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Free Convective Heat and Mass Transfer in the Presence of Magnetic Field with Thermally Stratified High-Porosity Medium

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Abstract The analytical solutions are performed to examine the MHD free convective heat and mass transfer flow with thermal diffusion of an incompressible viscous and electrically conducting fluid with large suction. The equivalent momentum, energy and concentration equations are formed by introducing the usual similarity transformations. Perturbation technique is used to solve the similarity equations. The effects of the various parameters entering into the problem on the velocity, temperature and concentration field are presented and showed the effect of variation with the values of other parameters. The major effect of changes are found for Prandtl number, Joule heating parameter, Soret number and suction parameter.

Keywords Free Convection, Heat Transfer, Mass Transfer, MHD Flow, Perturbation Technique

Introduction

Free convective heat and mass transfer in porous media has been received a world of careful attention because they frequently appear in many physical problems and engineering applications for contemporary technology such as geothermal systems, grain storage, fiber and granular insulation, packed sphere beds, heat exchangers, chemical catalytic reactors, petroleum reservoirs, coal combustors, nuclear waste repositories and filtration.

The convection problem in a porous medium has important applications in geothermal reservoirs and geothermal extractions. The process of heat and mass transfer is encountered in aeronautics, fluid fuel nuclear reactor, chemical process industries and many engineering applications in which the fluid is the working medium. The wide range of technological and industrial applications has stimulated considerable amount of interest in the study of heat and mass transfer in convection flows. Free convective flow past a vertical plate has been studied extensively by [1]. In [2], Siegel investigated the transient free convection from a vertical flat plate. In the above mentioned studies, the effect of porosity, permeability and the thermal resistance of the medium was ignored or treated as constant. However, porosity measurements by Benenati and Broselow [3] showed that, porosity is not constant but varies from the surface of the plate to its interior. In case of unsteady free convective flow, Soundalgekar [4] studied the effects of viscous dissipation on the flow past an infinite vertical porous plate. The combined effect of buoyancy forces from thermal and mass diffusion on forced convection was studied by Chen *et al.* [5]. Free convection flow near a vertical plate or surface with different conditions has been extensively studied by various authors, see, for example, [6-9]. Free convection flow with mass transfer past a vertical moving plate has been studied in the papers [10-15]. Various worked on hydro-magnetic natural convection flow past a vertical surface under different conditions was performed by Revankar [16], Anwar [17] and Sahoo *et al.* [18].

Two decades ago, many investigators have been studied the problem of boundary layer natural convection along an isothermal vertical surface [19-22] with thermally stratified saturated porous medium. The stratified situation occurs, for example, in cooling ponds, lakes solar ponds, and in the atmosphere. The effects of heat and mass transfer on a free convection flow near an infinite vertical porous plate has been extensively investigated numerically by Hossain *et al*. [23], Israel *et al*. [24], Sahoo *et al*. [25], Ali [26], Chaudhary and Jain [27]. Alam and Sattar [28] studied the steady two dimensional MHD free convective and mass transfer flow with thermal diffusion and large suction past an infinite vertical porous plate in rotating system. Effects on non-uniform wall temperature or mass transfer in finite suctions of an inclined plate on the MHD free convection flow in a temperature stratified high-porosity medium was studied by Takhar *et al*. [29]. Recently, Rushi Kumar and Nagarajan [30] studied the mass transfer effects of MHD free convection flow of incompressible viscous dissipative fluid past an infinite vertical plate. Mass transfer effects on free convection flow of an incompressible viscous dissipative fluid have been studied by Manohar and Nagarajan [31]. Sivaiah *et al*. [32] studied heat and mass transfer effects on MHD free convective flow past a vertical porous plate. Sharma *et al*. [33] analyzed radiation and heat source effect on MHD free convection flow with heat and mass transfer past a vertical porous plate. Hence it appears that the analytical solution of this problem will be of greater interest.

In recent time, Ibrahim and Suneetha did the work on MHD free convection boundary layer flow of radiation in porous medium [34]. Another work of Reddy [35], on thermal radiation was done in convection boundary layer flow of a nanofluid past a vertical plate. Fluid flow and heat transfer analysis of a nanofluid was investigated numerically by Mehryan *et al.* [36] and in very recent time, another paper on boundary layer analysis of an incessant moving needle in MHD radiative nanofluid with joule heating was published [37].

Hence our aim is to study of the steady two dimensional problem of the MHD free convective heat and mass transfer flow past an infinite vertical porous plate with thermally stratified medium. Similarity equations are derived by introducing usual similarity transformation and obtained non-linear ordinary coupled differential equations. Then the obtained non-dimensional non-linear differential equations are solved analytically by perturbation technique.

Mathematical Model

Consider a model of steady MHD free convective and mass transfer flow past an infinite vertical porous plate which is thermally stratified. For this problem let us consider a steady free convective and mass transfer flow of an electrically conducting viscous fluid through a porous medium along a semi-infinite vertical porous plate $y=0$ in a rotating system with large suction under the influence of a transversely applied magnetic field. The flow is also assumed to be in the x-direction which is taken along the plate in the upward direction and y-axis is normal to it. Initially the fluid as well as the plate is at rest, after that the whole system is allowed to rotate with a constant angular velocity $\Omega=\left(0,-\Omega,0\right)$ about the y–axis. The temperature and the species concentration at the plate are constantly raised from T_w and C_w to T_∞ and C_∞ respectively, which are thereafter maintained constant, where T_∞ and C_∞ are the temperature and species concentration of the uniform flow respectively. A uniform magnetic field B is taken to be acting along the y-axis which is assumed to be electrically non-conducting. The magnetic Reynolds number of the flow is considered to be small enough so that the induced magnetic field is negligible in comparison with applied one [38], so that $B=\left(0,\beta_0,0\right)$ and the magnetic lines of force are fixed relative to the fluid. The equation of conservation of charge $\nabla.J=0$ gives $J_y=$constant, where the current density $J=\left(J_x,J_y,J_z\right)$. Since the plate is electrically non-conducting, this constant is zero and hence $J_y=0$ at the plate in everywhere. The physical configuration considered here is shown in the Figure 1.

