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Analytical Study of MHD Mixed Convection in a Heated Vertical Porous Channel

Saurabh Kapoor[1], Durgaprasad Nayak[2,*], Anasuya Nath[2]

[1]*Department of Mathematics, Regional Institute of Education (NCERT), Bhubaneswar, Odisha, India*

[2]*P.G. Department of Mathematics, Utkal University, Bhubaneswar, Odisha, India*

Abstract

An analytical analysis is made to examine the influence of MHD flow in a laminar mixed convection flow through a vertical channel embedded with a porous medium. The momentum equations are modeled using the non-Darcy Brinkman extended formulation. The flow is assumed to be steady, laminar and fully developed of an electrically conducting fluid with internal heat generation or absorption. The governing systems of equations are solved analytically to derive expressions for velocity and temperature distributions. Moreover, parametric analysis is conducted to investigate the effects of the Magnetic field strength (M), heat source parameter (Q), mixed convection parameter ($Gr_1 = \frac{Gr}{Re}$), and Darcy number (Da) on the velocity and temperature distribution. The analysis show that increasing M progressively smooths the inflection point in the velocity profile, leading to a more flattened flow structure. Higher values of Q induce the formation of an inflection point along with backflow in the velocity field. Furthermore, an increase in thermal buoyancy forces (Gr/Re) promotes the development of inflection points and flow separation near the channel walls.

Keywords: Non Darcy Brinkman Extended Model; MHD; Hartmann Number; Heat Source Parameter.

2020 Mathematics Subject Classification: 76S05, 76W05, 80A20.

1. Introduction

The investigation of magnetohydrodynamic (MHD) flows involving electrically conductive fluids within porous configurations holds substantial importance across a range of industrial and experimental contexts in fluid dynamics [14]. To understand the mixed convection in vertical porous channels subjected to magnetic fields is particularly relevant for applications such as liquid metal blankets in thermonuclear reactors, fusion energy systems, cooling strategies for electronic components, MHD energy conversion devices, and materials processing like crystal growth. Among these, fusion blanket technology represents a key area where such MHD-porous interactions are

*Corresponding author (durgapnayak99@gmail.com)

critically important [8,9]. One of the important applications of magnetohydrodynamic (MHD) convection in porous media arises in fusion blanket systems, where electrically conducting fluids flow through permeable structures under strong magnetic fields. Consider a sufficiently long vertical porous channel subjected to heating, with its length much larger than its width and with open ends such that end effects at the inlet and outlet can be neglected. Under the influence of a transverse magnetic field, the flow within the central region of the channel becomes fully developed, and it is primarily governed by a constant pressure gradient. In such a configuration, the transport process can be modeled as a mixed convective flow through a porous medium in the presence of a uniform magnetic field. Many practical MHD systems operate under moderate to high magnetic field strengths, where additional physical effects become significant. In particular, neutron irradiation in fusion environments can generate internal volumetric heat within the fluid, which alters the thermal and flow characteristics substantially. Therefore, incorporating internal heat generation within the porous medium is essential for realistic modeling of such systems. To contextualize the present works, the key findings of the previous studies examining mixed convection flows under magnetic field strength across various geometries are summarized below:

The theoretical foundations of fluid transport and thermal energy transfer is extensively established in the seminal literature by Nield and Bejan [4]. Concurrently, the mixed convection in pure fluid media have been widely investigated, with substantial research focused on fundamental geometric domains such as vertical pipes [7,17,20], vertical annulus [3,10], and vertical channels [11,15]. MHD flow of electrically conducting fluids plays a crucial role in diverse technical and industrial systems, giving rise to highly complex transport phenomena [14]. Extensive efforts have been dedicated to addressing the free, forced and mixed convection in various porous configurations under the influence of magnetic field [18,19,22,24]. A review of existing literature on mixed convection flow within vertical geometries specifically channels, annuli, and pipes-is presented below.

