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Hall and Rotational Effects on Steady MHD Natural Convection Couette Flow of a Heat Generating/Absorbing Fluid: An Analytical Approach

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Abstract
This study presents an analytical investigation into the free convective flow of a viscous, incompressible, electrically conducting fluid within a vertical porous channel, considering the effects of Hall currents and an inclined magnetic field. The system is assumed to rotate uniformly about an axis perpendicular to the channel plates. The channel comprises a stationary plate and a moving plate in the flow direction, with regions filled with porous media. The governing coupled nonlinear differential equations are solved using the Homotopy Perturbation Method (HPM), yielding analytical expressions for velocity and temperature distributions. Results are illustrated through graphical representations, providing insights into the influence of various physical parameters on the flow behavior.Notably, both velocity and thermodynamic distributions of the fluid increase with higher viscous dissipation (Ec). Additionally, decreases with an increase in the magnetic field (M), whereas it increases with higher permeability of the porous materials (K). Furthermore, velocity and temperature distributions decrease with increased suction (λ_0).

Keywords: Magnetohydrodynamic (MHD) flow, porous medium, Suction/injection,Homotopy Perturbation Method (HPM),Incompressible electrically conducting fluid,Rotation, Hall effect.

Introduction

The study of Couette flow that is formed between two parallel, infinite plates whereinone moves relative to the other is a classic configuration in fluid mechanics. When the working fluid is electrically conducting and subject to magnetic fields, the study enters the realm of magnetohydrodynamics (MHD).Additionally incorporating Hall current effects and system rotation, while considering the natural convection and internal heat generation or absorption, enriches the model significantly. Such configurations are directly relevant to engineering and biomedical scenarios, especially when heat and magnetic interactions are crucial. In systems where conductive fluids (e.g., plasma or liquid metals) flow under strong magnetic fields, Hall currents influence current density and Lorentz forces, impacting performance and efficiency of generators and accelerators.Porous rotating channels used in centrifuges, filtration, and chemical processing benefit from enhanced control of flow by accounting for Hall and rotational effects, aiding in the design of efficient reactors and heat transfer modules. MHD enhanced cooling of turbine blades or reactor components, especially when heat sources or sinks are present can be optimized by understanding how Hall current, rotation, and volumetric heating affect fluid behavior and heat transfer. Models of electrically conducting fluids subject to magnetic fields and heat sources

are instrumental in designing magnetic drug delivery systems, where hall and convective effects impact particle trajectories and thermal responses within blood vessels. In porous media mimicking biological tissues or engineered scaffolds, the interplay of rotation, heat generation/absorption, and Hall currents influences nutrient transport, thermal regulation, and microbial biofilm development. In devices such as centrifuges or rotational perfusion systems used in biomedical research or treatment, understanding Hall affected MHD flows with heat sources or sinks aids in predicting shear stress and temperature distributions crucial for cell viability.In analytical investigation of steady MHD natural convection Couette flow with both Hall and rotational effects, in the presence of volumetric heat source or sink, is not only academically rich but also directly applicable to modern engineering systems like MHD power devices,rotating heat exchangers and biotechnological settings such as magnetic drug delivery and tissue-fabrication devices.

In the view of the above, the effects of chemical reaction and radiation absorption on an unsteady MHD natural convection flow through a semi infinite vertical channel in the presence of heat source an suction was studied by Ibrahim et al.[1]. Jha and Ajibade[2] studied a transient case of a free convective flow of heat generating/absorbing fluid in a vertical channel. They showed that an increase in heat absorption led to increase in the rate of heat transfer on the moving plate and causes a decrease in the heat transfer on the stationary plate. Asadolah M et al [3 Magnetic field effect on fluid flow characteristics in a pipe for Laminar flow. Seth GS et al.[4], Capturing the transient behaviour of MHD double-diffusive free convection in vertical channel with adiabatic and isothermal walls and mass inflow at adiabatic wall. Nadeem et al. [5] studied MHD flow of a three-dimensional casson fluid past a porous sheet. It is found that the velocity profile decreases with increase in magnetic field and porosity parameters. O. D. Makinde[6] made analysis on thermodynamics analysis of variable viscosity hydromagnetic Couette flow in a rotating system with Hall effects. Effect of Hall current on unsteady MHD Couette flow and heat transfer of nanofluids in a rotating system was studied by A. O. Ali et al [7]. A deep study was made by Egere AC, et al[8] on MHD oscillatory flow through a porous channel saturated with porous medium. Seth GS, et al [9],discussed about the transient behaviour of MHD double-diffusive free convection in vertical channel with adiabatic and isothermal walls and mass inflow at adiabatic wall. P. Dasha, et al[10], examined MHD Couette flow and heat transfer in a rotating channel in presence of viscous dissipation and heat source. The present work provides analytical and numerical insights into the effects of magnetic field, permeability, suction/injection, viscous dissipation, heat source/sink, and rotation on fluid flow and heat transfer in a rotating porous channel.