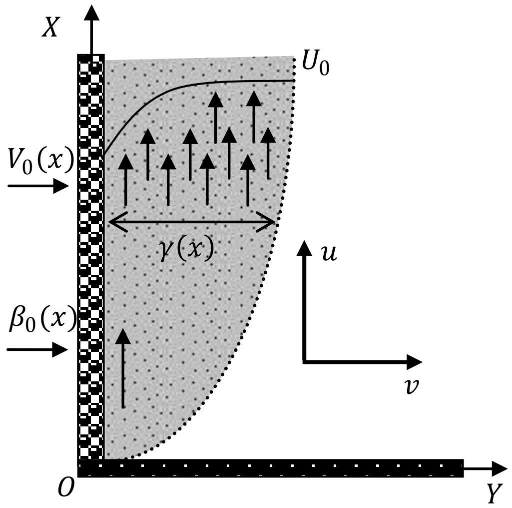

Figure 1: Geometrical configuration of boundary layer and coordinate system

With reference to the generalized equations the two dimensional problem under the above assumptions and Boussinesq approximation can be put in the following form:

The continuity equation $\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$ (1)

Momentum equations

$$\frac{1}{\varepsilon^2}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)-2\Omega w=\frac{\nu}{\varepsilon}\frac{\partial^2 u}{\partial y^2}+g\beta\left(T-T_\infty\right)+g\beta^*\left(C-C_\infty\right)-\frac{\nu}{k}u-cu^2-\frac{\sigma\beta_0{}^2u}{\rho} \quad (2)$$

$$\frac{1}{\varepsilon^2}\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}\right)+2\Omega u=\frac{\nu}{\varepsilon}\frac{\partial^2 w}{\partial y^2}-\frac{\nu}{k}w-cw^2-\frac{\sigma\beta_0{}^2w}{\rho} \quad (3)$$

Energy equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2}+\frac{1}{\varepsilon^2}\frac{\nu}{c_p}\left[\left(\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial w}{\partial y}\right)^2\right]+\frac{\sigma\beta_0{}^2}{\rho c_p}\left[u^2+w^2\right] \quad (4)$$

Concentration equation

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}+\frac{Dk_T}{T_m}\frac{\partial^2 T}{\partial y^2} \quad (5)$$

with the corresponding initial and boundary conditions are:

$$\left.\begin{array}{lll} u=U_0,\ v=v_0\left(x\right),\ w=0,\ T=T_w,\ C=C_w & \text{at} & y=0 \\ u=0,\ v=0,\ w=0,\ T\to T_\infty,\ C\to C_\infty & \text{as} & y\to\infty \end{array}\right\} \quad (6)$$

where u,v,w are the velocity components in the x,y,z direction respectively, ν is the kinetics viscosity, g is the acceleration due to gravity, ρ is the density, β is the coefficient of volume expansion, β^* is the volumetric coefficient of expansion with concentration. k^* is the permeability of the porous medium, k is the thermal conductivity of the medium, D is the coefficient of mass diffusivity, c_p is the specific heat at constant pressure, T_m is the mean fluid temperature, k_T is the thermal diffusion ratio and other symbols have their usual meaning.

To solve the above system of Eqs (1)-(5) under the boundary conditions (6), the well defined similarity analysis has been adopted to attain similarity solutions. For this purpose, the following dimensionless variables have been introduced as:

$$\eta = y\sqrt{\frac{U_o}{2\nu x}}\ ,\ u = U_o f'(\eta)\ ,\ w = U_o g_o(\eta),\ \theta(\eta) = \frac{T - T_\infty}{T_{w-T_\infty}},\ \varphi(\eta) = \frac{C - C_\infty}{C_{w-C_\infty}} \tag{7}$$

Thus the Eqs (2)-(5), reduces to the following dimensionless ordinary nonlinear coupled differential equations:

$$f''' + \frac{1}{\varepsilon} ff'' + \varepsilon G_r \theta + \varepsilon G_m \varphi - \left(k^* + M\right)\varepsilon f' - \varepsilon Q f'^2 + \varepsilon R g_0 = 0 \tag{8}$$

$$g_0'' + \frac{1}{\varepsilon} f g_0' - \left(k^* + M\right)\varepsilon g_0 - \varepsilon Q g_0^{\ 2} - \varepsilon R f' = 0 \tag{9}$$

$$\theta'' + P_r f\theta' + \frac{1}{\varepsilon^2} P_r E_c\left[f''^2 + g_o'^2\right] + P_r J_H\left[f'^2 + g_o^{\ 2}\right] = 0 \tag{10}$$

$$\varphi'' + S_c f\varphi' + S_c S_o \theta'' = 0 \tag{11}$$

Subject to the above formulations the boundary conditions (6) now transform to:

$$\left.\begin{array}{ll} f = f_w\ ,\quad f' = 1\ ,\quad g_o = 0\ ,\quad \theta = 1\ ,\quad \varphi = 1 & at\ \ \eta = 0 \\ f' = 0,\quad g_o = 0\ ,\quad \theta = 1\ ,\quad \varphi = 1 & as\ \ \eta \to \infty \end{array}\right\} \tag{12}$$

where the notation prime denote differentiation with respect to η and the parameters are defined as:

$G_r = \frac{2xg\beta}{U_0^{\ 2}}\left(T_w - T_\infty\right)$ = Grashof number $G_m = \frac{2xg\beta^*}{U_0^{\ 2}}\left(C_w - C_\infty\right)$ = modified Grashof number

$K^* = \frac{2\nu x}{KU_0}$ = Permeability parameter $Q = 2xc$ = Inertia resistance

$M = \frac{2x\sigma\beta_0^{\ 2}}{\rho U_0}$ = Magnetic parameter $R = \frac{4x\Omega}{U_0}$ = Rotational parameter

$P_r = \frac{\nu\rho c_p}{k}$ = Prandlt number $E_c = \frac{U_0^{\ 2}}{c_p\left(T_w - T_\infty\right)}$ = Eckert number

$J_H = \frac{\sigma\beta_0^{\ 2}}{\rho c_p}\frac{2xU_0}{\left(T_w - T_\infty\right)}$ = Joule-Heating parameter $S_c = \frac{\nu}{D}$ = Schmidt number

$S_0 = \frac{Dk_T}{T_m \nu}\frac{\left(T_w - T_\infty\right)}{\left(C_w - C_\infty\right)}$ = Soret number

To obtain the solutions, the following transformations have been considered as:

$$\left.\begin{array}{l} \xi = \eta f_w,\quad f(\eta) = f_w F(\xi),\quad g_o(\eta) = f_w^{\ 2} G(\xi) \\ \quad \theta(\eta) = f_w^{\ 2} H(\xi),\qquad \varphi(\eta) = f_w^{\ 2} P(\xi) \end{array}\right\} \tag{13}$$

The above Eqs (8)-(11) become:

$$F''' + \frac{1}{\varepsilon} FF'' + \varepsilon G_r H\delta + \varepsilon G_m P\delta - \varepsilon\left(k^* + M\right)F'\delta - \varepsilon QF'^2 + \varepsilon RG\delta = 0 \tag{14}$$

$$G'' + \frac{1}{\varepsilon} FG' - \left(k^* + M\right)\varepsilon G\delta - \varepsilon QG^2 - \varepsilon RF'\delta = 0 \tag{15}$$

$$H'' + P_r F H' + \frac{1}{\varepsilon^2} P_r E_c \frac{1}{\delta}\left[F''^2 + G'^2\right] + P_r J_H \left[F'^2 + G^2\right] = 0 \quad (16)$$

$$P'' + S_c F P' + S_c S_o H'' = 0 \quad (17)$$

where, $\delta = \frac{1}{f_w^{\,2}}$ is very small as for large suction $f_w > 1$.

Now the boundary conditions (12) reduce as:

$$\left.\begin{array}{l} F = 1\,,\ F' = \delta\,,\ G = 0\,,\ H = \delta\,,\ P = \delta \quad at\ \xi = 0 \\ F' = 0\,,\quad G = 0\,,\quad H = 0\,,\quad P = 0 \quad as\ \xi \to \infty \end{array}\right\} \quad (18)$$

Therefore, following Bestman (1990), F, G, H and P can be expanded in terms of small perturbation quantity δ as:

$$F(\xi) = 1 + \delta F_1 + \delta^2 F_2 + \delta^3 F_3 + \cdots\cdots\cdots \quad (19)$$

$$G(\xi) = \delta G_1 + \delta^2 G_2 + \delta^3 G_3 + \cdots\cdots\cdots \quad (20)$$

$$H(\xi) = \delta H_1 + \delta^2 H_2 + \delta^3 H_3 + \cdots\cdots\cdots \quad (21)$$

$$P(\xi) = \delta P_1 + \delta^2 P_2 + \delta^3 P_3 + \cdots\cdots\cdots \quad (22)$$

Then substituting $F(\xi), G(\xi), H(\xi)$ and $P(\xi)$ from (19)-(22) in the Eqs (14)-(17) the set of ordinary differential equations and the boundary conditions for $F_i(\xi), G_i(\xi), H_i(\xi)$ and $P_i(\xi)(i = 1,2,3\ldots\ldots)$ have been obtained.

Results and Discussion

In this paper, free convective heat and mass transfer flow in the presence of magnetic field with thermally stratified high-porosity medium have been investigated and the obtained system of dimensionless non-linear differential equations are solved analytically by perturbation technique. To study the physical situation of this problem, the analytical results of primary velocity $f'(\eta)$, secondary velocity $g_o(\eta)$, temperature $\theta(\eta)$ and concentration $\varphi(\eta)$ have been computed.

For different values of P_r (Prandtl number), E_c (Eckert number), J_H (Joule Heating parameter), S_o (Soret number), K (Permeability parameter), M (Magnetic parameter), f_w (Suction parameter) and fixed values of G_r (Grashof number) and G_m (Modified Grashof number), the velocities, temperature and concentration distributions have been presented graphically. The value of G_r is taken to be large ($G_r = 4 \text{and} 5$) through out the whole calculations. For Prandtl number P_r, three values 0.71, 1.0 and 7.0 ($P_r = 0.71$ for air, $P_r = 1.0$ for solid water and $P_r = 7.0$ for water) are considered and 0.6 of the Schmidt number S_c is considered for those which represent specific conditions of the flow. In the calculations E_c ,J_H ,S_o ,K ,M ,f_w and G_m are chosen arbitrarily.

