*Journal of Scientific Research and Development (2023) Vol. 22 (1) 70-93*

***A bi-annual journal published by the Faculty of Science, University of Lagos, Nigeria***
http://jsrd.unilag.edu.ng/index.php/jsrd

# Numerical investigation of an unsteady magnetohydrodynamic boundary layer flow over a permeable surface with suction and chemical reaction

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*(Received 09 March 2023/Revised 18 May 2023/Accepted 20 May 2023)*

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**Abstract**

This work investigates an unsteady magnetohydrodynamics(MHD) of an electrically conducting boundary layer flow over a permeable vertical surface with suction and chemical reaction. Appropriate similarity variables are used to transform the time-dependent system of partial differential equations governing the fluid flow to a boundary value problem of coupled ordinary differential equations and the problem is solved numerically using a fourth order Runge-Kutta-Fehlberg integration scheme with shooting method. The influence of various thermophysical parameters in the flow field on velocity and temperature profiles, Skin friction, Nusselt number, suction and chemical reaction are presented graphically and discussed quantitatively. The computational results of the Skin friction and nusselt number for this work are in excellent agreement with extended work in literature. Results show that increase in suction parameter decrease the momentum boundary layer with the profile tending asymptotically to free stream value away from the plate thereby increasing the fluid motion in the boundary layer region. The fluid concentration is highest at the surface and decreases exponentially to the free stream zero value satisfying the prescribed far field boundary condition.

**Keywords**: Unsteady Flow, Magnetohydrodynamics (MHD), Boundary layer, Permeable surface, Suction, Chemical reaction

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## NOMENCLATURE

| Symbols | Physical Quantities | Units |
|---|---|---|
| $\rho$ | Fluid density | $kgm^{-3}$ |
| $\nu$ | Kinematic viscosity | $m^2s^{-1}$ |
| $u$ | Fluid velocity | $ms^{-1}$ |
| $\mu$ | Dynamic viscosity | $kgm^{-1}s^{-1}$ |
| $\mu_e$ | Magnetic permeability of the medium | |
| $T_\infty$ | Free-stream temperature | $K$ |
| $u_\infty$ | Free-stream velocity | $ms^{-1}$ |
| $\alpha$ | Thermal diffusivity | $m^2s^{-1}$ |
| $C_p$ | Specific heat at constant pressure | $Jkg^{-1}K^{-1}$ |
| $k$ | Thermal conductivity | $Wm^{-1}K^{-1}$ |
| $J$ | Electric current density | $Am^{-2}$ |
| $H$ | Magnetic field | $Am^{-1}$ |
| $B$ | Magnetic field induction | Tesla or $Weber\ m^{-2}$ |
| $Ns$ | Entropy Generation Rate | |
| $Nr$ | Thermal radiation parameter | |
| $Nu$ | Nusselt number | |
| $\lambda$ | Velocity slip parameter | |
| $L$ | Velocity slip length | |
| $\delta$ | Temperature jump parameter | |
| $E$ | Electric field | $NCoulomb^{-1}$ |
| $\sigma$ | Electrical conductivity | $siemens\ m^{-1}$ |