Model Description and Problem Definition

The steady free-convective Couette flow of a viscous, electrically conducting, incompressible fluid through a vertical porous channel is considered. The system rotates uniformly about an axis perpendicular to the channel plates, characterized by angular velocity Ω. One porous plate is heated and moves at constant speed U, injecting fluid uniformly into the channel, while the opposite porous plate remains stationary at ambient temperature and applies uniform suction. The flow is influenced by an inclined magnetic field, Hall currents and is further affected by thermal buoyancy forces. Employing the Boussinesq approximation, density variation with temperature is included solely in the buoyancy term, while all other fluid properties are assumed constant. Flow and thermal variables depend exclusively on the transverse spatial coordinate y.

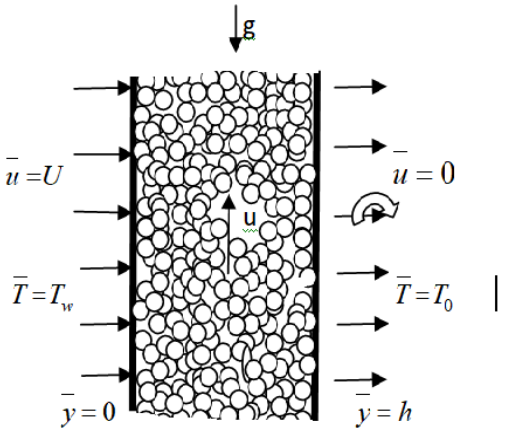


Figure 1: Schematic diagram of the problem.

The model yields a set of coupled nonlinear differential equations representing momentum and energy balances for a saturated porous medium, which is solved subject to specified injection, suction, plate motion, and thermal boundary conditions.

GoverningEquations and Problem Framework

$$-\frac{2}{\upsilon}\Omega\bar{v}+\upsilon\frac{d^2\bar{u}}{d\bar{y}^2}-\lambda\frac{d\bar{u}}{d\bar{y}}+g\beta(\bar{T}-\bar{T}_0)-\frac{B_0^2\sigma\,Sin\theta}{\rho(1+m^2\,Sin^2\theta)}(\bar{u}+\bar{v}m\,Sin\theta)-\frac{\upsilon}{\bar{k}}\bar{u}=0 \quad (1)$$

$$\frac{2}{\upsilon}\Omega\bar{u}+\upsilon\frac{d^2\bar{v}}{d\bar{y}^2}-\lambda\frac{d\bar{u}}{d\bar{y}}+g\beta\,(\bar{T}-\bar{T}_0)-\frac{B_0^2\sigma\,Sin\theta}{\rho(1+m^2\,Sin^2\theta)}(\bar{u}m\,Sin\theta-\bar{v})-\frac{\upsilon}{k}\bar{v}=0 \quad (2)$$

$$\frac{k}{\rho c_p}\frac{d^2\bar{T}}{d\bar{y}^2}-\lambda\frac{d\bar{T}}{d\bar{y}}-\frac{Q_0}{\rho c_p}(\bar{T}-\bar{T}_0)+\frac{\upsilon}{c_p}\left(\frac{d\bar{u}}{d\bar{y}}\right)^2=0$$

(3)

Boundary conditions are $\begin{matrix}\bar{u}=U,\quad \bar{T}=T_w,\quad \bar{y}=0\\ \bar{u}=0,\quad \bar{T}=T_0,\quad \bar{y}=h\end{matrix}$ (4)

The dimensionless quantities employed are

:

$$u=\bar{u}/U,\ v=\bar{v}/V,\ T=\frac{\bar{T}-T_0}{T_W-T_0},\ \lambda=\frac{\bar{\lambda}h}{\upsilon},\ Gr=\frac{g\beta(T_w-T_0)h^3}{\upsilon^2},\ \mathrm{Pr}=\frac{\upsilon}{\alpha},\ S=\frac{Q_0h^2}{k},$$

$$Ec=\frac{U^2}{c_p(T_w-T_0)},\ M=\frac{\sigma B_0^2h^2}{\upsilon\rho},\ K=\frac{\bar{K}}{h^2}$$