Kapoor and Nayak [18] examined the mixed convection with heating effects vertical pipe. They examined that both velocity and temperature are affected by heat source effects. Subsequently the authors extended their study in thermosolutal convection with MHD effects [19] and heat source effects [21]. Nayak and Kapoor examined the influence of MHD effects in vertical pipe in purely fluid medium [7]. In other hand, the influence of magnetic effects and buoyancy in a vertical annulus is examined by Barletta [3]. Recently, In annular geometry, Negi and Khandelwal [12] examined both linear and nonlinear instability mechanisms in non-isothermal Poiseuille flow under magnetic fields, revealing subcritical instabilities beyond the predictive capacity of linear theory. Barletta [1,2] investigated the laminar mixed convection flow in vertical channel taking viscous dissipation into accounts. Kumar and Singh [5] studied the natural convective flow of incompressible fluid over a vertical annulus with heat source effect. They noticed that with increasing of heat source effect, the velocity and temperature profile are increases. Sankar [13] examined the stability analysis of MHD combined convection (free and force) in a vertical channel for lower values of Hartmann number.

Recently, Nayak and Kapoor [6] examined analytically the MHD natural free convection flow in a vertical porous plate. From a mathematical point of view most of the existing literature is based on the numerical approaches. Therefore, an attempt has been made to analytically investigate the combined effects of magnetic fields and heat source on mixed convection in vertical porous channel.

2. Mathematical Formulation

Consider the fully developed hydromagnetic mixed convective flow in a vertical porous channel of length 2L subject to internal heat source parameter. The channel is saturated with a homogeneous and isotropic porous medium and the flow is modeled using the Darcy-Brinkman formulation. A uniform internal heating of uniform volume density Q is spread out in the flow within the channel. An incompressible fluid with constant properties is considered, except for the density in the momentum equation's buoyancy term, which assumes density varies linearly with temperature expressed as $\rho = \rho_f[1 - \beta_T(T - T_0)]$. Under the low magnetic Reynolds number approximation, both the induced magnetic fields and Hall effects are negligible. It is assumed that fluid and porous medium are everywhere in a state of local thermal equilibrium, the porous medium is both homogeneous and isotropic and the fluid is incompressible.

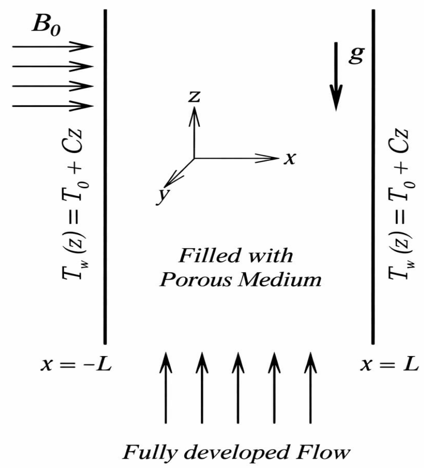


Figure 1: Schematic of the physical problem.

To describe the model, the governing laws for mass, linear momentum, and energy are extended to account for the combined boundary and inertia effects of the porous medium, buoyancy forces, and the influences of magnetohydrodynamics (MHD) alongside internal heat generation or absorption.

$$\nabla \cdot \mathbf{V}_* = 0 \tag{1}$$

$$\left[\rho_f \frac{1}{\varepsilon}\frac{\partial \mathbf{V}_*}{\partial t} + \rho_f \frac{1}{\varepsilon^2}\mathbf{V}_* \cdot \nabla \mathbf{V}_*\right] = \bar{\mu}\nabla^2 \mathbf{V}_* - \frac{\mu_f}{K}\mathbf{V}_* - \nabla P_* - \rho g \mathbf{e}_{z^*} - \sigma B_0^2 \mathbf{e}_{z^*} V_* \tag{2}$$

$$\sigma_1 \frac{\partial T}{\partial t} + (\mathbf{v}_* \cdot \nabla) T = \alpha_e \nabla^2 T + \frac{q}{\rho c_p}, \tag{3}$$