**Introduction**

Ludwig Prandtl (1904) was the German fluid dynamist, physicist and aerospace scientist who proposed the boundary layer theory when he presented a paper on the science of aerodynamics at a third International Mathematics Congress in Heidelberg, Germany. The boundary layer theory has gained global acceptance and it is now applicable in aerodynamics, hydrodynamics and meteorology such as design of airplanes, engine components, micro-electro-mechanical systems like micro magnetohydrodynamics pumps, micro-electronic devices, rapid mixing of fluids in biological processes, biological transportation and drug delivery. Chiam(1993) investigated Magnetohydrodynamic boundary layer flow due to a continuously moving flat plate using the local non singularity method. Abel and *et al.* (2010) worked on hydromagnetic boundary layer flow and heat transfer in viscoelastic fluid over a continuously moving permeable stretching surface with non uniform heat source/sink embedded in fluid-saturated porous medium by using power series method where the solutions are obtained in terms of kummer's function. Bhattacharya and Layek (2010) investigated the chemically reactive solute distribution in hydromagnetic boundary layer flow over a permeable stretching sheet with suction or blowing using the finite difference method of quasi-linearization technique. Chandran *et al.* (2010) worked on boundary layer flow of electrically conducting liquids near an accelerated vertical plate and obtained a unified exact solution for the boundary layer velocity and skin friction for cases of magnetic field being fixed relative to the fluid or the vertical plate. Ashraf and Kamal (2011) investigated the numerical study of MHD boundary layer stagnation point flow and heat transfer of a micro polar fluid flow over a permeable horizontal surface with injection and suction effects by using an algorithm based on finite difference discretization. Mukhopadhyay (2011) examined with a shooting method a chemically reactive solute transfer in a boundary layer slip flow along a stretching cylinder. Shama *et al.* (2013) worked on boundary layer flow and heat transfer over a permeable exponentially shrinking sheet in the presence of thermal radiation with thermal slip and solve the problem numerically by using MATLAB routine solver. Mukhopadhyay (2013) used shooting method to investigate the slip effects on MHD boundary layer flow by an exponentially stretching sheet with suction/blowing and thermal radiation. Mutuku *et al.* (2014) investigated hydro magnetic boundary value flow of Nano fluid over a permeable moving surface with Newtonian heating using Shooting iteration technique together with fourth order Runge-Kutta-Fehlberg iteration scheme. Chandarki (2015) used series solution method to investigate an MHD flow over a stretching permeable surface. Choudhary *et al* (2015) used a fourth order Runge-Kutta Method with Shooting technique to examine an unsteady MHD flow and heat transfer over a stretching permeable surface with suction or injection. Hirschom *et al.* (2015) analyzed the magnetohydrodynamic boundary layer slip flow and heat transfer of a power law fluid over a flat plate by using MATLAB's boundary value solver and shooting method. Hayat *et al* (2016) solved analytically the hydromagnetic boundary layer flow problem of Williamson fluid in the presence of thermal radiation and ohmic dissipation. Yirga (2016) used Keller Box Method to examine the hydromagnetic boundary later flow of Nano fluids over a permeable moving surface with partial slip in the presence of Newtonian heating. Shateyi and Muzara (2020) worked on the numerical analysis of unsteady MHD boundary layer flow of a Williamson fluid over a stretching sheet and heat and mass transfer by using spectral quasilinear method. This paper extends the work of Mohammad and Makinde (2017) with suction and chemical reaction.

**Materials and Method**

This work considers an unsteady mixed convective flow of an incompressible, electrically conducting and optically dense . fluid over a vertical surface with chemical reaction. It is assumed that the surface of the plate is permeable, fixed and slippery, the y-axis is along the plate surface and x-axis is orthogonal to it. A magnetic field of strength $H_0$ is applied normal to the plate surface and the magnetic Reynolds number $(Re_m)$ is assumed to be small so that the induced magnetic field is neglected in comparison with the applied magnetic field. The physical flow model and coordinate system is as shown in Figure 1.