Applying the boundary conditions to the governing equations, we get

$$-2R_0v+\frac{d^2u}{dy^2}-\lambda\frac{du}{dy}-\left(\frac{M\,Sin\theta}{\rho(1+m^2\,Sin^2\theta)}(u+vm\,Sin\theta)+\frac{1}{k}u\right)+GrT=0 \quad (5)$$

$$2R_0u+\frac{d^2v}{dy^2}-\lambda\frac{du}{dy}-\left(\frac{M\,Sin\theta}{\rho(1+m^2\,Sin^2\theta)}(um\,Sin\theta-v)+\frac{1}{k}v\right)+GrT=0 \quad (6)$$

$$\frac{d^2T}{dy^2}-\lambda\,\mathrm{Pr}\frac{dT}{dy}-ST+Ec\,\mathrm{Pr}\left(\frac{du}{dy}\right)^2=0 \quad (7)$$

The transformed boundary conditions are

$$\begin{matrix}u=1,\quad T=1,\ y=0\\ u=0,\quad T=T_0,\ y=h\end{matrix} \quad (8)$$

Methodology Of The Problem

In order to combine the velocity equations into a single equation consider $F=U+iV$,

And to solve the problem by the Homotopy perturbation method, construct the convex Homotopy of the momentum equations.

$$\frac{d^2F}{dy^2} = p\left[\lambda\frac{dF}{dy} + bF - GrT\right] \quad (9)$$

$$F = F_0 + pF_1 + p^2F_2 + p^3F_3 + \ldots\ldots\ldots\ldots$$
$$T = T_0 + pT_1 + p^2T_2 + p^3T_3 + \ldots\ldots\ldots\ldots \quad (10)$$

Substituting equation (10) into the equation (9) ,the following equation is formed

$$\frac{d^2F_0}{dy^2} + p\frac{d^2F_1}{dy^2} + p^2\frac{d^2F_2}{dy^2} + \ldots\ldots\ldots = p\lambda\frac{dF_0}{dy^2} + p^2\lambda\frac{dF_1}{dy^2} + p^3\lambda\frac{dF_2}{dy^2} + \ldots\ldots + pbF_0 + p^2bF_1 + p^3bF_2 + \ldots\ldots$$
$$- pGrT_0 - p^2GrT_1 - p^3GrT_2 + \ldots\ldots \quad (12)$$

Comparing the coefficient $p^0, p^1, p^2, p^3, \ldots\ldots\ldots\ldots$

$$p^0 : \frac{d^2F_0}{dy^2} = 0 \quad (13)$$

$$p^1 : \frac{d^2F_1}{dy^2} = \lambda\frac{dF_0}{dy} + bF_0 - GrT_0 \quad (14)$$

$$p^2 : \frac{d^2F_2}{dy^2} = \lambda\frac{dF_1}{dy} + bF_2 - GrT_1 . \quad (15)$$

$$p^3 : \frac{d^3F_3}{dy^3} = \lambda\frac{dF_2}{dy} + bF_2 - GrT_2 \quad (16)$$

The transformed boundard conditions are

$$F_0(0) = 1, F_1(0) = F_2(0) = F_3(0) = \ldots\ldots\ldots = 0$$
$$F_0(1) = F_1(1) = F_2(1) = F_3(1) = \ldots\ldots\ldots\ldots = 0 \quad (17)$$

Equation is transformed as follows since no initial approximation is considered

$$\frac{d^2T}{dy^2} = p\left[St - Ec\,\mathrm{Pr}\left(\frac{du}{dy}\right)^2\right] \quad (18)$$

$$\frac{d^2T_0}{dy^2} + p\frac{d^2T_1}{dy^2} + p^2\frac{d^2T_2}{dy^2} + \ldots\ldots\ldots = p\lambda\,\mathrm{Pr}\frac{dT_0}{dy^2} + p^2\lambda\,\mathrm{Pr}\frac{dT_1}{dy^2} + p^3\lambda\,\mathrm{Pr}\frac{dT_2}{dy^2} + \ldots\ldots + pST_0 + p^2ST_1 + p^3ST_2 + \ldots\ldots$$
$$- pEc\,\mathrm{Pr}\left(\frac{dF_0}{dy}\right)^2 - 2p^2Ec\,\mathrm{Pr}\left(\frac{dF_0}{dy}\frac{dF_1}{dy}\right). - p^3\left[2Ec\,\mathrm{Pr}\left(\frac{dF_0}{dy}\frac{dF_2}{dy}\right). + Ec\,\mathrm{Pr}\left(\frac{dF_1}{dy}\right)^2\right] + \ldots\ldots\ldots\ldots (19)$$