We non-dimensionalize the governing equations by introducing the following characteristics scale

$$(x, y, z) = \frac{(x_*, y_*, z_*)}{L}, \quad \mathbf{V} = \frac{\mathbf{V}_*}{\overline{W}_0}, \quad P = \frac{p_*}{\rho_f \overline{W}_0^2}, \tag{4}$$

$$\theta = \frac{T - T_0}{\Delta T}, \quad Q = \frac{qL^2}{k\Delta T}, \quad t = \frac{t^* \overline{W}_0}{L} \tag{5}$$

Here, $\mathbf{V} = (u, v, w)$ represents the dimensionless velocity vector, t is the dimensionless time, and P denote the dimensionless pressure, Q represent the heat source parameter, $\mathbf{j}$ is the current density, θ is the temperature. The subscript asterisk($_*$) represent the dimensional variable. The parameter $\overline{W}_0$ represent the characteristic velocity, k is the thermal conductivity. The final dimensionless, inductionless equations governing the convection flow in Cartesian coordinates are presented below:

$$\nabla \cdot \mathbf{V} = 0 \tag{6}$$

$$\frac{1}{\epsilon}\frac{\partial \mathbf{V}}{\partial t} + \frac{1}{\epsilon^2}\mathbf{V} \cdot \nabla \mathbf{V} = -\nabla P + \frac{1}{Re}\nabla^2 \mathbf{V} - \frac{1}{ReDa}\mathbf{V} - \frac{M^2}{Re}\mathbf{V} + \frac{Gr}{Re^2}\theta \tag{7}$$

$$\frac{\partial \theta}{\partial t} + \mathbf{V} \cdot \nabla \theta = \frac{1}{Re\,Pr}\nabla^2 \theta + \frac{Q}{Re\,Pr}, \tag{8}$$

The equation above is characterized by the following dimensionless parameters: the Grashof number ($Gr = \frac{gL^4 \beta_T \Delta T}{\nu^2}$), Reynolds number ($Re = \frac{\overline{W}_0 L}{\nu}$), Prandtl number ($Pr = \frac{\nu}{\alpha_e}$) and the Hartmann number ($M = \sqrt{\frac{\sigma L^2 B_0^2}{\rho_f \nu}}$) and the Darcy number ($Da = \frac{K}{L^2}$). Since the flow is assumed to be fully developed, laminar and unidirectional flow, the governing differential equations (6)–(8) becomes

$$\frac{d^2 W}{dx^2} - \left(\frac{1}{Da} + M^2\right) W + Gr_1\,\theta = Re\,\frac{dP}{dZ} \tag{9}$$

$$\frac{d^2\theta}{dx^2} + Q = 0 \tag{10}$$

with the boundary conditions: $W_0 = 0$ at $x = \pm 1$, and $H_0 = \pm\frac{1}{2}$ at $x = \pm 1$. Thus the temperature distribution becomes

$$\theta_0(x) = -\frac{Q}{2}x^2 + \frac{1}{2}x + \frac{Q}{2} \tag{11}$$

Therefore, The final velocity distribution becomes

$$W_0(x) = C_1 e^{kx} + C_2 e^{-kx} - \frac{Gr_1 Q}{2k^2}x^2 + \frac{Gr_1}{2k^2}x + \frac{Gr_1 Q}{2k^2} - \frac{Gr_1 Q}{k^4} - \frac{Re}{k^2}\frac{dP}{dy} \tag{12}$$

where,

$$k^2 = \left(\frac{1}{Da} + M^2\right) \quad and \quad A = \frac{Gr_1 Q}{2k^2} - \frac{Gr_1 Q}{k^4} - \frac{Re}{k^2}\frac{dP}{dy}$$

$$C_1 = \frac{1}{2}\left[\frac{\frac{Gr_1 Q}{k^2} - 2A}{2\cosh k} - \frac{Gr_1}{2k^2 \sinh k}\right] \tag{13}$$

$$C_2 = \frac{1}{2}\left[\frac{\frac{Gr_1 Q}{k^2} - 2A}{2\cosh k} + \frac{Gr_1}{2k^2 \sinh k}\right] \tag{14}$$