The effects of various parameters on the primary and secondary velocities are shown in Figures (2)-(15). With the above mentioned flow parameters, it is observed from Figures (2) and (9) that the increase of the value of Prandtl number P_r leads to a decrease the primary velocity and increase the secondary velocity. The variations of the primary and secondary velocities for different values of Eckert number E_c are shown in Figures (3) and (10). From these figures it is observed that both the primary and secondary velocities have a minor increasing effect for different values of E_c. From Figures (4) and (11), for different values of Joule Heating parameter J_H, there has a minor increasing effect on the primary and secondary velocity.

Now, Figures (5)and (12) show the effects of Soret number S_o on the primary and secondary velocity profiles. It is observed that the primary velocity increases with the increase of Soret number S_o and for the secondary velocity, the effects of Soret number S_o are opposite to that of the primary velocity.

In Figures (6), (7)and (13), (14) the variations of the primary and secondary velocities for different values of permeability parameter K and magnetic parameter M are shown respectively. From these figures it is also observed that the primary velocity decreases with the increase of K and increases with the decrease of M. On the other hand, for same values of K and M, the secondary velocity has a minor increasing effect at a certain level.

With the above mentioned flow parameters, it is seen from Figures (8) and (15) that the increase of the suction parameter f_w leads to a decrease the primary velocity and increase the secondary velocity.

The effects of various parameters on non-dimensional temperature are shown in Figures (16)-(22). It is noted from Figure (16) that the Prandtl number P_r increases due to the decrease of temperature. In Figure (17) temperature presents a minor increasing effect for different values of E_c.

The variation of temperature for different values of Joule Heating parameter and Soret number are shown in Figures (18) and (19) respectively. It is observed from these figures that J_H has an increasing effect while S_o has a decreasing effect. In Figures (20) and (21), the temperature profiles for different values of permeability parameter K and magnetic parameter M are shown respectively. For both of them, they have a minor increasing effect on the temperature. In Figure (22), it is seen that the temperature decreases as the suction parameter f_w increases.

The effects of various parameters on the concentration field are shown in Figures (23)-(29). It is presented from Figure (23) that the concentration decreases as the P_r increases and found a minor increasing effect of different values of E_c in Figure (24).

The variation of concentration for different values of J_H and S_o are shown in Figures (25) and (26) respectively. It is observed from these figures that J_H has a minor increasing effect while S_o has a large increasing effect. From Figures (27) and (28), different values of K and M are shown as the function of concentration profiles. For both K and M have a minor increasing effect on the concentration. In Figure (29), it is seen that the concentration decreases as the suction parameter f_w increases.

