$  on the flow variables and the induced field.

**Keywords:** Magnetohydrodynamics; Porous Plates; Injection and Suction

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# 1 Introduction

MHD Couette flow is the flow of an electrically conducting fluid between two surfaces, one of which moves relatively to the other, in presence of a magnetic field. The configuration of Couette flow often takes the form of two parallel plates (called Planer-Couette flow) or the gap between two concentric cylinders (called Taylor-Couette flow). The equations describing MHD flow are a combination of continuity equation, Navier-stokes equations for fluids dynamics and Maxwell's equations for electromagnetism.

The MHD flow between porous plates studied has many important applications in areas such as the designing of cooling systems with liquid metals, geothermal reservoirs, in petroleum and mineral industries, in underground energy transport, MHD generators, pumps, flow meters, purification of crude oil, among many other areas [12].

Studies related to MHD flow between two parallel porous plates have been conducted in recent years by many scientists and researchers.

[2] studied the unsteady magneto-hydrodynamic Couette flow when the fluid flow is confined to porous boundaries with suction and injection considering two cases of interest, viz (i) impulsive movement of the lower plate and (ii) uniformly accelerated movement of the lower plate. They concluded that the suction exerted a retarding influence on the fluid velocity whereas injection has accelerating influence on the flow. [3] studied MHD flow between two parallel plates through porous medium with one in uniform motion and the other plate at rest and uniform suction at the stationary plate. They found that the axial velocity of the fluid decreases as density, time, and Hartmann number increases and that the transverse velocity of fluid increases as density, Hartmann number and suction increases. [4] analysed Unsteady MHD Couette flow between two infinite parallel porous plates in an inclined magnetic field with heat transfer and the lower plate considered porous. They concluded that magnetic field has significant effect on the flow. of an unsteady MHD Couette flow between two infinite parallel.[5] considered Steady MHD flow of viscous fluid between two parallel porous plates with heat transfer in an inclined magnetic field. They observed that fluid with high viscosity causes reversed flow and the applied magnetic force at different inclination controls this flow; also that the temperature distribution in fluid layers is directly linked to the vis-

cosity. [6] investigated Heat transfer between two parallel porous plates for Couette flow under pressure gradient and Hall current. They concluded that the Hall term gives rise to a velocity component  $w$  in the  $z$ -direction and affects the main velocity  $u$  in the  $x$ -direction and that the viscosity variation parameter has a marked effect on the velocity components  $u$  and  $w$ . They also found that porosity parameter has a marked effect on the velocity and temperature distributions and that by increasing Hartman number, the  $x$ -component of the velocity  $u$  and temperature  $\theta$  will decrease, while the  $z$ -component of the velocity  $w$  will increase.

[7] considered laminar viscous incompressible fluid between two infinite parallel plates when the upper plate is moving with constant velocity and the lower plate is held stationary under the influence of inclined magnetic field and concluded that the increase in magnetic field strength and magnetic inclination results into decreases in the velocity profiles. [8] considered magneto hydrodynamic flow between two parallel porous plates with injection and suction in the presence of a uniform transverse magnetic field with the magnetic field lines fixed relative to the moving plate with a constant pressure gradient and concluded that the magnetic field, pressure gradient, time and injection have an accelerating influence on the fluid flow with a constant pressure gradient in the direction of the flow on both cases of suction and injection while viscosity and suction exert a retarding influence.

[9] analysed Hydromagnetic Fluid Flow between Parallel Plates where the upper plate is porous in Presence of Variable Transverse Magnetic Field. They found that: an increase in Suction parameter leads to a decrease in the velocity profile and an increase in the temperature profiles respectively; imposing transverse magnetic field decreases both velocity and temperature of the fluid; increasing Eckert number causes an increase in temperature profiles whereas increasing Prandtl number leads to a decrease in the temperature profiles.

[10] investigated hydrodynamic radiating fluid flow past an infinite vertical porous plate in presence of chemical reaction and induced magnetic field and concluded that velocity decreases with increasing magnetic parameter, which is due to Lorentz force that opposes the fluid motion; velocity components are also reduced by the increased values of the permeability of the plate; but velocity increases with the increase of Grashof number.

[10] also concluded that temperature increases as the Eckert number, mag-

netic strength, radiation and surface permeability increase; and that induced magnetic field was elevated near the plate by increasing magnetic Prandtl number while this trend is reversed away from the plate.

[11] studied the effect of injection/suction on the free convective flow through the porous medium bounded by two infinite vertical plates with chemical reaction. They concluded that Velocity decreases with increasing values of chemical reaction parameter, Hartmann number and Schmidt number while temperature decreases with increasing values of Prandtl number  $Pr$ . [12] studied Unsteady hydromagnetic flow between parallel plates both moving in presence of a constant pressure gradient. They concluded that the magnetic field, pressure gradient and injection have an accelerating influence on the fluid flow with a constant pressure gradient in the direction of the flow on both cases of suction and injection; also, that the injection and suction of fluid from either of the plates has a significant effect on the velocity profiles with injection leading to increased velocities and suction leading to decreased velocities of the fluid. Unsteady Stokes flow of dusty fluid between two parallel plates through porous medium in the presence of magnetic field was analysed by [13]. They concluded that the velocity of dust particle is higher than that velocity of the fluid for all the parameters of the problem; the velocity of the fluid and dust particle decreases as density and number of dust particles increase.