3. Results and Discussion

The results presented in this section illustrate the influence of medium permeability, represented by the Darcy number ($Da = 10^{-4} - 10^{-2}$) and the heat generation/absorption parameter (Q) the Hartmann number (M), on the flow and thermal fields, along with other dimensionless parameters. These include the Hartmann number (M), the applied pressure gradient (dP^*/dX), and the mixed convection parameter ($Gr_1 = Gr/Re$). The combined effects of these parameters on the velocity profiles, temperature distribution, and Nusselt number are investigated in detail. Throughout the analysis, the Prandtl number (Pr) and the pressure gradient (dP^*/dX) are held constant at 0.7 and 0.1, respectively, following the benchmark values established by Mahmud [23].

To maintain consistency with established non-dimensional frameworks, the primary governing parameters are selected within the following intervals $10^{-4} \leq Da \leq 10^{-2}$, $0.1 \leq Gr/Re \leq 200$, and $0 \leq M \leq 25$, $1 \leq Q \leq 30$. Unless stated otherwise, the default parameter values used in the simulations are $Da = 10^{-2}$ and $Gr/Re = 10^2$.

3.1 Influence of the heat generation/absorption parameter(q)

Figure 2a represents the impact of heat generation parameter Q on the velocity profile for $Da = 0.01$ and $M = 1$. First observation is, for lower values of Q, the velocity profile near the walls of the channel becomes negative., it indicates that the presence of backflow or flow reversal in these regions. This phenomenon is physically attributed to the increasing strength of the heat generation, i.e., as the heat source parameter increases, more heat enters the fluid, leading to its heating. The observed inflection point and backflow in the velocity profile suggests potential flow instability [16].

In contrast, at higher values of Q, the increased dominance of buoyancy forces stabilizes the flow by suppressing reverse motion and reducing shear-induced disturbances. Figure 3a and 3b illustrates the impact of heat absorption parameter on both velocity and temperature profiles for fixed values of $Da = 0.01$ and $M = 1$. It is observed that the velocity remains negative throughout the channel for all values of Q, indicating a dominant reverse flow. Moreover, the magnitude of the negative velocity increases significantly with increasing Q, implying a strengthening of the backflow.

This behavior can be interpreted in terms of the relative balance between buoyancy and resistive forces. In the presence of heat absorption, thermal energy is removed from the fluid, leading to a reduction in temperature, as shown in figure 3(b). Consequently, the buoyancy force, which is proportional to the temperature difference (or equivalently the mixed convection parameter Gr/Re), is significantly weakened. As a result, the ratio of buoyancy force to the combined resistive forces—namely porous resistance (inversely proportional to Da) and magnetic damping (proportional to M^2)—becomes very small. This allows the resistive forces to dominate the flow, thereby enhancing the reverse motion across the entire channel.

As the magnitude of the heat absorption parameter Q increases, the fluid temperature decreases further, leading to a continued reduction in buoyancy effects. Consequently, the ratio of buoyancy to resistive forces decreases even more, resulting in a stronger backflow and a deeper velocity profile. The flow thus becomes increasingly dominated by viscous and resistive effects, with negligible contribution from buoyancy.