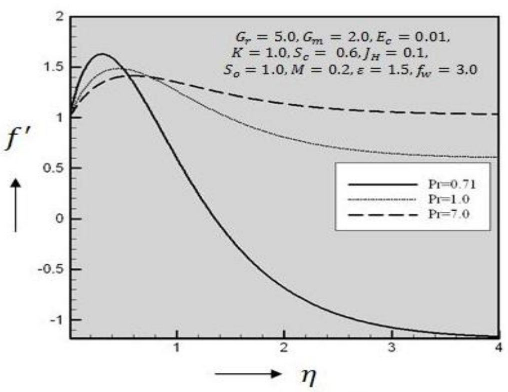

Figure 2: Primary velocity profiles for different values of P_r

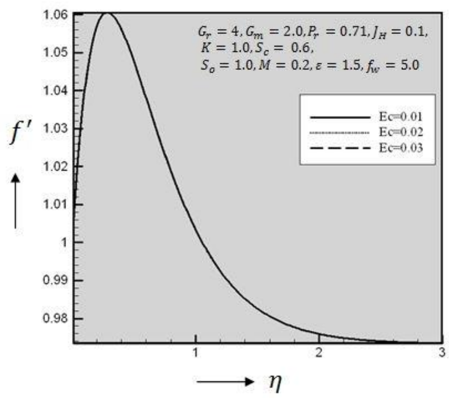

Figure 3: Primary velocity profiles for different values of E_c

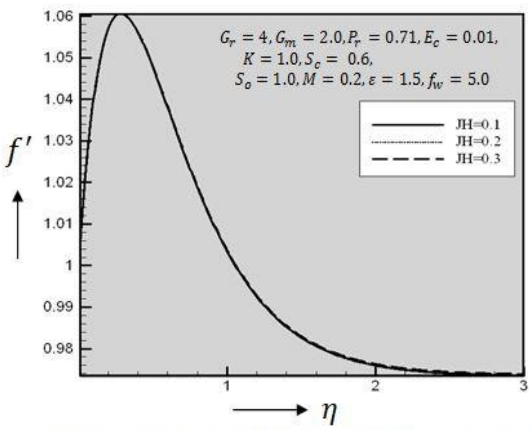

Figure 4: Primary velocity profiles for different values of J_H

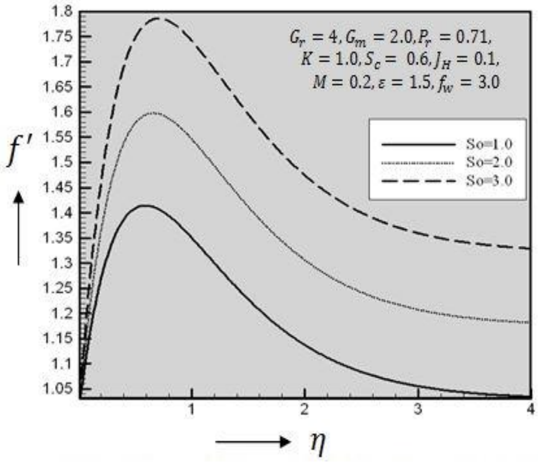

Figure 5: Primary velocity profiles for different values of S_o

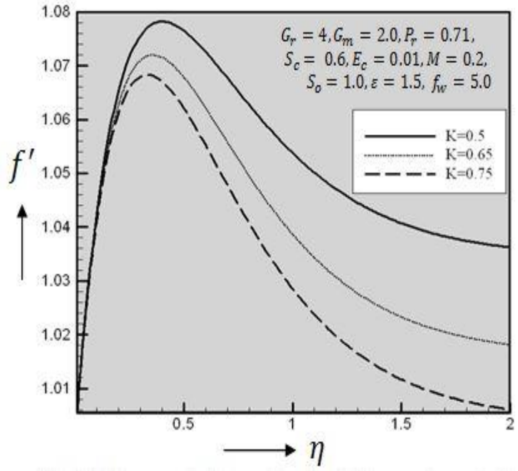

Figure 6: Primary velocity profiles for different values of K

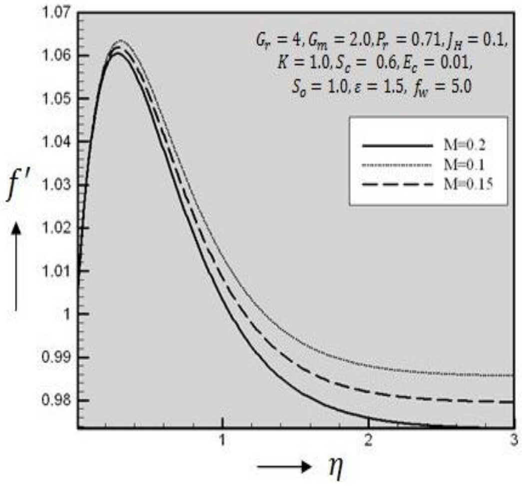

Figure 7: L Primary velocity profiles for different values of M

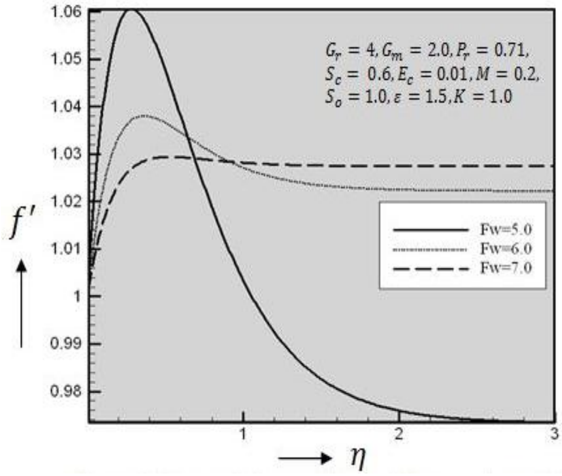

Figure 8: Primary velocity profiles for different values of f_w

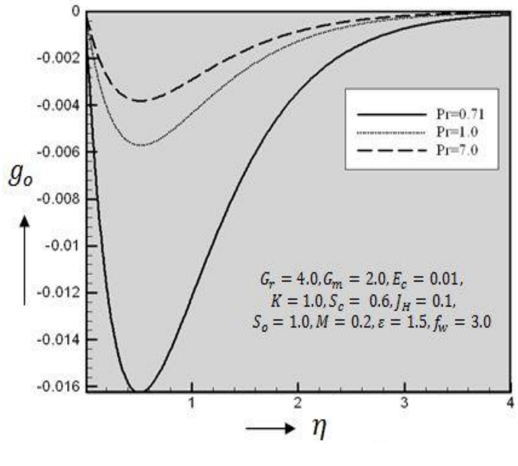

Figure 9: Secondary velocity profiles for different values of P_r

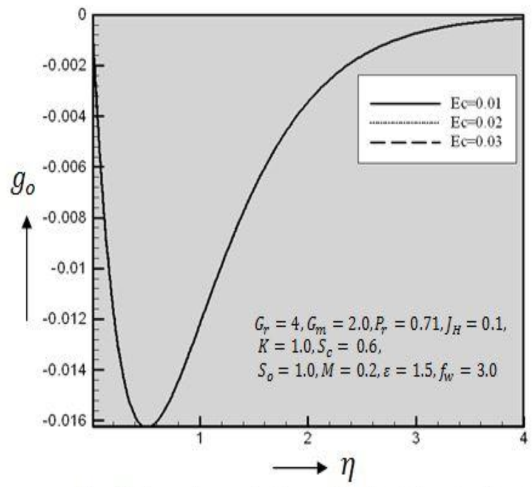

Figure 10: Secondary velocity profiles for different values of E_c

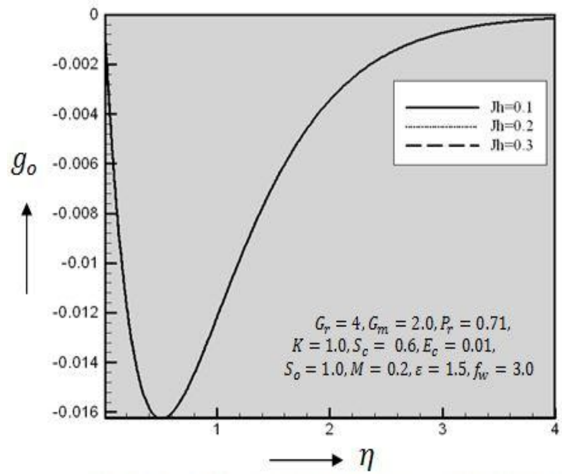

Figure 11: Secondary velocity profiles for different values of J_H