$$p^0 : \frac{d^2T_0}{dy^2} = 0 \quad (20)$$

$$p^1 : p^2 \frac{d^2T_2}{dy^2} = \lambda \Pr \frac{dT_0}{dy^2} + ST_0 - Ec \Pr \left(\frac{dF_0}{dy} \right)^2 \quad (21)$$

$$p^2 : \frac{d^2T_2}{dy^2} = \lambda \Pr \frac{dT_1}{dy^2} + ST_1 - 2Ec \Pr \left(\frac{dF_0}{dy} \frac{dF_1}{dy} \right). \quad (22)$$

$$p^{3:} \frac{d^3T_2}{dy^3} = \lambda \Pr \frac{dT_2}{dy^2} + ST_2 - \left[2Ec \Pr \left(\frac{dF_0}{dy} \frac{dF_2}{dy} \right). + Ec \Pr \left(\frac{dF_1}{dy} \right)^2 \right] \quad (23)$$

$$T_0(0) = 1, T_1(0) = T_2(0) = T_3(0) = \ldots\ldots\ldots = 0$$
$$T_0(1) = T_1(1) = T_2(1) = T_3(1) = \ldots\ldots\ldots\ldots = 0 \quad (24)$$

$$F_0 = A_1 y + A_2 \quad (25)$$

$$T_0 = B_1 y + B_2 \quad (26)$$

Applying the boundary conditions

$$F_0(0) = 1, F_0(1) = 0, T_0(0) = 1, T_0(1) = 1$$
$$A_1 = -1, A_2 = 1, B_1 = -1, B_2 = 1$$

$$F_0 = 1 - y \quad (27)$$
$$T_0 = 1 - y \quad (28)$$

$$F_1 = -\lambda \frac{y^2}{2} + b \left[\frac{y^2}{2} - \frac{y^3}{6} \right] - Gr \left[\frac{y^2}{2} - \frac{y^3}{6} \right] + A_3 y + A_4 \quad (29)$$

$$T_1 = -\lambda \Pr \frac{y^2}{2} + S \left[\frac{y^2}{2} - \frac{y^3}{6} \right] - Ec \Pr \frac{y^2}{2} + B_3 y + B_4 \quad (30)$$

Applying the boundary conditions $F_1(0) = 0$, $F_1(1) = 0$ and $T_1(0) = 0$, $T_1(1) = 0$

$$A_3 = \frac{\lambda}{2} + \frac{Gr}{3} - \frac{1}{3} b$$
$$A_4 = 0$$
$$B_3 = \frac{\lambda \Pr}{2} + \frac{Ec \Pr}{2} - \frac{S}{3}$$
$$B_4 = 0$$

$$F_1 = -\lambda \frac{y^2}{2} + b \left[\frac{y^2}{2} - \frac{y^3}{6} \right] - Gr \left[\frac{y^2}{2} - \frac{y^3}{6} \right] + \left[\frac{\lambda}{2} + \frac{Gr}{3} - \frac{1}{3} b \right] y \quad (31)$$

$$T_1 = -\lambda \Pr \frac{y^2}{2} + S\left[\frac{y^2}{2} - \frac{y^3}{6}\right] - Ec \Pr \frac{y^2}{2} + \left[\frac{\lambda \Pr}{2} + \frac{Ec \Pr}{2} - \frac{S}{3}\right] y \tag{32}$$

$$\begin{aligned} F_2 = & -\lambda^2 \frac{y^3}{6} + \lambda b\left[\frac{y^3}{6} - \frac{y^4}{24}\right] - Gr\lambda\left[\frac{y^3}{6} - \frac{y^4}{24}\right] + \left[\frac{\lambda^2}{2} + \frac{Gr\lambda}{2} - \frac{\lambda b}{3}\right]\frac{y^2}{2} - \lambda b \frac{y^4}{24} \\ & + b^2\left[\frac{y^4}{24} - \frac{y^5}{120}\right] - Grb\left[\frac{y^4}{24} - \frac{y^5}{120}\right] + b\left[\frac{\lambda}{2} + \frac{Gr}{3} - \frac{1}{3}b\right]\frac{y^3}{6} + Gr\lambda \Pr \frac{y^4}{24} \\ & - GrS\left[\frac{y^4}{24} - \frac{y^5}{120}\right] + GrEc \Pr \frac{y^4}{24} - \left[\frac{Gr\lambda \Pr}{2} + \frac{GrEc \Pr}{2} - \frac{GrS}{3}\right]\frac{y^3}{6} + \\ & A_5 y + A_6 \end{aligned} \tag{33}$$