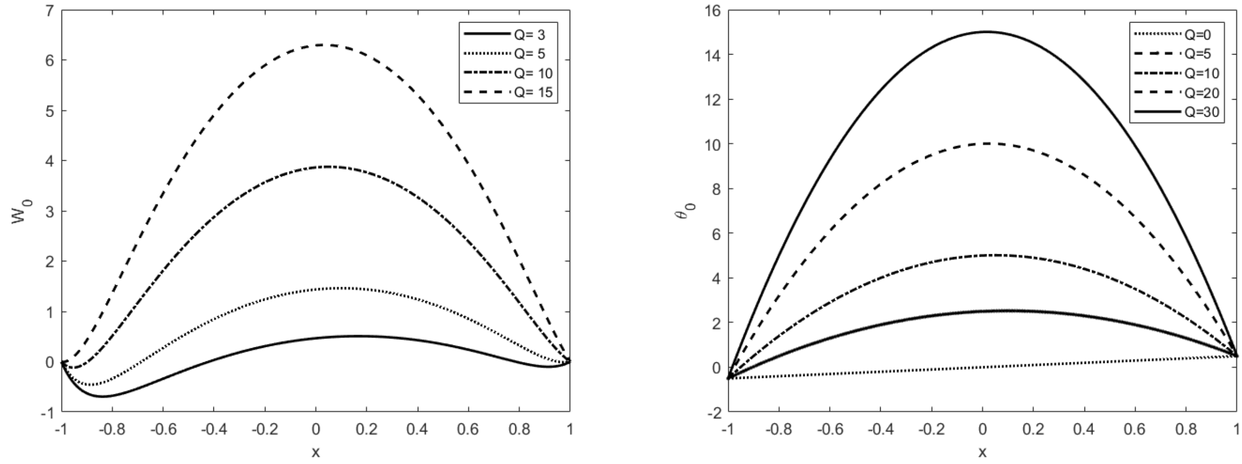
From a stability perspective, the presence of strong backflow throughout the channel, along with steep velocity gradients, may promote hydrodynamic instability due to enhanced shear and possible inflectional behavior in the velocity profile. Therefore, heat absorption tends to destabilize the flow by suppressing buoyancy-driven stabilization and amplifying reverse motion within the channel.

Since all physical parameters and pressure gradient are fixed, enhancing the value of heat source parameter (Q) at that time in order to satisfy the global mass conservation the flow becomes unstable. Hence, our assumption that unidirectional flow becomes invalid. Thus, the inflection points and reversed flow arise in the velocity profile. Also, at larger value of heat source parameters show the more warming of the fluid in the vertical channel to enhance the buoyancy effect.

A similar type of unnatural deviation in the flow profile has been reported in a vertical pipe for negative Rayleigh numbers by [21] and [19]. An unnatural deviation in the flow profile has been observed in the presence of a heat generation parameter; however, no such deviation has occurred when a heat absorption parameter is considered.

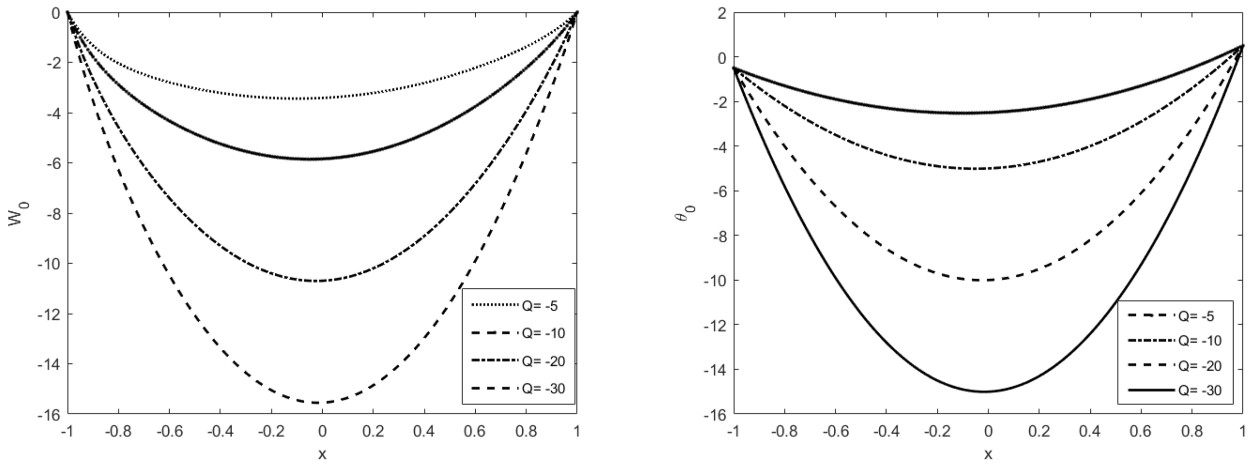
The impact of heat absorption parameter is illustrated in figure 3. As Q decreses from -5 to -30, its influence on velocity profile becomes reverses. Specifically, the upward parabola becomes flattens as Q drops from -30 to -5. Similarly on temperature profile, the fluid temperature drops significantly with decreasing value of Q. This behavior occurs because enhanced heat absorption intensifies the cooling effect within the medium, thereby flattening the parabolic temperature profile in the core region and leading to a more uniform temperature distribution across the center of the channel.

