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Study of Induced Magnetic Field for MHD Convective Flow

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ABSTRACT

In this study, we examined the influence of an induced magnetic field on the steady magneto hydrodynamic (MHD) flow of an electrically conducting fluid over a vertical porous plate within a porous medium. It is assumed that the magnetic Reynolds number of the MHD flow is sufficiently large, necessitating the consideration of the induced magnetic field. The governing equations of motion, along with their boundary conditions, are rendered dimensionless through similarity transformations. The resulting transformed equations are solved numerically using the fourth-order Runge-Kutta method in conjunction with the shooting technique. The effects of relevant parameters on the velocity, temperature, and induced magnetic field profiles are analyzed graphically, and the physical implications are discussed in detail.

Keywords: Porous medium; MHD, Magnetic Reynolds number, Induced magnetic field.

INTRODUCTION

In the current analysis, the specific problem under investigation is the magnetohydrodynamic (MHD) convective flow of an electrically conducting fluid over a vertical porous plate within a porous medium, accompanied by an induced magnetic field. The induced magnetic field generates its own magnetic field, thereby modifying the original magnetic field. This phenomenon has been applied in various fields, including fusion reactors, metal dispersion, metallurgy, and the design of MHD pumps, generators, and flow meters. Consequently, it is essential to incorporate the effects of the induced magnetic field in hydromagnetic equations for several physical problems. [1] examined the combined free-forced convection and mass transfer flow past a vertical porous plate in a porous medium with heat generation and thermal diffusion. Non-similar laminar, steady, electrically-conducting forced convection flow with induced magnetic field effects has been studied by [2]. [3] investigated hydromagnetic natural convection boundary layer flow under the influence of a transverse magnetic field with magnetic induction effects. Additionally, [4] explored the influence of an induced magnetic field on radiating fluid over a porous vertical plate. [5] presented the unsteady MHD free convective flow past a semi-infinite vertical wall with an induced magnetic field. The hydromagnetic free convective flow of an incompressible viscous and electrically conducting fluid between two parallel vertical porous plates in the presence of an induced magnetic field has been studied by [6].

The induced magnetic field plays a significant role in both experimental and theoretical investigations of magnetohydrodynamic (MHD) flow, owing to its relevance in numerous industrial and technological applications. [7] demonstrated the effects of heat transfer on a viscous dissipative fluid flow past a vertical plate in the presence of an induced magnetic field. Similarly, [8] examined the impact of an induced magnetic field on forced convective heat transfer from an isothermal sphere. Regardless of the magnetic Reynolds number selected, the induced magnetic field is considered. Mathematical modeling of two-dimensional MHD flow with

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an induced magnetic field has been provided by [9]. [10] explored the effects of an induced magnetic field on fully developed laminar natural convective flow of a viscous, incompressible, and electrically conducting fluid in the presence of a radial magnetic field, taking the induced magnetic field into account. Furthermore, [11] investigated MHD flow resulting from the linear stretching of a non-conducting sheet in the presence of an induced magnetic field. The stagnation-point flow of nanofluid toward a stretching sheet with an induced magnetic field was presented by [12]. [13] discussed the role of the induced magnetic field on MHD natural convection flow in a vertical microchannel formed by two electrically non-conducting infinite vertical parallel plates. An analysis was conducted by [14] to study the influence of the induced magnetic field on the transient free convective flow of an electrically conducting and viscous incompressible fluid over a vertical cone. Additionally, [15] investigated the case of unequal diffusivities in homogeneous–heterogeneous reactions within viscoelastic fluid flow in the presence of an induced magnetic field and nonlinear thermal radiation. [16] studied the influence of thermophoresis and the induced magnetic field on chemically reacting mixed convective flow of Jeffrey fluid between porous parallel plates. A theoretical analysis was performed by [17] to examine the effects of the induced magnetic field and slip on nonlinear convective Casson fluid flow. [18] studied the induced magnetic field in pseudo plastic Nano fluid near a stagnant point. The effect of a uniform magnetic field in the transverse direction to the flow on overall bed permeability was studied by [19]. Thermal slip and variable viscosity analysis of magnetic flux through wedge in the presence of induced magnetic field is done by [20]

The objective of the present paper is to investigate the effects of the induced magnetic field on viscous incompressible flow over a vertical porous plate. The resulting governing equations have been solved numerically using the Runge-Kutta fourth-order method with a shooting scheme for velocity, induced magnetic field, and temperature profiles. Finally, the effects of various parameters are analyzed through graphs and tables.