## 2 Mathematical Formulation

The problem concerns the flow of an electrically conducting fluid between two moving parallel porous plates assumed to be along  $y = 0$  and  $y = h$  of infinite length in  $x$  and  $z$  directions with a constant pressure gradient, suction and injection through the walls of the channel in presence of an inclined applied uniform magnetic field  $\vec{B}_0$  taking into account the induced magnetic field. The applied magnetic field is inclined to the  $(x, y)$  plane at an angle  $\alpha$  from  $x$ -axis. Initially (when time  $t \leq 0$ ), the fluid and the porous plates of the channel are assumed to be at rest with the initial temperature  $T_0$ . When time  $t > 0$ , the two plates start moving with a constant velocity  $u_0$  in the  $x$ -direction with a temperature  $T_p$ ; a constant pressure gradient  $\nabla p$  is imposed in the  $x$ -direction, and a constant suction from above and injection from below, with velocity  $v_0$ ,

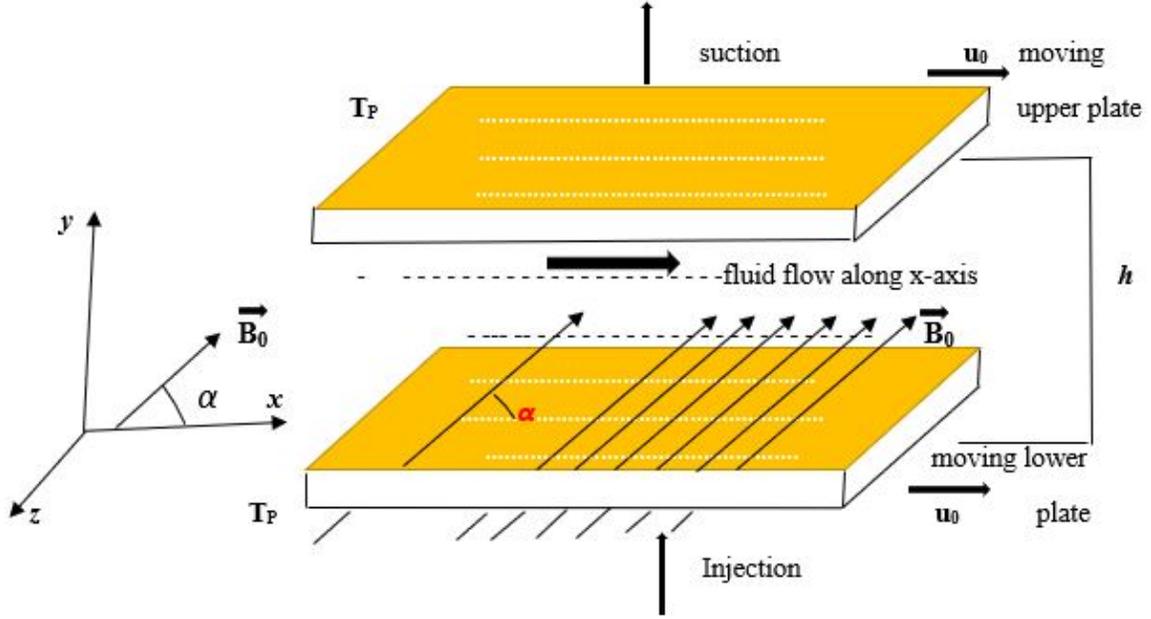


Figure 1: Flow Problem Configuration.

are impulsively applied.

Since the plates are of infinite length in the  $x$  and  $z$ -directions, the physical quantities do not depend on  $x$  and  $z$ . The velocity of the fluid and the magnetic induction vector are given as:

$$\vec{q} = (u, v_0, 0) \quad \vec{B} = (B_0 \cos \alpha + b_x, B_0 \sin \alpha + b_y, 0) = (B_x, B_y, 0)$$

where  $\vec{b} = (b_x, b_y, 0)$  represents the induced magnetic field.

In order to describe and analyse the problem mathematically, the following assumptions are made:

1. The fluid flow is restricted to a laminar domain
2. The fluid is incompressible and Newtonian
3. Electrical and thermal conductivities, Dynamic viscosity are constant.
4. There is no chemical reaction
5. There is no applied external electric field.
6. The plates are non-conducting and uniformly porous.