Mathematically, the reason for this variation can be understood from equations 11 and 12. Both the velocity (W_0) and temperature profile (θ_0) contain the terms that vary negatively with respect to variable x^2 and positively with respect to x. Consequently, when negative values are assigned to the Q, the terms associated with Q becomes increasingly negative, resulting in the observed physical deviations.



(a) (b)

Figure 2: (a)Velocity and (b) temperature profile under different heat source parameter for M = 1.



(a) (b)

Figure 3: (a)Velocity and (b) temperature profile under different heat absorption parameter for M = 1.

3.2 Influence of Hartmann Number

The influence of the magnetic field strength (M) on the velocity profile at $Q = 1$ is illustrated in Fig. 4. An increase in magnetic parameter M, the velocity profile exhibits a progressive reduction across the whole domain. The maximum velocity at the channel centerline declines monotonically and an overall suppression in the flow profile.

This behavior can be explained in terms of the balance between driving and resistive forces. The applied magnetic field generates a Lorentz force, which acts opposite to the direction of fluid motion and is proportional to M^2. As M increases, the Lorentz force becomes stronger, thereby enhancing the overall resistive effect in the system. Consequently, the ratio of buoyancy force (proportional to Gr/Re) to the combined resistive forces (porous drag and magnetic damping) decreases, leading to a reduction in flow velocity. Near the channel walls, the velocity profiles tend to flatten with increasing

M, indicating suppression of velocity gradients. The flow becomes more uniform but weaker in magnitude due to the dominant magnetic damping effect.

The Lorentz force scales with the magnetic parameter (M), which acts as a resistive body force that counteracts as a velocity fluctuation and dampens the buoyancy driven motion. For the onset of instability, buoyancy forces must exceeds the systems viscous and electromagnetic damping thresholds. Higher magnetic fields therefore shift the initiation of convection toward larger critical Rayleigh numbers. This physical relationship underlies the monotonic increase in Ra_c with M, highlighting the robust stabilizing influence of magnetic damping in convection within a porous channel.