PROBLEM FORMULATION

Consider a steady, viscous, incompressible, electrically conducting fluid over a semi-infinite vertical porous plate embedded in porous medium with induced magnetic field. The $\square$-axis is assumed to coincide with vertical plate and $\square$- axis is taken to be normal to the plate. A uniform induced magnetic field $\square_0$ is imposed in the $\square$ direction. The magnetic Reynolds number of MHD flow is not small in magnitude hence, the induced magnetic field ($\square_\square$, $\square_\square$, 0) is highly significant while the normal component of the induced magnetic field $\square_\square$ vanishes at plate and the parallel component $\square_\square$approaching the imposed magnetic field value $\square_0$. The vertical porous plate surface is subjected to a uniform constant temperature $\square_\square$. The free stream velocity $\square_\infty$ is assumed to be parallel to the vertical plate, is constant.

Under theses assumption the governing equations for flow and induced magnetic field profiles are as follows:

$$\frac{\square\square}{\square\square}+\frac{\square\square}{\square\square}=0 \tag{1}$$

$$\frac{\square\square_\square}{\square\square}+\frac{\square\square_\square}{\square\square}=0 \tag{2}$$

$$\square\frac{\square\square}{\square\square}+\square\frac{\square\square}{\square\square}=\square\frac{\square^2\square}{\square\square^2}+\square\square(\square-\square_\infty)-\frac{\square}{\square}\square+\frac{\square}{4\square}\left(\square_\square\frac{\square\square_\square}{\square\square}+\square_\square\frac{\square\square_\square}{\square\square}\right) \tag{3}$$

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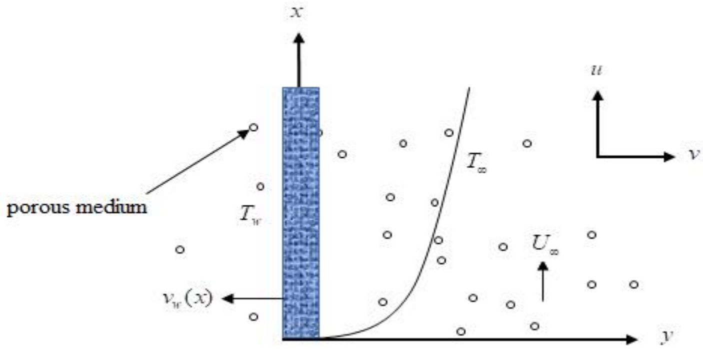

Figure 1 physical sketch of problem

$$\square\frac{\square\square_{\square}}{\square\square}+\square\frac{\square\square_{\square}}{\square\square}=\square_{\square}\frac{\square\square}{\square\square}+\square_{\square}\frac{\square\square}{\square\square}+\square_{1}\frac{\square^{2}\square_{\square}}{\square\square^{2}}$$
(4)

$$\square\frac{\square\square}{\square\square}+\square\frac{\square\square}{\square\square}=\square\frac{\square^{2}\square}{\square\square^{2}}+\frac{\square}{\square_{\square}}\left(\frac{\square\square}{\square\square}\right)^{2} \quad (5)$$

The boundary conditions at the plate and in the free stream are defined as follows

$$\square=0,\ \ \square=\square_{\square},\ \ \frac{\square\square_{\square}}{\square\square}=\square_{\square}=0, \square=\square_{\square}\text{at } \square=0$$

$$\square\to\square_{\infty},\ \ \square_{\square}\to\square_{0},\ \ \square\to\square_{\infty}\text{ as } \square\to\infty \quad (6)$$