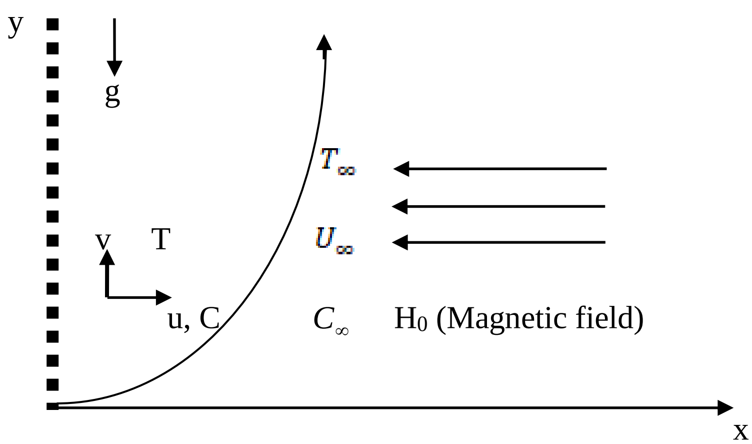


**Figure** 1: Flow geometry and coordinate system

The heat transfer analysis is carried out in the presence of thermal radiation absorption, Joule and viscous heating. Under the usual boundary layer approximations, the governing of continuity, momentum and concentration equations with Boussinesq approximations for the buoyancy forces and thermal energy are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \upsilon\frac{\partial^2 u}{\partial y^2} - \frac{\sigma H_0^{\ 2}}{\rho}(u - U) + g\beta(T - T_\infty) \tag{2}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}-\frac{\upsilon}{c_p}\left(\frac{\partial u}{\partial y}\right)^2+\frac{\sigma H_0{}^2}{\rho c_p}(u-U)^2-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial y} \tag{3}$$

$$\frac{\partial C}{dt}+u\frac{\partial C}{dx}+v\frac{\partial C}{dy}=D_m\frac{\partial^2 C}{dy^2}-K_r(C-C_\infty) \tag{4}$$

Under the boundary layer assumption, $\frac{\partial u}{\partial x}=0$, because the fluid is not flowing in the horizontal direction but only in the vertical direction as shown in Figure 1. In a similar manner, $\frac{\partial T}{\partial x}=0$ , $\frac{\partial C}{\partial x}=0$ and equations (2), (3) and (4) reduce to

$$\frac{\partial v}{\partial y}=0 \tag{5}$$

$$\frac{\partial u}{\partial t}+v\frac{\partial u}{\partial y}=\upsilon\frac{\partial^2 u}{\partial y^2}-\frac{\sigma H_0{}^2}{\rho}(u-U)+g\beta(T-T_\infty) \tag{6}$$

$$\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}-\frac{\upsilon}{c_p}\left(\frac{\partial u}{\partial y}\right)^2+\frac{\sigma H_0{}^2}{\rho c_p}(u-U)^2-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial y} \tag{7}$$

$$\frac{\partial C}{dt}+v\frac{\partial C}{dy}=D_m\frac{\partial^2 C}{dy^2}-K_r(C-C_\infty) \tag{8}$$

With the boundary conditions below for time $t>0$

$$u(t,0)=L\frac{\partial u}{\partial y},\ \ T(t.0)=T_w+m\frac{\partial T}{\partial y}\ ,\ \ C(t,0)=C_w \tag{9}$$

$$u\to U\ ,\ T\to T_\infty\ ,\ \ C\to C_\infty\ \text{ as }\ \ y\to\infty \tag{10}$$

where $u,v$ are respectively the velocity components in the $x$ and $y$ directions, $T$ and $C$ are fluid temperature and concentration respectively, $T_\infty$ and $C_\infty$ are the ambient or free stream temperature and concentration, $D_m$ is the mass diffusivity, $H_0$ is the magnetic strength, $K_r$ is the reaction rate constant$m$ is the temperature jump, $L$ denotes the velocity slip length, $k$ is the fluid thermal conductivity, $\upsilon$ is the kinematic viscosity, $\rho$ is the fluid density, U is the free stream velocity, $\beta$ is the volumetric thermal coefficient of expansion, $g$ is the acceleration due to gravity, the temperature at the plate surface is given by $T_w$ and the concentration at the fluid surface $C_f$ is given by $C_w$, $\alpha$ is the thermal diffusivity and $C_p$ is the specific heat at constant pressure, $q_r$ is the radiation heat flux. By using the Rosseland approximation for thermal radiation in an optically thick layer, the radiative heat flux $q_r$ is given as

$$q_r = -\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y} \approx -\frac{16\sigma^* {T_\infty}^3}{3k^*}\frac{\partial T}{\partial y} \tag{11}$$

where $T^4 \cong 4{T_\infty}^3 T - 3{T_\infty}^4$ by Taylor series approximation, $\sigma^*$ is the Stefan-Boltzmann constant, $k^*$ is the mean absorption coefficient. The continuity equation (5) shows that the normal velocity is either constant or a function of time. We, therefore, choose the time-dependent normal velocity as

$$v = -b\left(\frac{\nu}{t}\right)^{\frac{1}{2}} \tag{12}$$

where $b > 0$ is the suction parameter.