$$\begin{aligned} T_1 = & -\lambda^2 \Pr^2 \frac{y^3}{6} + \lambda \Pr S\left[\frac{y^3}{6} - \frac{y^4}{24}\right] - Ec \Pr^2 \lambda \frac{y^2}{6} - \lambda \Pr S \frac{y^4}{24} + S^2\left[\frac{y^4}{24} - \frac{y^5}{120}\right] \\ & + \left[\frac{\lambda^2 \Pr^2}{2} + \frac{Ec \Pr^2 \lambda}{2} - \frac{\lambda \Pr S}{3}\right]\frac{y^2}{2} - Ec \Pr S \frac{y^4}{24} + \left[\frac{\lambda \Pr S}{2} + \frac{Ec \Pr S}{2} - \frac{S^3}{3}\right]\frac{y^3}{6} \\ & - Ec \Pr \lambda \frac{y^3}{3} + 2Ec \Pr b\left[\frac{y^3}{6} - \frac{y^4}{24}\right] - 2GrEc \Pr\left[\frac{y^3}{6} - \frac{y^4}{24}\right] + \left[Ec \Pr \lambda + \frac{2GrEc \Pr}{3} - \frac{2Ec \Pr b}{3}\right]\frac{y^2}{2} \\ & + B_5 y + B_6 \end{aligned} \tag{34}$$

Applying the boundary conditions *$F_2(0) = 0$, $F_2(1) = 0$ and $T_2(0) = 0$, $T_2(1) = 0$*

$$A_5 = \frac{GrEc \Pr}{24} + \frac{GrS}{45} + \frac{Gr \Pr \lambda}{24} - \frac{Gr}{45}b + \frac{1}{45}b^2 - \frac{Gr\lambda}{24} - \frac{\lambda^2}{12}$$

$$A_6 = 0$$

$$B_5 = \frac{S^2}{12} - \frac{\lambda^2 \Pr^2}{2} - \frac{Ec \Pr^2 \lambda}{12} - \frac{Ec \Pr S}{24} - \frac{Ec \Pr \lambda}{6} + \frac{Ec \Pr}{12}b + \frac{GrEc \Pr}{12}$$

$$B_6 = 0$$

Therefore the approximate solution of equation are

$F = F_0 + F_1 + F_2 + F_3 + F_4 + \ldots\ldots\ldots\ldots\ldots$ (35)

$T = T_0 + T_1 + T_2 + T_3 + T_4 + \ldots\ldots\ldots\ldots\ldots$ (36)

Results and discutions

The Effects of magnetic field, permeability parameter and suction / injection in the presence of viscous dissipation on an incompressible and electrically conducting fluid is injected through one of the porous plates and simultaneously removed through the other porous plate with the same velocity. The entire system (consisting of Porous channel plates and the fluid) rotates about an axis perpendicular to the plates. The closed form solutions for the velocity and temperature fields are obtained analytically for different values of parameters appeared in the equations. To have better insight of the physical problem the variations of the velocity, the temperature profile are evaluated numerically for different sets of the values of injection/suction parameter S , rotation parameter R , Hartmann number M, the permeability parameter K, Grashof number Gr, Prandtl number Pr and the Eckert number Ec. These numerical values are then shown graphically to assess the effect of each

parameter .The velocity variations are presented graphically in Figs. 2 to 15 for Pr=0:71,S=2,Gr=4,Ec=0:6,L=2, M=0:2 h = 0.5,Ec=0.6,R=2 and K=0.5 except the ones shown in these figures.