*Momentum equation:*

$$\frac{\partial \vec{q}}{\partial t} + (\vec{q} \cdot \vec{\nabla}) \vec{q} = -\frac{1}{\rho} \vec{\nabla} P + \nu \nabla^2 \vec{q} + \frac{1}{\rho} \vec{F} \quad (1)$$

Where  $F = J \times B$  is the Lorentz force

Equation (1) reduces to:

$$\frac{\partial u}{\partial t} + v_0 \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + \nu \frac{\partial^2 u}{\partial y^2} + \frac{1}{\rho} F_x \quad (2)$$

Where  $F_x$  is the  $x$  - *direction* component of Lorentz force and is given by:

$$F_x = \sigma \left[ u (B_0 \sin \alpha)^2 - v_0 (b_x + B_0 \cos \alpha) (B_0 \sin \alpha) \right] \quad (3)$$

In this case where the magnetic field lines are fixed relative to the moving plates, from the model by [1], the velocity is considered as a relative velocity and reflects how fast the fluid is moving relative to the plates. The equation of motion hence becomes:

$$\frac{\partial u}{\partial t} + v_0 \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + \nu \frac{\partial^2 u}{\partial y^2} + \frac{\sigma}{\rho} B_0 \sin \alpha \left[ B_0 \sin \alpha (u - u_0) - v_0 (b_x + B_0 \cos \alpha) \right] \quad (4)$$

*Energy equation:*

$$\rho C_p \frac{DT}{Dt} = k \nabla^2 T + \mu \phi + \frac{J^2}{\sigma} \quad (5)$$

where  $\frac{D}{Dt}$  is the material derivative.

The viscous dissipation function  $\phi$  in three dimensions is expressed as:

$$\begin{aligned} \phi = & 2 \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial z} \right)^2 \right] + \left[ \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right)^2 + \left( \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right)^2 \right] \\ & - \frac{2}{3} \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right)^2 \end{aligned} \quad (6)$$

For the present analysis, the viscous dissipation reduces to:

$$\phi = \left( \frac{\partial u}{\partial y} \right)^2$$

The joule heating term becomes:

$$\frac{J^2}{\sigma} = \sigma \left[ u B_0 \sin \alpha - v_0 (b_x + B_0 \cos \alpha) \right]^2$$

Again, since the magnetic lines are fixed relative to the moving plates, the velocity is replaced by the relative velocity in the current density, thus the Joule heating term is finally written as:

$$\frac{J^2}{\sigma} = \sigma \left[ (u - u_0) B_0 \sin \alpha - v_0 (b_x + B_0 \cos \alpha) \right]^2$$

Substituting these in equation (5), yields:

$$\rho C_p \left( \frac{\partial T}{\partial t} + v_0 \frac{\partial T}{\partial y} \right) = k \frac{\partial^2 T}{\partial y^2} + \mu \left( \frac{\partial u}{\partial y} \right)^2 + \sigma \left[ (u - u_0) B_0 \sin \alpha - v_0 (b_x + B_0 \cos \alpha) \right]^2 \quad (7)$$

*Induction equation*

$$\vec{B} t = \frac{1}{\sigma \mu_e} \nabla^2 \vec{B} + \vec{\nabla} \times (\vec{q} \times \vec{B}) \quad (8)$$

where  $\frac{1}{\sigma \mu_e}$  is the magnetic diffusivity of the fluid.

Using the information above and evaluating the terms in equation (8), it reduces to:

$$\frac{\partial b_x}{\partial t} + v_0 \frac{\partial b_x}{\partial y} = \frac{1}{\sigma \mu_e} \frac{\partial^2 b_x}{\partial y^2} + B_0 \sin \alpha \frac{\partial u}{\partial y} \quad (9)$$

Initial and boundary conditions of this flow problem are as follows:

$$t = 0 : \begin{cases} u = 0 \\ T = T_0 \\ b_x = 0 \end{cases} \quad (10)$$

$$t > 0 : \begin{cases} u = u_0 \\ T = T_p \\ b_x = 0 \end{cases} \quad \text{at } y = 0 \text{ and } y = h \quad (11)$$

*Non-dimensionalization*

The following non-dimensional transformations have been used to transform the governing equations into their non-dimensional forms:

$$t^* = \frac{t\nu}{h^2}, \quad y^* = \frac{y}{h}, \quad u^* = \frac{uh}{\nu}, \quad x^* = \frac{x}{h},$$

$$T^* = \frac{T-T_0}{T_p-T_0}, \quad b_x^* = \frac{\sigma h^2 B_0}{\mu} b_x, \quad p^* = \frac{h^2 p}{\rho \nu^2},$$

Therefore it can be deduced that:

$$t = \frac{t^* h^2}{\nu}, \quad y = y^* h, \quad x = x^* h, \quad u = \frac{u^* \nu}{h}$$

$$T = T^*(T_p - T_0) + T_0, \quad b_x = \frac{\mu}{\sigma h^2 B_0} b_x^*, \quad p = \frac{\rho \nu^2 p^*}{h^2}$$