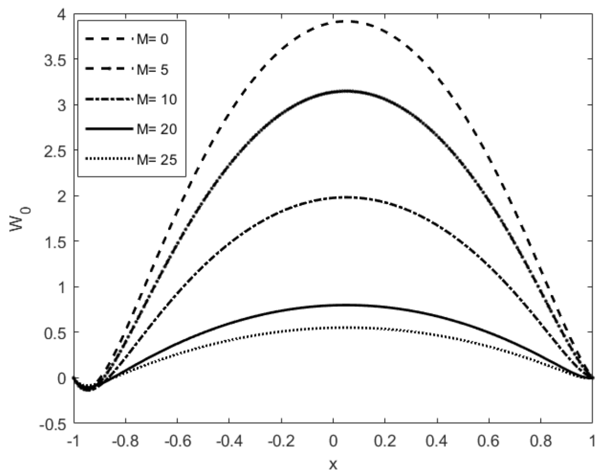


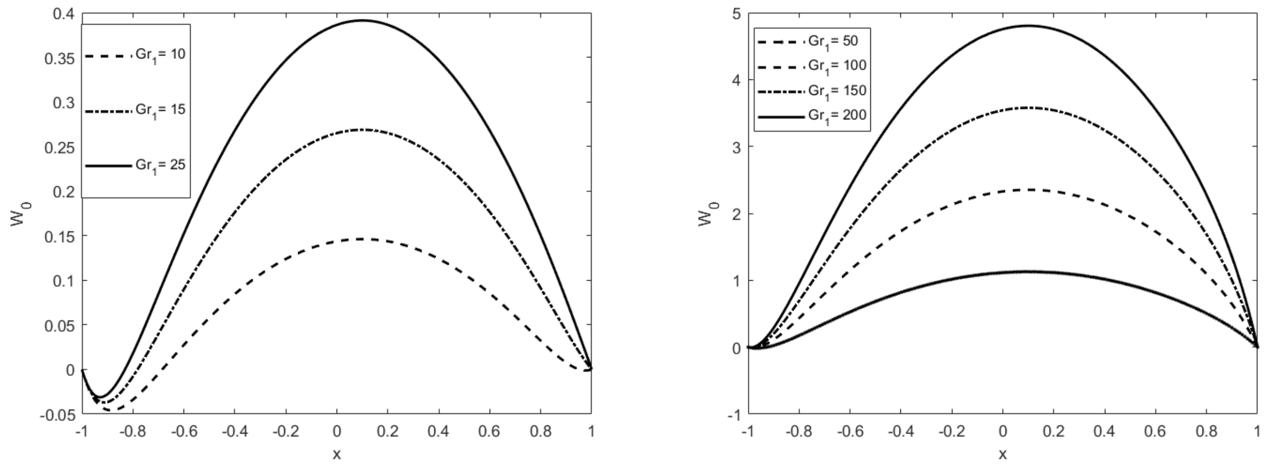
Figure 4: Velocity profile under different magnetic field strength (M) at Q = 1.

3.3 Effect of Mixed Convection Parameter

Figure 5(a) and 5(b) represents the impact of mixed convection parameter $Gr_1 = Gr/Re$ on the velocity profile for Da=10^{-2} at $M = 1$ and $Q = 1$. The velocity magnitude rises significantly with increasing value of Gr_1. Furthermore, the peak velocity at the channel centerline becomes more pronounced as Gr_1 increases. This behavior indicates a clear enhancement of the fluid flow.

Physically this acceleration is attributed to the competitive balance between the relative contribution of buoyancy forces. The parameter $Gr_1 = Gr/Re$ quantifies the strength of buoyancy relative to inertia. Higher values of Gr_1 denote a stronger thermal buoyancy effects. Consequently as buoyancy forces increases, it dominate the transport mechanisms, accelerating the flow throughout the channel.

At lower values of Gr_1, the resistive effects are comparatively dominant, and a slight backflow is observed near the channel walls due to insufficient buoyancy to overcome viscous and porous resistance. However, as Gr_1 increases, this backflow diminishes and eventually disappears, resulting in a fully forward flow across the channel. Increasing Gr_1 enhances the velocity gradient, and induces the inflection points which may trigger hydrodynamic instability. Consequently, while a higher Gr_1 strengthens the primary flow, the absolute dominance of buoyancy driven forces makes the system more unstable. From a stability perspective, the increase in Gr_1 enhances velocity gradients and may introduce inflectional characteristics in the velocity profile, which can promote hydrodynamic instability. Thus, while higher Gr_1 strengthens the flow, it may also make the system more susceptible to instability due to the dominance of buoyancy-driven convection.