**Model Similarity Equation**

To transform the model partial differential equations to a set of nonlinear ordinary differential equation, the following similarity variables are introduced (Mohammed and Makinde, 2017; Shateyi and Muzara, 2020).

$$\eta = \frac{y}{2\sqrt{\nu t}}, \quad u(\eta) = Uf(\eta), \quad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty} \quad \text{and} \quad \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty} \tag{13}$$

Substituting the similarity variables (13) into the governing momentum and thermal energy equations with the boundary conditions as contained in equations (6) to (10); then the three coupled nonlinear differential equations with the boundary conditions obtained are:

$$f''(\eta) + 2(\eta + b)f'(\eta) - M(f - 1) + Gr\theta(\eta) = 0 \tag{14}$$

$$(1 + Ra)\theta''(\eta) + 2\Pr(\eta + b)\theta'(\eta) + \Pr Ec\left[\{f'(\eta)\}^2 + M(f - 1)^2\right] = 0 \tag{15}$$

$$\phi''(\eta) + 2[\eta + bSc]\phi'(\eta) - \gamma Sc\phi(\eta) - 0 \tag{16}$$

With the boundary conditions

$$f(0) = \lambda f'(0), \quad \theta(0) = 1 + \delta\theta'(0), \quad \phi(0) = 1 \tag{17}$$

$$f(\infty) = 1, \quad \theta(\infty) = 0, \quad \phi(\infty) = 0 \tag{18}$$

where the prime symbol indicates derivative with respect to $\eta$, b >0 is the suction parameter, $\Pr = \frac{\nu}{\alpha}$ is the Prandtl number, $M = \frac{4t\sigma H_0^2}{\rho}$ is the magnetic parameter, $Ec = \frac{U^2}{C_p(T_w - T_\infty)}$ is the Eckert number, $\delta = \frac{m}{2\sqrt{\nu t}}$ is the temperature jump parameter, $Sc = \frac{\upsilon}{Dm}$ is the Schmidt number, $\gamma = 4tK_r$ is the chemical reaction parameter, $\lambda = \frac{L}{2\sqrt{\nu t}}$ is the velocity slip parameter , $Ra = \frac{16\sigma^* T_\infty^3}{3kk*}$ is the thermal radiation parameter and $Gr = \frac{4tg\beta\,(T_w - T_\infty)}{U}$ is the local Grashof number. However, the exact solution for the equations (14) to (16) exist for special flow and heat transfer case when $M = Gr = Ec = Sc = \gamma = 0$. Other physical quantities of engineering and industrial interests in this study are the local Skin friction coefficient ($Cf_x$), local Nusselt number ($Nu_x$) and local Sherwood number ($Sh_x$) are defined respectively according to Shateyi and Muzara (2020) as

$$\frac{\tau_w}{\rho U_w^{\ 2}} = 2\,\mathrm{Re}_x^{\frac{1}{2}}\, Cf_x = f''(0) \qquad (19)$$

$$\frac{xq_w}{k(T_w - T_\infty)} = 2\,\mathrm{Re}_x^{-\frac{1}{2}}\, Nu_x = -\theta'(0), \qquad (20)$$

$$\frac{xj_w}{k_\infty(C_w - C_\infty)} = \mathrm{Re}_x^{\frac{1}{2}}\, Sh_x = \phi'(0) \qquad (21)$$

where the $\tau_w$ , $q_w$ and $j_w$ are respectively the shear stress, heat transfer rate at the permeable surface , local concentration rate at the surface.

**Numerical Procedure**

The coupled nonlinear differential equations (14) to (16) are transformed into a set of non linear first order equations with some unknown initial conditions to be determined by the shooting technique.