Considering these, the equations (4), (7) and (9) become:

$$\frac{\partial u^*}{\partial t^*} + S_0 \frac{\partial u^*}{\partial y^{*2}} = \beta + \frac{\partial^2 u^*}{\partial y^{*2}} + M \sin \alpha \left[ (u^* - Re) \sin \alpha - S_0 \left( \frac{b_x^*}{M} + \cos \alpha \right) \right] \quad (12)$$

$$\frac{\partial T^*}{\partial t^*} + S_0 \frac{\partial T^*}{\partial y^{*2}} = \frac{1}{Pr} \frac{\partial^2 T^*}{\partial y^{*2}} + \frac{Ec}{Re^2} \left( \frac{\partial u^*}{\partial y^*} \right)^2 + \frac{MEc}{Re^2} \left[ (u^* - Re) \sin \alpha - S_0 \left( \frac{b_x^*}{M} + \cos \alpha \right) \right]^2 \quad (13)$$

$$\frac{\partial b_x^*}{\partial t^*} + S_0 \frac{\partial b_x^*}{\partial y^{*2}} = \frac{1}{Pr_M} \frac{\partial^2 b_x^*}{\partial y^{*2}} + M \sin \alpha \frac{\partial u^*}{\partial y^*} \quad (14)$$

Equations (12), (13), and (14) are respectively the equations of Momentum, Energy and Induction in dimensionless form.

The initial and boundary conditions in dimensionless form become:

$$t^* = 0 : \begin{cases} u^* = 0 \\ T^* = 0 \\ b_x^* = 0 \end{cases} \quad (15)$$

$$t^* > 0 : \begin{cases} u^* = Re \\ T^* = 1 \\ b_x^* = 0 \end{cases} \quad \text{at } y^* = 0 \text{ and } y^* = 1 \quad (16)$$

### 3 Results and Discussion

The Crank-Nicholson method has been used to obtain the numerical scheme for solving numerically the governing equations of the present flow problem. The numerical results have been obtained by implementing the corresponding Finite difference equations in a computer program.

The trends obtained by varying various fluid flow parameters, namely Magnetic parameter  $M$ , Reynold's number  $Re$ , Injection parameter  $S_0$ , Prandtl number  $Pr$ , Eckert number  $Ec$ , Magnetic Prandtl number  $Pr_M$  and magnetic inclination  $\alpha$  are discussed and explained.

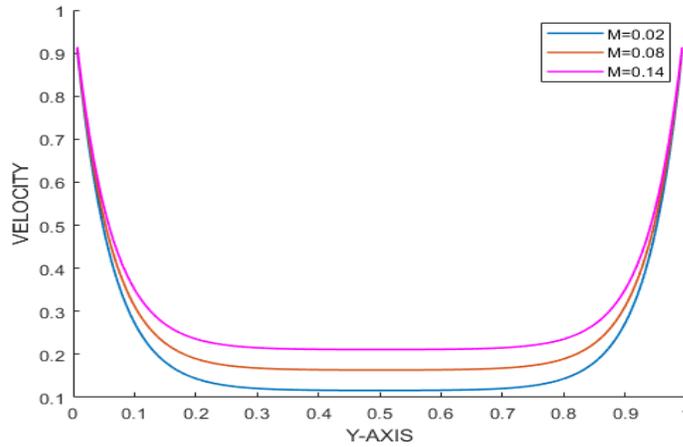


Figure 2: Effects of Magnetic parameter on velocity profiles

From Figure (2), it is observed that increasing Magnetic parameter ( $M$ ) leads to an increase in the velocity profiles. The Magnetic parameter is the ratio of the magnetic forces to viscous forces. The magnetic field lines are applied in the direction of the flow, inclined at an angle  $\alpha$  to the plates. Following the motion of the electrically conducting fluid through those lines, the Lorentz force is generated. Since the magnetic field lines, in this case, are fixed relative to the moving plates, the velocity of the fluid in the Lorentz force is replaced by the relative velocity. The  $x$  - *direction* component of Lorentz force then becomes positive, so, Lorentz force facilitates the fluid motion. An increase in the magnetic parameter, meaning an increase in the magnetic forces, leads to an increase in Lorentz force and therefore an increase in the fluid velocity.

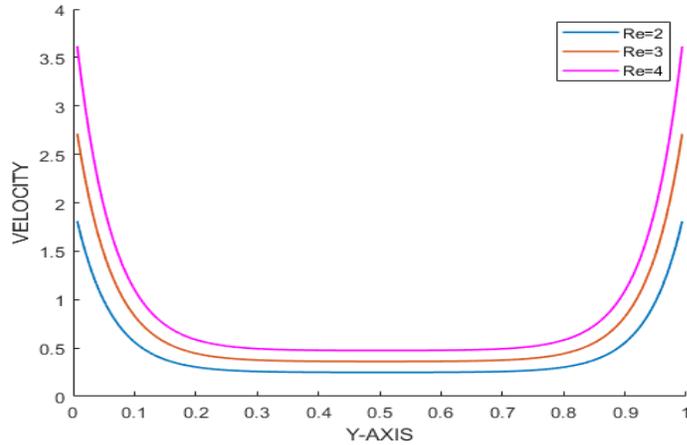


Figure 3: Effects of Reynold's number on velocity profiles

From Figure 3, the fluid velocity increases with increasing Reynold's number. Reynold's number is the ratio of the inertia forces to viscous forces, thus increasing Reynold's number implies a decrease in the viscous forces which oppose the motion of the fluid. Therefore an increase in Reynold's number leads to an increase in the velocity profiles.