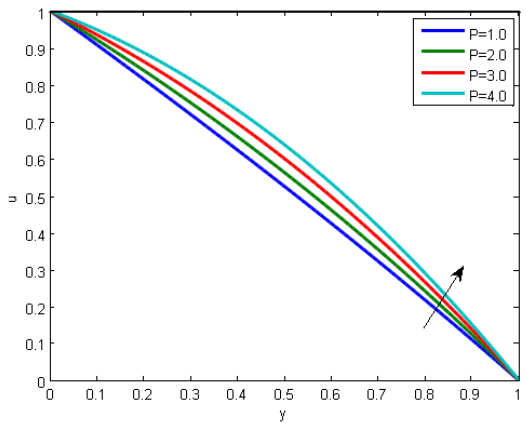


Figure 2. Effects of the Prandtl number (Pr) on velocityProfile

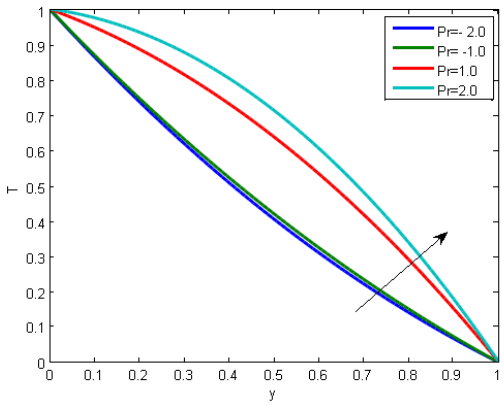


Figure 3. Effects of the Prandtl number (Pr) on temperature profiles

Figures 2 and 3 illustrate the effects of the Prandtl number (Pr) on velocity and temperature profiles, respectively. The velocity profile increases with rising Pr. Physically, this is expected since the Prandtl number represents the ratio of viscous diffusivity to thermal diffusivity. An increase in Pr corresponds to greater viscous diffusivity or reduced thermal diffusivity. Regarding temperature distribution, the fluid temperature near the heated plate decreases with increasing Pr, while the opposite trend is observed near the cold plate. The decrease near the heated plate is attributed to reduced thermal diffusivity, which limits the diffusion of heat into the system and consequently lowers the temperature as Pr rises. In contrast, near the cold plate, the higher Pr reduces the diffusion of heat generated by viscous dissipation, causing heat accumulation. This accumulation leads to an increase in the thermal boundary layer thickness of the fluid, thereby enhancing both thermodynamic and hydrodynamic effects

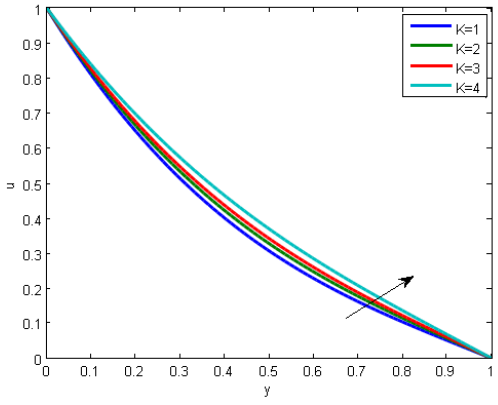


Figure 4. Effects of the permeability (K) on velocity profiles

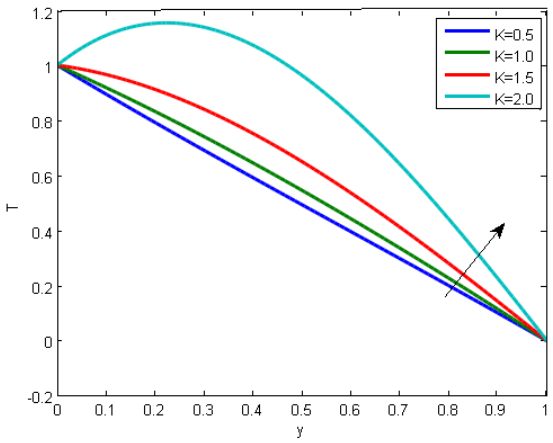


Figure 5. Effects of the permeability (K) on temperature profiles

Figures 4 and 5 shows the effect of permeability (K) on velocity and temperature distributions. Velocity increases with higher permeability due to reduced resistance in the porous medium. Temperature decreases near the heated plate with rising permeability, while an opposite effect is observed near the cold plate. The increase near the heated plate is attributed to the injection of externally heated fluid, which raises the adjacent fluid temperature.