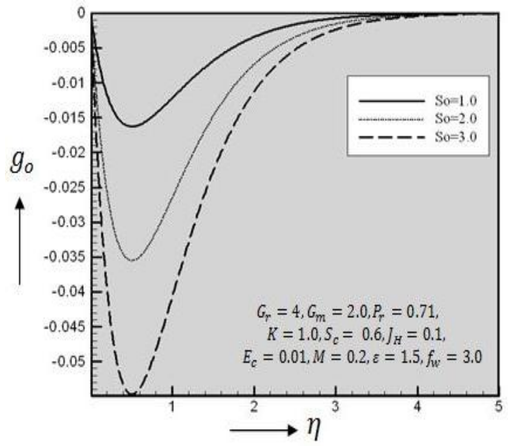

Figure 12: Secondary velocity profiles for different values of S_o

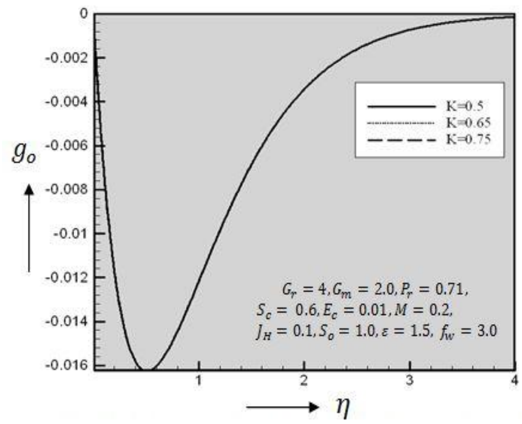

Figure 13: Secondary velocity profiles for different values of K

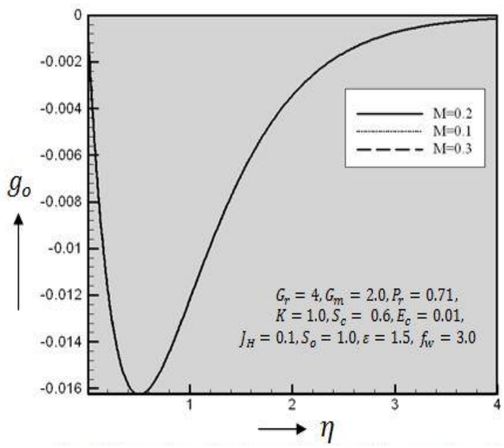

Figure 14: Secondary velocity profiles for different values of M

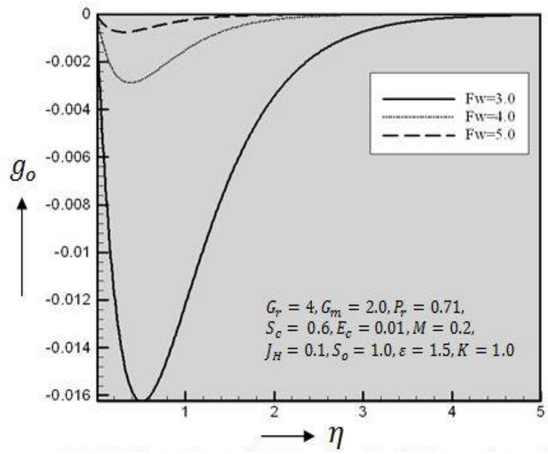

Figure 15: Secondary velocity profiles for different values of f_w

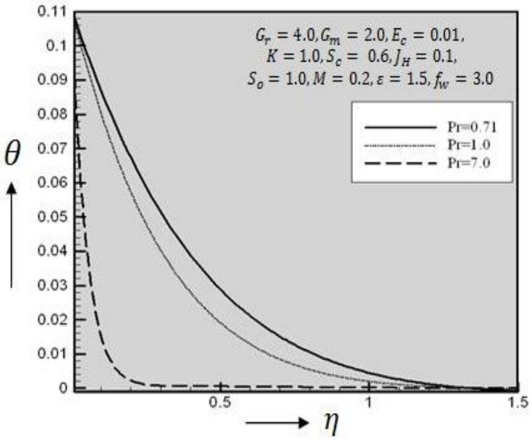

Figure 16: Temperature profiles for different values of P_r

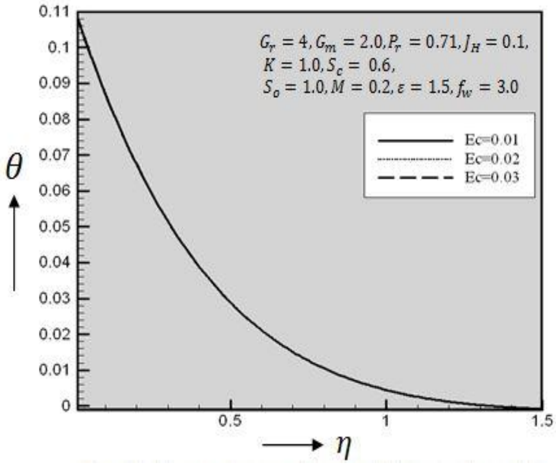

Figure 17: Temperature profiles for different values of E_c

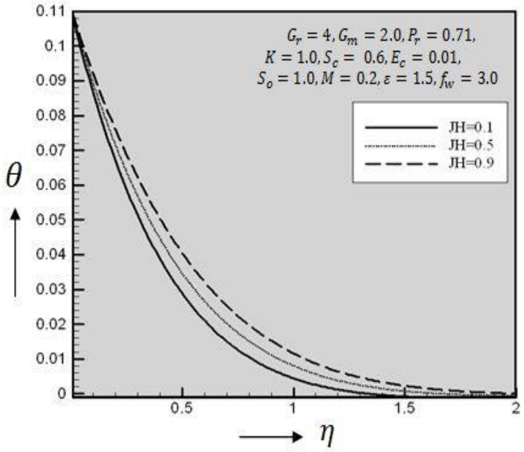

Figure 18: Temperature profiles for different values of J_H

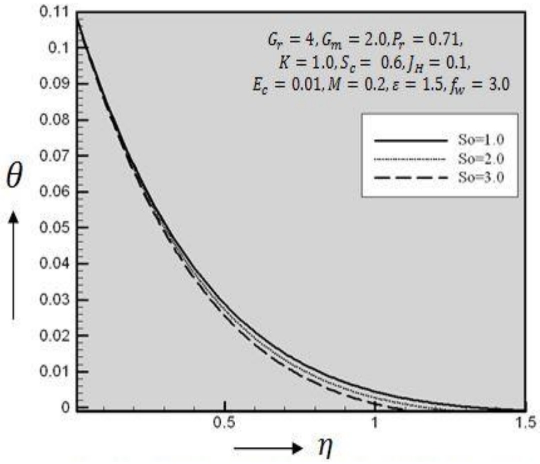

Figure 19: Temperature profiles for different values of S_o

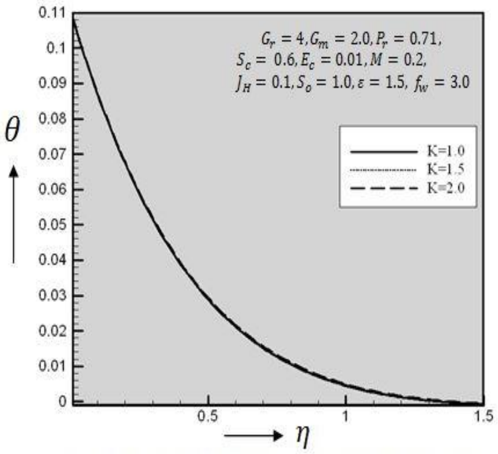

Figure 20: Temperature profiles for different values of K

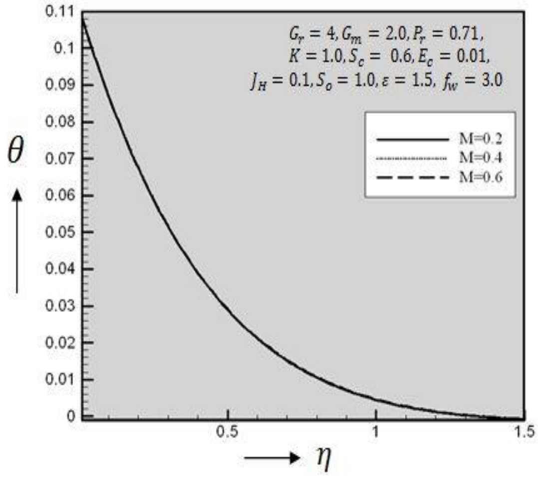

Figure 21: Temperature profiles for different values of M

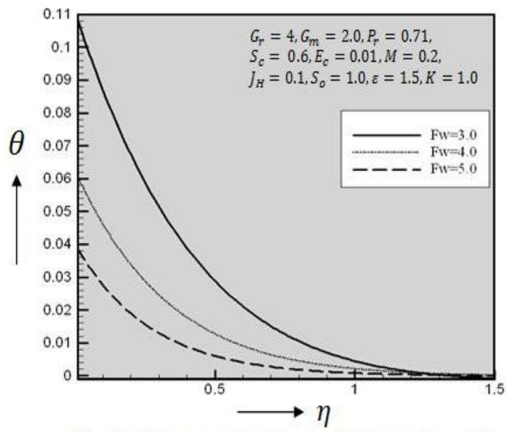