We introduce the following non dimensional variables

$$\begin{aligned}
&\square(\square,\square)=(\square\square_{\infty}\square)^{\frac{1}{2}}\square(\square), \square=\frac{\square\square}{\square\square}, \square=-\frac{\square\square}{\square\square}\\
&\square(\square,\square)=\left(\frac{\square\square}{\square_{\infty}}\right)^{\frac{1}{2}}\square_{0}\square(\square), \square_{\square}=\frac{\square\square}{\square\square}, \square_{\square}=-\frac{\square\square}{\square\square}\\
&\square=\square\left(\frac{\square_{\infty}}{\square\square}\right)^{\frac{1}{2}}, \square(\square)=\frac{\square-\square_{\square}}{\square-\square_{\infty}}
\end{aligned} \quad (7)$$

Now substituting the equation (7) in equation (3)-(5), the following nonlinear coupled ordinary differential equations are obtained

$$\square_{\square\square\square}+\square\square_{\square\square}/2+\square_{\square}\square-\square\square_{\square}-\square\square\square_{\square\square}=0$$
(8)

$$\square_{\square\square\square}=\frac{\square\square_{\square}}{2}(\square\square_{\square\square}-\square\square_{\square\square})$$
(9)

$$\frac{1}{\square\square}\square_{\square\square}=-\left(\frac{\square\square_{\square}}{2}+\square\square(\square_{\square\square})^{2}\right)$$
(10)

The dimensionless boundary conditions for the problem is

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$$□_{□}(0) = 0, □(0) = □_{□}, □(0) = □_{□□}(0) = 0, □(0) = 1$$

$$□_{□}(\infty) = 1, □_{□}(\infty) = 1, □(\infty) = 0 \tag{11}$$

Where $□_{□} = -2□_{□}(□)\sqrt{\frac{□}{□□_{\infty}}}$ is suction parameter, $□ = \frac{□□}{□_{\infty}□}$ is the local permeability parameter, $□□ = \frac{□□(□_{□}-□_{\infty})□^{3}}{□^{2}}$ is the Grashof number, $□□ = \frac{□_{\infty}□}{□}$ is the local Reynolds number, $□□ = \frac{□□}{□□^{2}}$ is the local buoyancy parameter, $□ = \frac{□□_{0}^{2}}{□_{\infty}^{2}}$ is the magnetic force number, $□□ = \frac{□□_{□}□}{□} = \frac{□}{□}$ is the Prandtl number, $□□_{□} = \frac{□}{□_{1}}$ is magnetic Prandtl number, $□□ = \frac{□_{\infty}^{2}}{□_{□}(□_{□}-□_{\infty})}$ is the Eckert number.

Skin friction

The wall shear stress τ_w is defined as $\tau_w = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0}$ therefore, the skin friction coefficient C_f at surface is given by

$$C_f = \frac{\tau_w}{\rho U_{\infty}^{2}} = \frac{f''(0)}{\mathrm{Re}_x^{1/2}} \tag{12}$$

Nusselt number

The rate of heat flux q_w at wall is defined as $q_w = -\kappa\left(\frac{\partial T}{\partial y}\right)_{y=0}$ therefore, the Nusselt number is given by

$$Nu = \frac{x\, q_w}{(T_w - T_{\infty})\kappa} = -\theta'(0)\,\mathrm{Re}_x^{1/2} \tag{13}$$

NUMERICAL SOLUTION

The transformed equations (8) - (10) under the boundary conditions (11) are to be solved computationally using fourth order Runge Kutta method with shooting technique (missing and guessing). We assumed the unspecified initial conditions for unknown variables and the checked by comparing the calculated value of the different variables at the terminal point with its given value there. The calculations are carried out by a program in MATLAB package.

RESULTS AND DISCUSSIONS

The purpose of this section is to analyses the effects of various physical parameters on velocity, induced magnetic field and temperature therefore Figure (2) -(15) demonstrate the influence of substantial parameters embedded in the governing flow system.