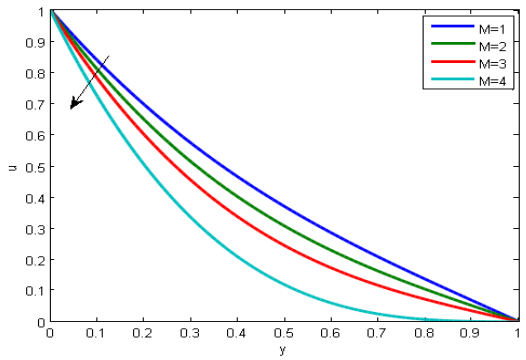


Figure 6. Effects of the magnetic field parameter (M) on velocity Profile

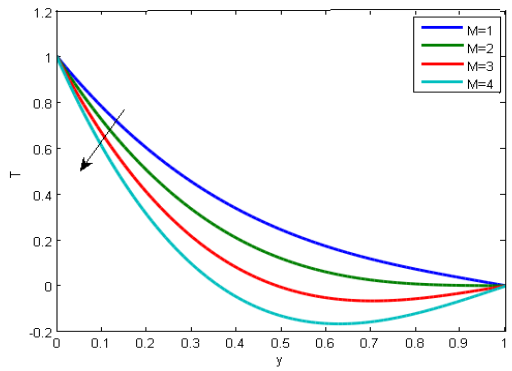


Figure 7. Effects of the magnetic field parameter (M) to temperature profile

Figures 6 and 7 presents the velocity and temperature profiles for different values of the magnetic field parameter (M). The velocity decreases with increasing M due to the Lorentz force, which opposes fluid motion. Meanwhile the temperature profile decreases with higher Mwhich is responsible for enhancing the energy generation, strengthening convection currents and reducing fluid density.

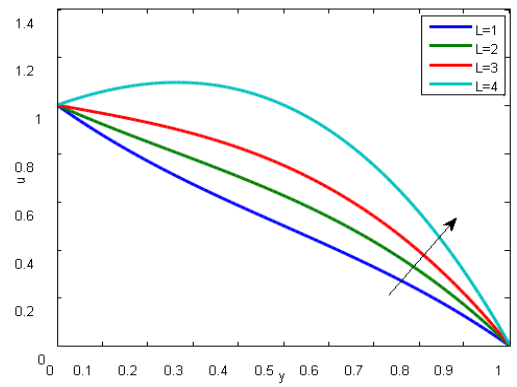


Figure 8. Effects of the suction/injection parameter (L) on velocity Profile

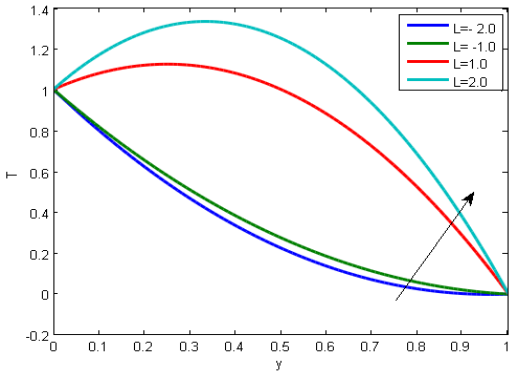


Figure 9. Effects of the suction/injection parameter (L) to temperature profile

Figures 8 and 9shows the influence of the suction/injection parameter (L) on velocity and temperature profiles. Both velocity and temperature increase with injection (L>0) through the heated plate, as fluid enters the system via the porous plates, enhancing the motion and distributing dissipated energy. In contrast, with suction (L<0) through the cold plate, both profiles decrease because heated fluid escapes and is replaced by cooler fluid, thereby reducing temperature, weakening convection currents, and lowering fluid motion.

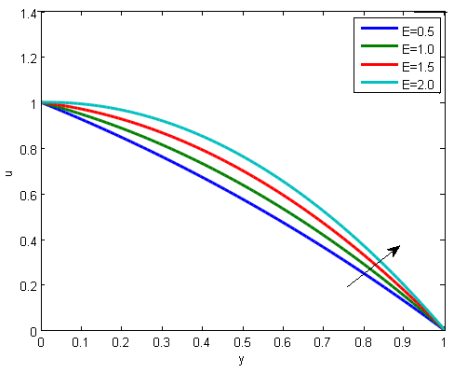


Figure 10. Effects of the viscous dissipation (Ec) on velocityProfiles

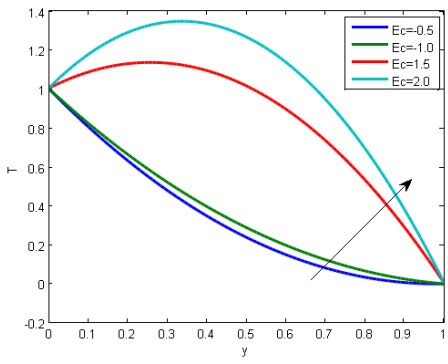


Figure 11. Effects of the viscous dissipation (Ec) to temperature profile

Figures 10 and 11 show the velocity and temperature profiles, respectively. Both profiles increase with rising viscous dissipation (Ec), as greater internal energy generated by fluid particle interactions reduces fluid density and enhances convection, thereby promoting stronger fluid motion and energy transfer within the channel.