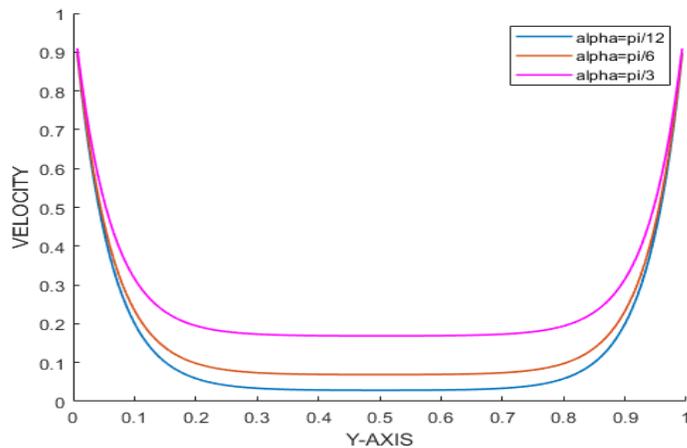


Figure 4: Effects of Angle of inclination on velocity profiles

From Figure 4, it is noted that fluid velocity increases as  $\alpha$  increases. The magnetic field lines are applied at the angle  $\alpha$  from the plate. The  $x$ -component of the Lorentz force is proportional to  $\sin \alpha$ , and the function  $\sin \alpha$  is increasing on the interval  $[0, \pi/2]$ . Therefore, since the Lorentz force acts in

the direction of the flow, an increase in the angle of inclination  $\alpha$  leads to an increase in the Lorentz force, and hence, an increase in the velocity profiles.

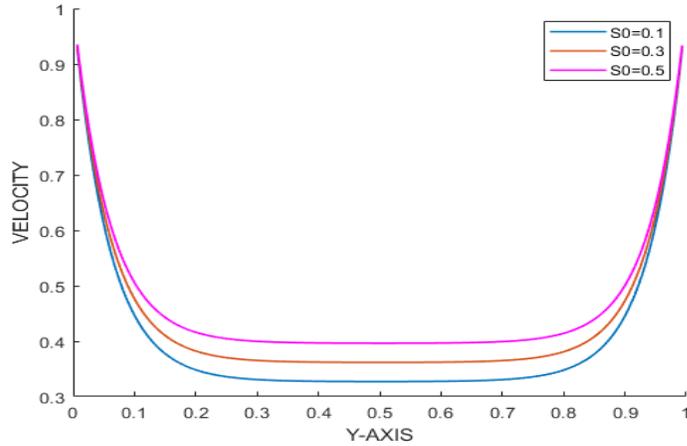


Figure 5: Effects of Injection parameter on velocity profiles

From Figure 5, it is noted that fluid velocity increases with increasing  $S_0$ . The Injection parameter,  $S_0$  increases with increasing the injection velocity  $v_0$ , and Lorentz force is increased by increasing the injection velocity. Since the Lorentz force acts in the direction of the flow, therefore increasing  $S_0$  leads to an increase in the Lorentz force, and hence an increase in the velocity profiles.

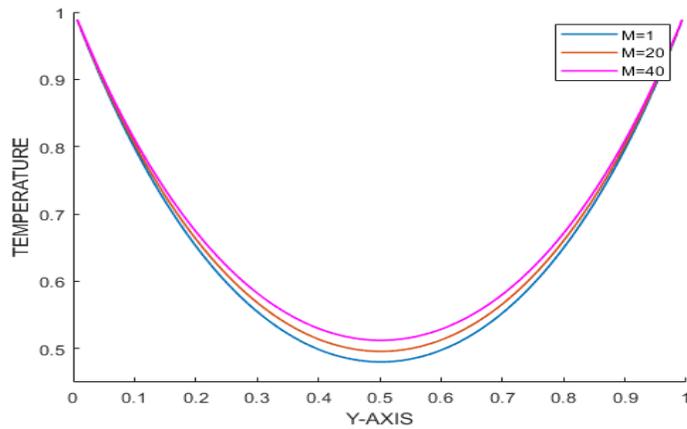


Figure 6: Effects of Magnetic parameter on Temperature profiles

From Figure 6, it is noted that fluid temperature increases as  $M$  increases. The magnetic parameter ( $M$ ) is the ratio of the magnetic forces to viscous

forces. Increasing  $M$  implies a decrease in viscous forces which oppose the fluid motion. When the viscous forces decrease, the velocity of the fluid increases which increases the collision of the fluid particles leading to an increase of the self-heating effects due to the dissipation of heat in the boundary layers. Hence increasing  $M$  leads to an increase in temperature profiles.