Figure 2 -5 depict velocity distribution and induced magnetic field for different values of magnetic force number□. It is observed that velocity and induced magnetic field decrease as magnetic force number increases in both case when $□□ = 0.5$ and $□□ = 1.5$.

Figure 6 and Figure 7 exhibit the influence of magnetic Prandtl number $□□_{□}$ on induced magnetic field under two cases for $□□ = 0.5$ and $□□ = 1.5$. It is evident from Figure (6) and (7) that, increasing the magnetic Prandtl number leads to diminution in the induced magnetic field.

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Figure 8-11 reflects the impact of permeability parameter towards velocity and induced magnetic field within flow regime. We noticed an inverse relation between permeability parameter and velocity as well as for induced magnetic field i-e an increase in permeability parameter the velocity and induced magnetic field decrease.

Figure (12) and Figure (13) show the effect of Prandtl number on velocity and temperature distribution. Here velocity and temperature decrease as Prandtl number decrease. Figure (14) represents the temperature distribution for different values of magnetic Prandtl number. It’s found that temperature increases slightly with the increase of □□$_{□}$. Figure (15) portrays the temperature distribution for different values of Eckert number. It can be observed that temperature increases □□ increase.

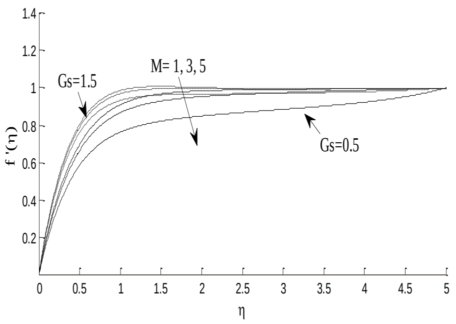

Figure 2. Velocity profile for different values of magnetic number

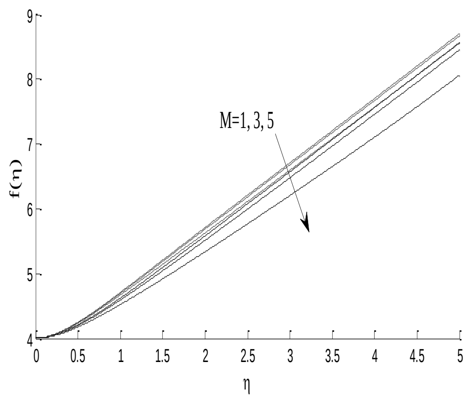

Figure 3. Velocity profile f for different values of magnetic number.

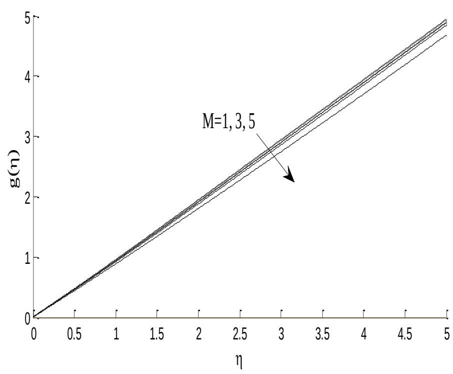

Figure 4. Induced magnetic field g for different values of magnetic number.

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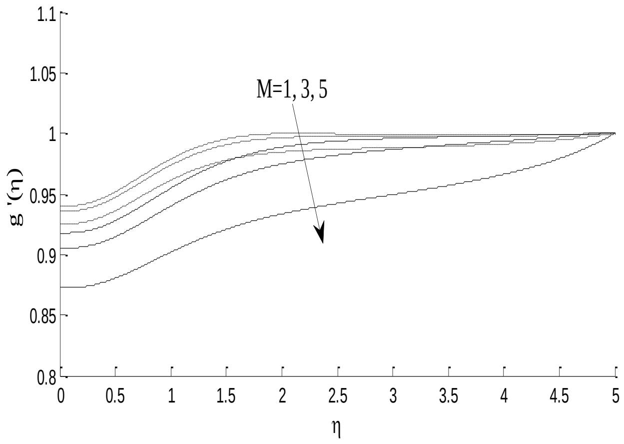

Figure 5. Induced magnetic field g' for different values of magnetic number.