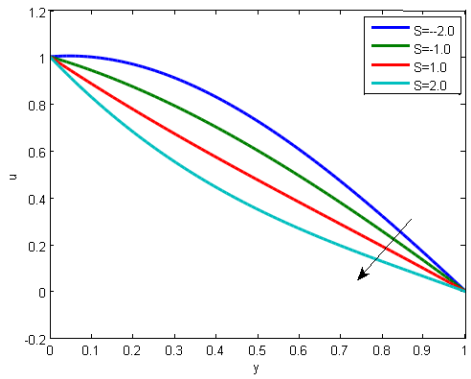


Figure 12. Effects of the heat source/sink parameter(S)on velocity Profile

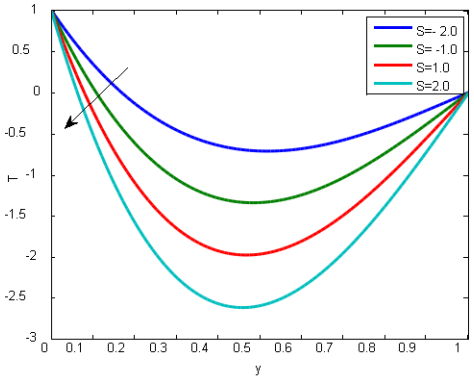


Figure 13. Effects of the heat source/sink parameter(S) to temperature profile

Figures 12 and 13 present the velocity and temperature profiles for different values of the heat source/sink parameter(S). Both profiles decrease with increasing heat sink (S<0), since heat absorption makes the fluid denser and weakens convection currents, thereby reducing temperature and flow. In contrast, with increasing heat generation (S>0), both profiles rise as convection strengthens, fluid density decreases, and temperature and velocity increase.

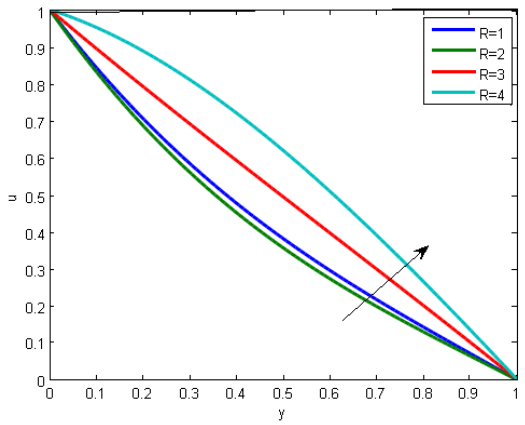


Figure 14. Effects of the rotation parameter (Ω) on velocityProfile

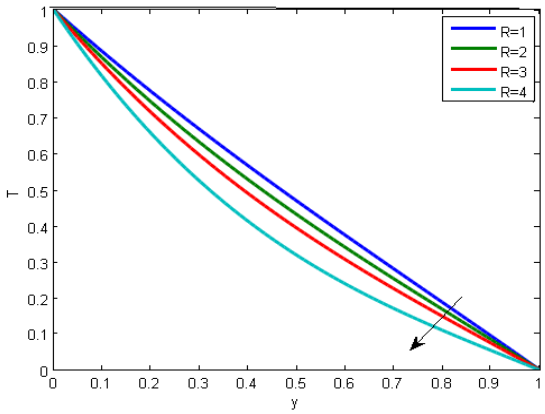


Figure 15 ffects of the rotation parameter (Ω)to temperature profile

Figure 14 and 15illustrates the influence of the rotation parameter Ω on velocity and temperature profiles. It is observed that the velocity profile increases with an increase in Ω, indicating that rotation enhances fluid motion. In contrast, the temperature profile decreases as Ω increases, suggesting that stronger rotation reduces thermal buildup within the fluid.

Conclusion

The study reveals that the velocity and temperature distributions of an incompressible, electrically conducting fluid in a rotating porous channel are strongly influenced by the governing parameters. Heat generation, injection, permeability, viscous dissipation, and rotation enhance fluid velocity and energy transfer, whereas suction, magnetic field effects, and heat absorption suppress them. Temperature behavior shows a dual nature: it decreases near heated surfaces with higher Prandtl number, permeability, or magnetic field strength, but may increase near the cold plate due to reduced thermal diffusion or heat accumulation. Overall, the results highlight the delicate balance between hydrodynamic and thermal effects in magnetohydrodynamic flows. The findings

provide useful insights for practical applications in thermal management, porous media flows, and rotating MHD systems where controlled heat and mass transfer play a crucial role.

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