(a) (b)

Figure 5: Effect of the velocity profile for different values of $Gr_1 = \frac{Gr}{Re}$

3.4 Influence of Media Permeability

The impact of media permeability on the velocity distributions is depicted in figure 6. A reduction in the permeability, corresponding to a decrease in Da from 10^{-2}-10^{-4} results in a pronounced reduction in fluid velocity across the domain. Notably, a backflow develops near the wall of the channel at Da $\leq 10^{-3}$ but disappears under the deeper permeability reductions. This behavior can be mathematically explained by the relations

$$k^2 = \frac{1}{Da} + M^2,$$

where a decrease in Da causes a sharp increase in k. Since the velocity terms contain several terms inversely proportional to k^2 and k^4, namely

$$-\frac{Gr_1 Q}{2k^2}x^2, \quad \frac{Gr_1}{2k^2}x, \quad -\frac{Gr_1 Q}{k^4}, \quad \text{and} \quad -\frac{Re}{k^2}\frac{dP}{dy}$$

their magnitudes decrease rapidly as Da decreases. Furthermore, the exponential terms $C_1e^{kx} + C_2e^{-kx}$ become increasingly localized near the channel walls. Since the terms C_1 and C_2 contains hyperbolic functions ($\sinh k$ and $\cosh k$) in their denominators, their global magnitudes decay rapidly with decreasing Da. However, the strong exponential variation near the boundary produces a sharp change in the velocity gradient close to the wall. As a result, an adverse near wall motion develops, giving rising to the observed backflow regions $Da \leq 10^{-3}$.

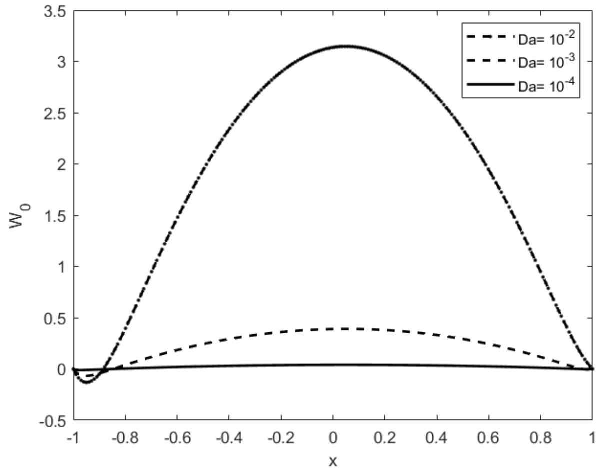


Figure 6: Velocity profile under different values of Media Permeability (Da) for q = 1 and M =1.

4. Conclusion

The current study focused on analytical study of MHD convection in a vertical porous channel together with the heat source parameter. We have used the non Darcy Brinkman extended model to describe the flow in porous medium. First, we non-dimensionalize the governing equations, and then the system of differential equations is solved using analytically. The key findings of this study is as follows

- Both velocity and temperature increase as the heat source intensity increases. Beyond a certain threshold value, backflow and inflection points appear in the velocity profile because the amplified heat source intensifies the fluid heating.
- The magnitude of temperature decreses as Q decreses. Also an inflection point is observed in the velocity profile for all negative values of Q.
- At low magnetic strengths, an inflection points emerges on the velocity profile near the wall, which may lead to hydrodynamics stability. Beyond a certain threshold, the profile flattens across the entire domain as the increased Lorentz force opposes the fluid flow.
- The velocity magnitude rises significantly with increasing value of Gr_1. Furthermore, the peak velocity at the channel centerline becomes more pronounced as Gr_1 increases. This behavior indicates a clear enhancement of the fluid flow.

Future Scope

To fully comprehend the dynamics of the flow, future work will extend this study by implementing a linear stability analysis. This analytical approach will provide deeper mathematical insights into the precise nature and onset of the flow instabilities.

Declarations

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