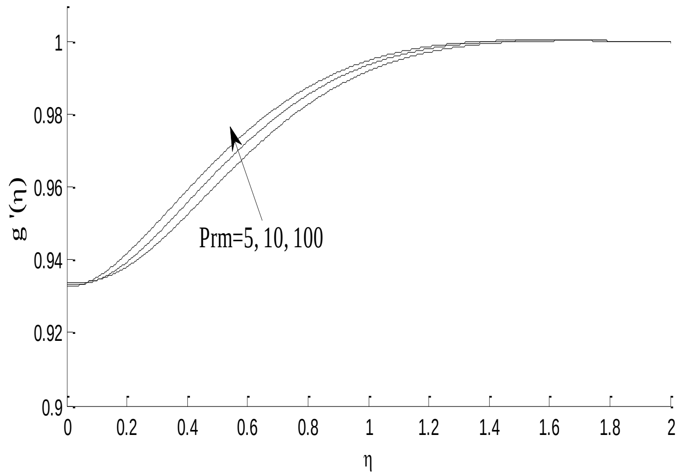

Figure 6. Induced magnetic field g' for different values of magnetic Prandtl number.

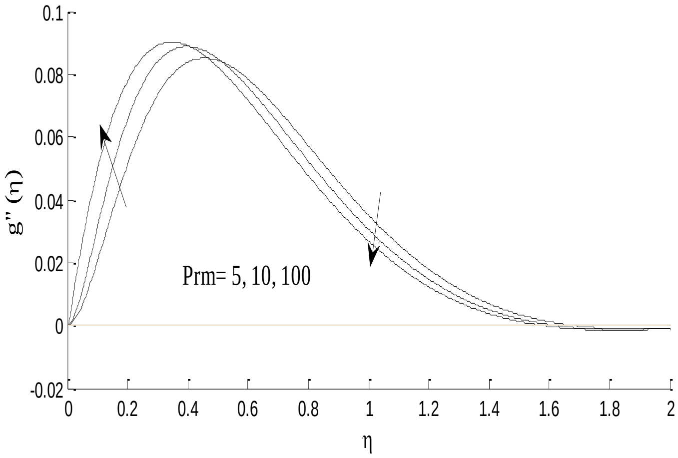

Figure 7. Induced current density g'' for different values of magnetic Prandtl number.

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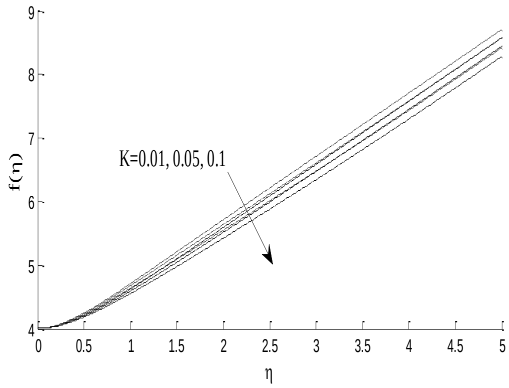

Figure 8. Velocity profile for different values of permeability parameter.

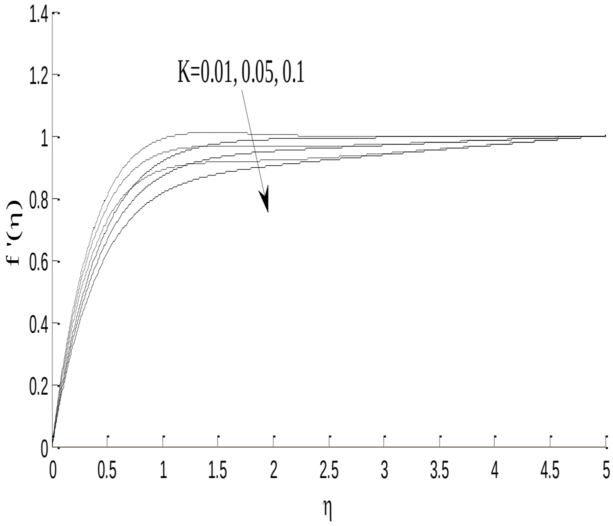

Figure 9. Velocity profile for different values of permeability parameter.