Figure 22: Temperature profiles for different values of f_w

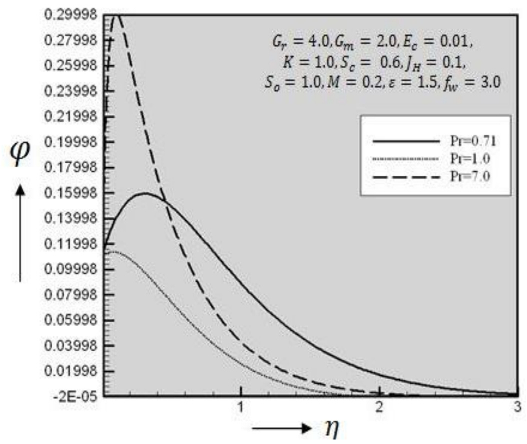

Figure 23: Concentration profiles for different values of P_r

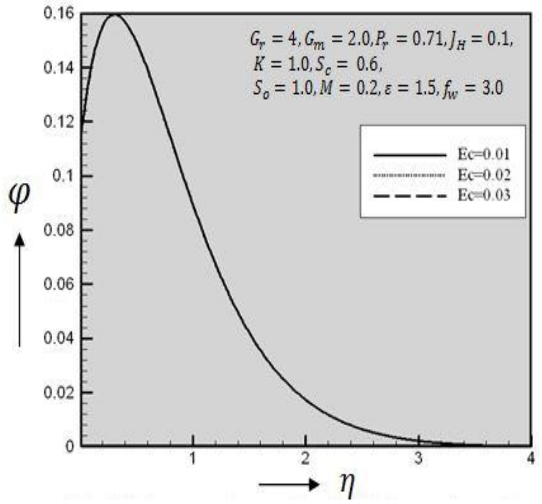

Figure 24: Concentration profiles for different values of E_c

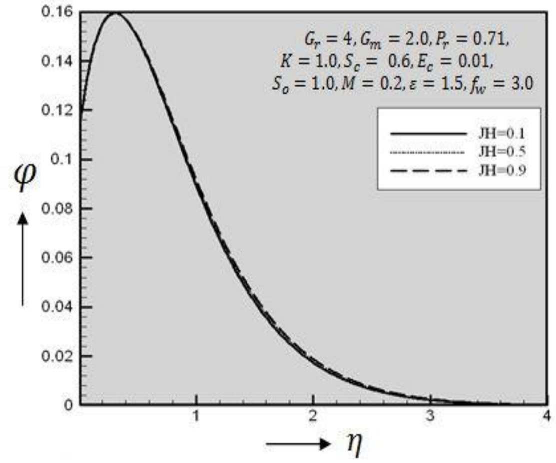

Figure 25: Concentration profiles for different values of J_H

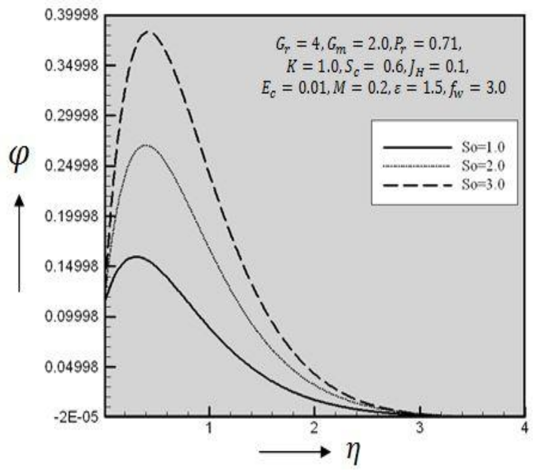

Figure 26: Concentration profiles for different values of S_o

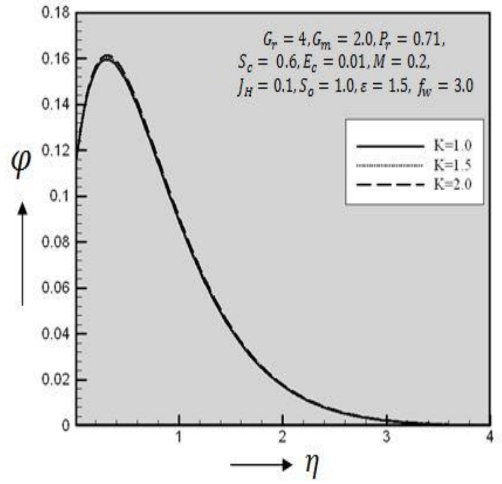

Figure 27: Concentration profiles for different values of K

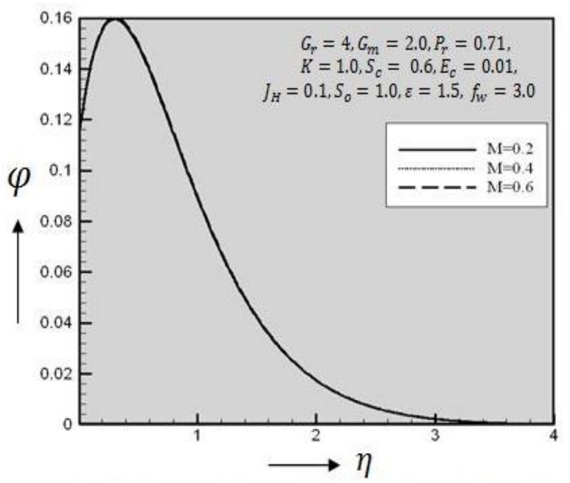

Figure 28: Concentration profiles for different values of M

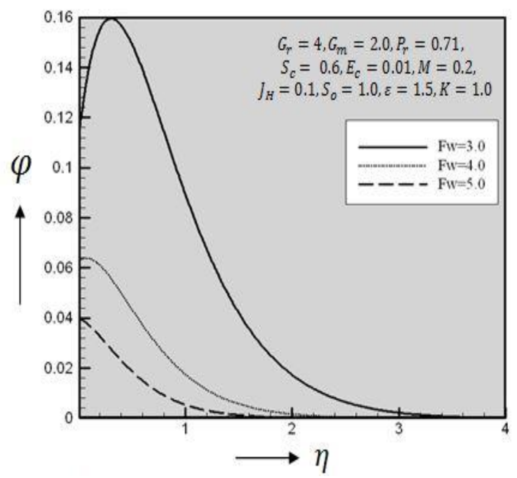

Figure 29: Concentration profiles for different values of f_w

Conclusions

The present work on free convection heat and mass transfer flow on MHD of a fluid past an infinite vertical porous plate with thermally stratified medium was studied. This study was found applications in geothermal reservoirs and geothermal extractions. The wide range of technological and industrial applications has been stimulated considerable amount of interest in the study of heat and mass transfer in convection flows. The governing equations were approximated to a system of non-linear ordinary coupled differential equations by similarity transformation. Perturbation technique has been used to solve the problem. The effects of various parameters such as Prandlt number, Permeability parameter, Magnetic parameter, Rotational parameter, Eckert number, Joule-Heating parameter, Schmidt number, Soret number, suction parameter respectively were examined. The following conclusions were drawn as:

1. For Suction parameter, primary velocity, temperature, concentration decreases while secondary velocity increases.
2. For Soret number, primary velocity and concentration increase, on the other hand, secondary velocity and temperature decrease.
3. For Joule-heating parameter, primary velocity, secondary velocity and concentration have a minor increasing effect but temperature increases.

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