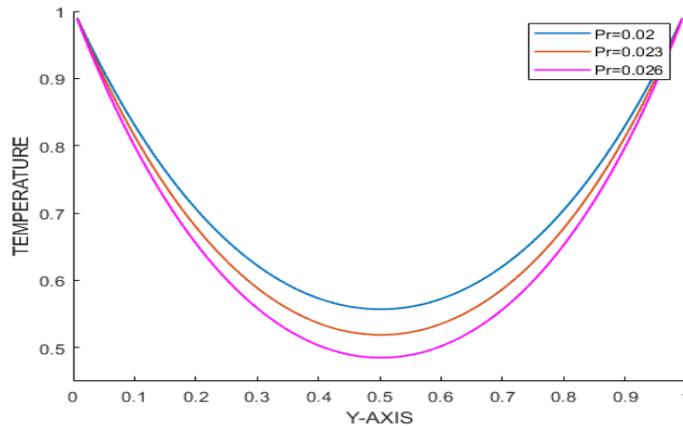


Figure 7: Effects of Prandtl number on Temperature profiles

From Figure 7, it is observed that increasing  $Pr$  decreases fluid temperature.

Prandtl number ( $Pr$ ) is the ratio of momentum diffusivity to thermal diffusivity. A fluid with high Prandtl number possesses a relatively small thermal conductivity. Thus, as  $Pr$  increases, there will be a reduction of the thermal boundary layer thickness and hence a decrease in the temperature profiles.

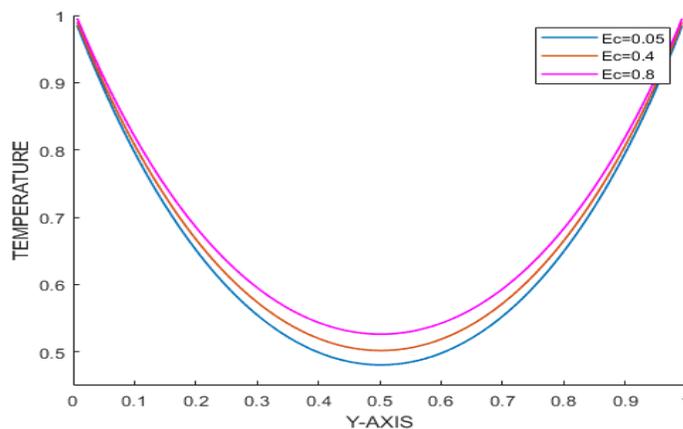


Figure 8: Effects of Eckert number on Temperature profiles

From Figure 8, it is observed that increasing Eckert number ( $Ec$ ) leads to increase fluid temperature.  $Ec$  is the ratio of kinetic energy to the enthalpy. Increasing  $Ec$  leads to increase the kinetic energy. The kinetic energy increases with increasing the fluid velocity. As the fluid velocity increases, the collision of the fluid particles increases causing the dissipation of heat in the boundary layers and hence an increase in fluid temperature.

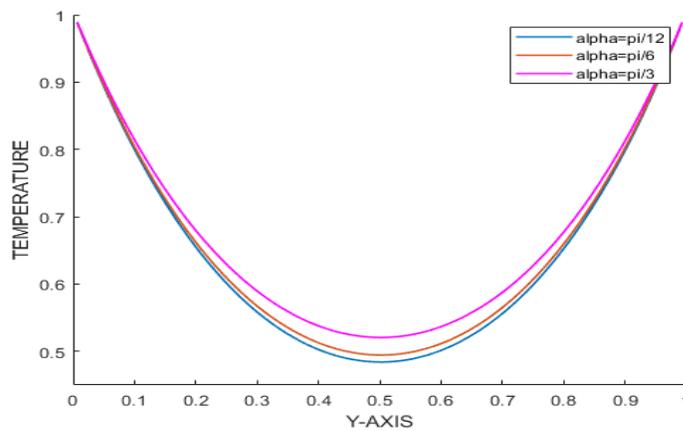


Figure 9: Effects of Angle of inclination on Temperature profiles

From Figure 9, it is observed that an increase in the angle of inclination ( $\alpha$ ) leads to an increase in the temperature profiles. By increasing  $\alpha$ , the fluid velocity increases, thus, the collision of fluid particles increases which brings about dissipation of heat and hence an increase in the temperature profiles.

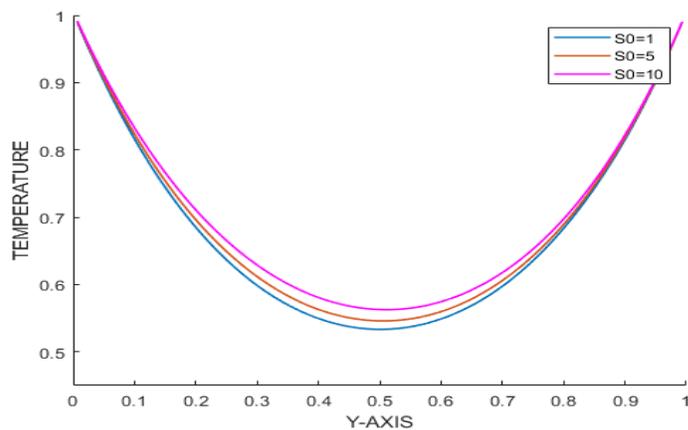


Figure 10: Effects of Injection parameter on Temperature profiles

From Figure 10, it is observed that increasing injection parameter increases the temperature profiles.