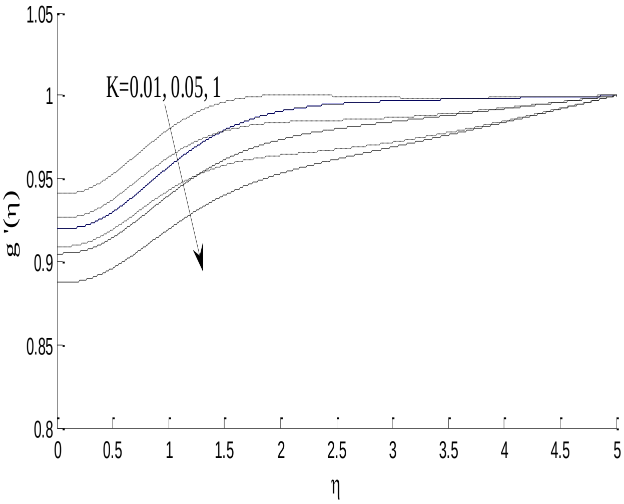

Figure 10. Induced profile for different values of permeability parameter.

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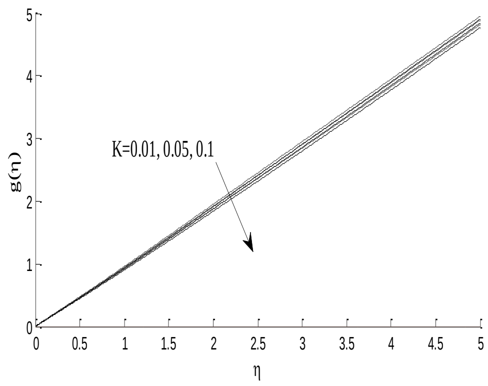

Figure 11. Induced profile for different values of permeability parameter

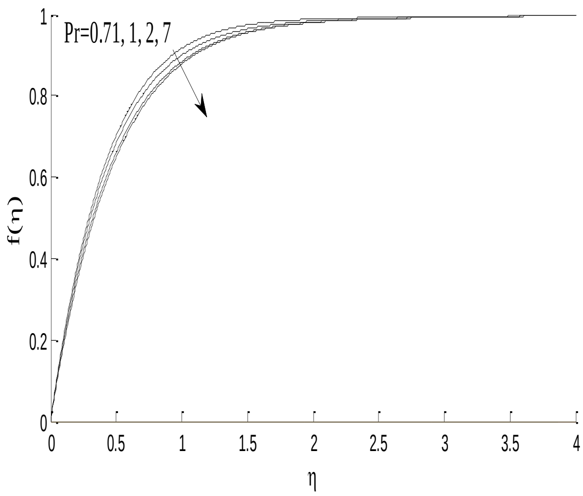

Figure 12. Influence of Prandtl number on velocity profile.

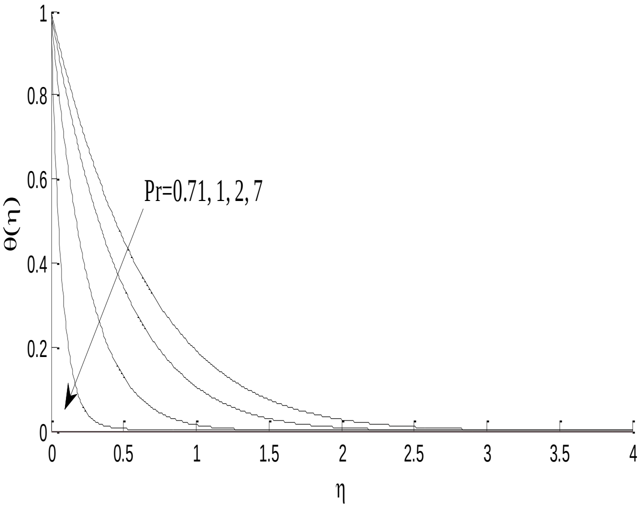

Figure 13. Influence of Prandtl number on temperature profile.