An increase in Injection parameter implies an increase of the injection velocity  $v_0$ . The Joule heating term in Energy equation is increased by increasing the injection velocity. Therefore, increasing  $S_0$  leads to an increase in Joule heating term, and hence, an increase in the temperature profiles.

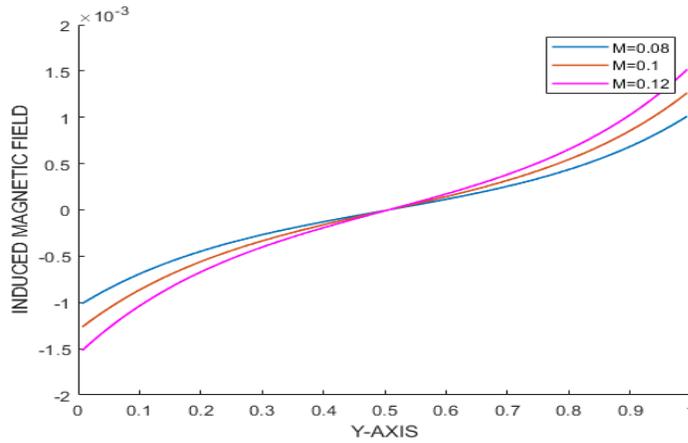


Figure 11: Effects of Magnetic parameter on the Induced magnetic field

From Figure 11, it is observed that an increase in magnetic parameter  $M$  leads to an increase in the induced magnetic field on the interval  $0.5 < y < 1$  and a decrease on  $0 < y < 0.5$ .

Increasing  $M$  implies increase in magnetic forces, implying also an increase of the magnitude of the applied magnetic field. The induced magnetic field itself, is generated as a result of the motion of the electrically conducting fluid in presence of magnetic field, so, as the magnitude of that field increases, the magnitude of the induced field also increases.

The induced magnetic field is negative on the interval  $0 < y < 0.5$  and positive on  $0.5 < y < 1$ . Since the magnitude of the induced field increases on both intervals by increasing  $M$ , hence, as  $M$  increases, the induced field profile decreases on  $0 < y < 0.5$  and increases on  $0.5 < y < 1$ . Therefore an increase in  $M$  leads to a decrease in the induced field profile on the interval  $0 < y < 0.5$  and an increase on  $0.5 < y < 1$ . From Figure (12), it is observed that an increase in  $Pr_M$  leads to a decrease in the induced magnetic field on the interval  $0.5 < y < 1$  and a decrease on  $0 < y < 0.5$ .

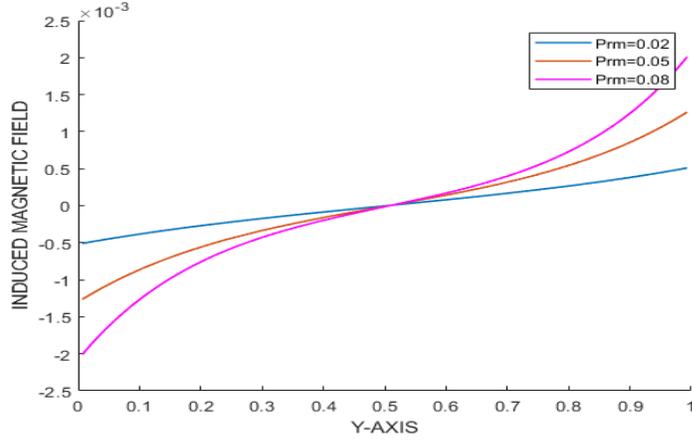


Figure 12: Effects of Magnetic Prandtl number on the induced magnetic field

$Pr_M$  is the ratio of momentum diffusivity to magnetic diffusivity. Increasing  $Pr_M$  implies increasing the electrical conductivity of the fluid which makes the fluid more conducting, and hence, increases the magnitude of the induced magnetic field thus generated. Therefore, increasing  $Pr_M$  leads to an increase in magnitude of the induced field, and hence, a decrease in the induced field profile on the lower half of the channel and an increase on the upper half.

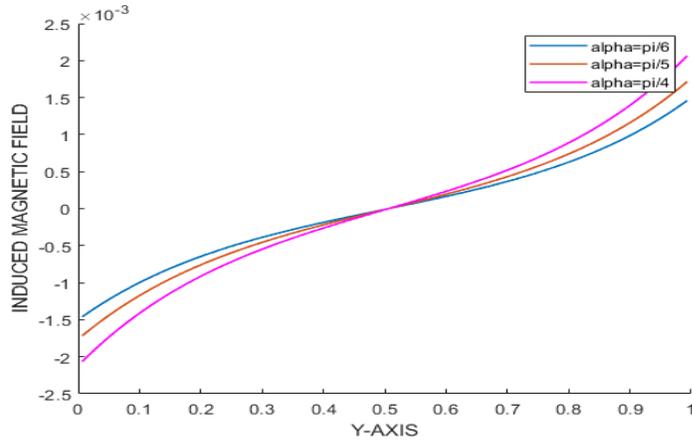


Figure 13: Effects of Angle of inclination on the induced magnetic field

From Figure 13, it is observed that increasing  $\alpha$  leads to a decrease in the induced magnetic field on  $0 < y < 0.5$  and the reverse effect on  $0.5 < y < 1$ .