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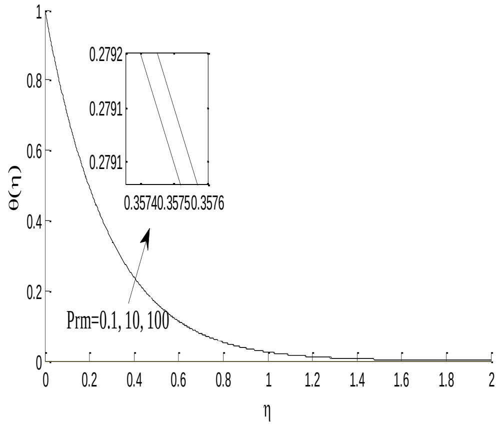

Figure 14. Influence of magnetic Prandtl number on temperature profile.

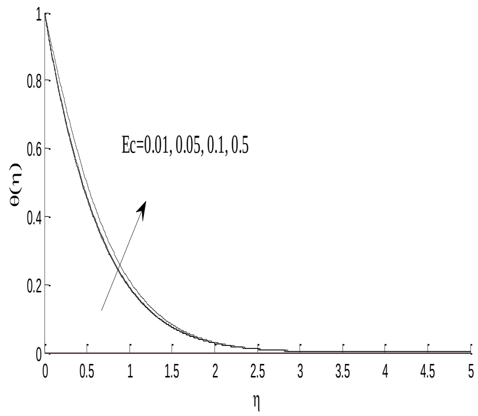

Figure 15. Influence of Eckert number on temperature profile.

Table 1 Numerical values of skin friction and Nusselt number.

M	K	$\Pr$	$\Pr_m$	G_s	Ec	f_w	$C_f \operatorname{Re}_x^{1/2}$	$Nu(\operatorname{Re}_x)^{-1/2}$
0.5	0.01	0.71	1	1.5	0.05	4	2.889668	-1.49998
5	0.01	0.71	1	1.5	0.05	4	2.74203	-1.4991
0.5	0.2	0.71	1	1.5	0.05	4	2.36299	-1.4966
0.5	0.01	1	1	1.5	0.05	4	2.7019352	-2.0519
0.5	0.01	0.71	2	1.5	0.05	4	2.857241	-1.540011
0.5	0.01	0.71	1	0.5	0.05	4	2.34121	-1.4998

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0.5	0.01	0.71	1	0.5	0.5	4	2.36168	-1.12311
0.5	0.01	0.71	1	1.5	0.05	3	2.48112	-1.24641

CONCLUSIONS

MHD free convection flow of viscous incompressible fluid over a vertical plate under the influence of induced magnetic field has been carried out. The dimensionless governing equations have been solved by using Runge-Kutta fourth order method with shooting technique. The effects of various parameters on the velocity, induced magnetic field and temperature profiles have been shown in the line graphs. The following conclusions have been drawn from the present analysis:

- The velocity, induced magnetic field have decreasing tendency with increase in the value of magnetic parameter and reverse tend occurs with the increase of local buoyancy parameter.
- An increase in magnetic Prandtl number, increases induced magnetic boundary layer but exerts negligible influence on the temperature in the boundary layer.
- Increasing porous parameter, causes a decrease in velocity and induced magnetic field also decreases the skin friction and Nusselt number.
- The effect of Prandtl number on the velocity, temperature, skin friction and Nusselt number is found to have a decreasing nature but Eckert number causes an enhancement in temperature, skin friction and Nusselt number.
- The magnitude of skin friction is higher for local buoyancy parameter and suction/injection parameter but reduces with magnetic parameter

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