It is noted that in the Induction equation, the induced magnetic field increases with increase of the velocity gradient  $\frac{\partial u}{\partial y}$ . The velocity gradient in

Induction equation is amplified by  $\sin \alpha$ . So, as  $\alpha$  increases, the term  $\sin \alpha \frac{\partial u}{\partial y}$  decreases on  $[0 \ 0.5]$  and increases on  $[0.5 \ 1]$  because the velocity gradient  $\frac{\partial u}{\partial y}$  is negative on  $[0 \ 0.5]$  and positive on  $[0.5 \ 1]$ . Therefore, increasing the magnetic inclination leads to an increase in the induced magnetic field.

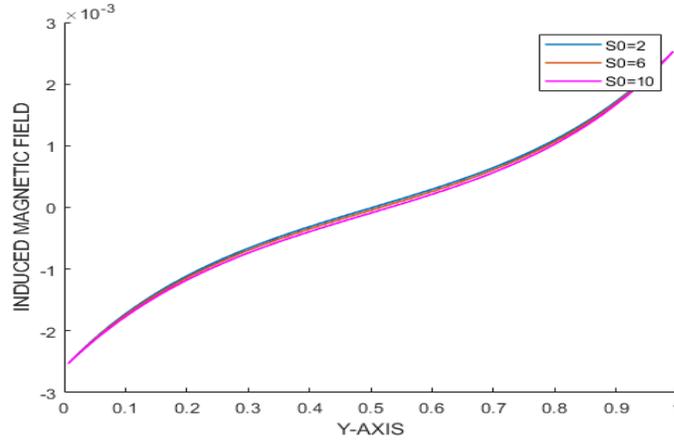


Figure 14: Effects of Injection parameter on the Induced magnetic field

From Figure (14), it is observed that increasing injection parameter leads to a decrease in the induced magnetic field. This is due to the fact that, as the injection velocity increases, the gradient of the induced magnetic field decreases which then leads to a decrease in the induced magnetic field.

## 4 Conclusion

The unsteady fluid flow between two moving plates in presence of an inclined applied magnetic field with magnetic fields lines fixed relative to the moving plates has been studied. The obtained model has been solved using Crank Nicholson method and simulated with MATLAB.

The effects of flow parameters have been determined. From the results obtained, the following conclusions have been outlined: The velocity increases with an increase in the magnetic parameter  $M$ , Reynold's number  $Re$ , the magnetic inclination  $\alpha$  and the Injection parameter  $S_0$ .

The temperature increases with an increase in  $M$ ,  $\alpha$ , Eckert number  $Ec$  and the Injection parameter  $S_0$ . However, the temperature decreases as Prandtl number  $Pr$  increases.

An increase in  $M$ , magnetic Prandtl number  $Pr_M$  and  $\alpha$  leads to a decrease in the induced magnetic field in the lower half of the channel and an increase in the upper half of the channel. Increasing  $S_0$  leads to a decrease in the induced field but the effect is not well pronounced.

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## Nomenclature

$B$	Magnetic induction vector, [ $wbm^{-2}$ ]
$B_0$	Applied uniform magnetic vector, [ $wbm^{-2}$ ]
$H$	Magnetic field intensity, [ $wbm^{-2}$ ]
$E$	Electric field intensity, [ $v$ ]
$D$	Electric displacement [ $Cm^{-2}$ ]
$J$	Induction current density, [ $AM^{-2}$ ]
$T$	Temperature of the fluid, [ $K$ ]
$T_p$	Temperature of the moving plates [ $K$ ]
$T_0$	Temperature at rest [ $K$ ]
$P$	Pressure force, [ $Nm^{-2}$ ]
$q$	Velocity vector, [ $ms^{-1}$ ]
$u_o$	velocity of the moving plates, [ $ms^{-1}$ ]
$v_o$	Injection velocity, [ $ms^{-1}$ ]
$k$	Thermal conductivity, [ $Wm^{-1}K^{-1}$ ]
$F$	Body forces, [ $N$ ]
$\frac{D}{Dt}$	Material derivative, $(\frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z})$
$\rho$	Fluid density, [ $kgm^{-3}$ ]
$\rho_e$	Charge density, [ $C$ ]
$\mu$	Coefficient of viscosity, [ $kgm^{-1}s$ ]
$\mu_e$	Magnetic permeability, [ $Hm^{-1}$ ]
$\sigma$	Electrical conductivity, [ $\Omega^{-1}m^{-1}$ ]
$\alpha$	Magnetic inclination, [ $rad$ ]
$\mu_e$	Magnetic permeability [ $Hm^{-1}$ ]
$\nabla$	Gradient operator, $(i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\frac{\partial}{\partial z})$
$\nabla^2$	Laplacian operator $(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2})$
$\nu$	Kinematic viscosity [ $m^2s^{-1}$ ]
$\phi$	Viscous dissipation function, [ $s^{-1}$ ]