Let $f(\eta) = y_1$, $f'(\eta) = y_2$, $\theta(\eta) = y_3$ , $\theta'(\eta) = y_4$, $\phi(\eta) = y_5$ and $\phi'(\eta) = y_6$ . Then equations (14) to (16) become

$$\left.\begin{array}{l} y_1' = y_2, y_2' = -2(\eta+b)y_2 + M(y_1-1) - Gry_3 \\ y_4' = \dfrac{-1}{1+Ra}\left[2\Pr(\eta+b)y_4 + \Pr Ec\left\{y_2^2 + M(y_1-1)^2\right\}\right] \\ y_{6'}' = \gamma Scy_5 - 2(\eta+bSc)y_6 \end{array}\right\} \tag{22}$$

With the corresponding initial conditions

$$\left.\begin{array}{l} y_1(0) = \lambda y_2(0) \\ y_3(0) = 1+\delta y_4(0), y_5(0) = 1 \\ y_1(\infty) = 1, y_3(\infty) = 0, y_5(\infty) = 0 \end{array}\right\} \tag{23}$$

The initial conditions are first guessed and subsequently determined using Newton Raphson's method for each set of parameter values with respect to the prescribed boundary conditions.

**Numerical Solution and Validation**

The resulting initial value problem is numerically solved using the fourth order Runge-Kutta Fehlberg integration scheme with Shooting technique as in Na, T.Y(1979). The step size of $\Delta\eta = 0.001$ is used and the convergence criterion is $10^{-6}$. A maximum value is used as an infinity value of $\eta$ where $\eta$ is arbitrary as long as it is chosen large enough so that the free stream conditions are satisfied. Then the values of the local skin friction $C_f$, local Nusselt number $Nu$ and the local Sherwood number $Sh$ are obtained from the process of numerical computation as given by equations (19) to (21).

To examine the behaviours of the velocity, temperature and concentration profiles of the physical problems, numerical calculations are carried out for various values of suction parameter b>0, magnetic field parameter M, Grashof number Gr, thermal radiation parameter Ra, Prandtl number Pr, Eckert number Ec, Schmidth number Sc, chemical reaction parameter $\gamma$, velocity slip parameter $\lambda$ and temperature jump parameter $\delta$.

**Results for skin friction coefficient, Nusselt and Sherwood numbers**

The results for skin friction, Nusselt and Sherwood numbers are compared with the previous published results in literature and are shown in Tables 1. It was observed that the present results are in excellent agreement with the published result by Mohammad and Makinde, 2017.

Table 1 shows the value of skin friction coefficient $f''(0)$, Nusselt number $-\theta'(0)$ and Sherwood number $\phi'(0)$ for different values of velocity slip parameter $\lambda$ and temperature jump parameter $\delta$ where $M = Gr = Ec = Sc = \gamma = 0$, Pr=0.75, Ra=0.1 and b=0.1 . The present result was then compared with work of Mohammad and Makinde (2017) and it was in excellent agreement. The skin friction coefficients $f''(0)$, the Nusselt number $-\theta'(0)$ and the sherwood number $\phi'(0)$ decrease as velocity slip parameter $\lambda$ and temperature jump parameter $\delta$ increase.

**Table 1: Comparative study of $f''(0)$, $-\theta'(0)$ and $\phi'(0)$ for diverse values of $\lambda$ and $\delta$**

**Gr=M=Ec=Sc= $\gamma$ =0, Pr=0.75, Ra=0.1 and b=0.1**

| $\lambda$ | $\delta$ | Muhammad and Makinde (2017) | | | Present work | | |
|---|---|---|---|---|---|---|---|
| | | $f'(0)$ | $-\theta'(0)$ | $\phi'(0)$ | $f'(0)$ | $-\theta'(0)$ | $\phi'(0)$ |
| 0.1 | 0.1 | 1.1179876 | 0.90730785 | - | 1.1179866 | 0.90730788 | 0.32326535 |
| 0.2 | 0.2 | 1.0055665 | 0.83183482 | - | 1.0055658 | 0.83183487 | 0.31236798 |
| 0.3 | 0.3 | 00.9136889 | 0.76795375 | - | 0.9136886 | 0.76795379 | 0.28990328 |
| 0.4 | 0.4 | 0.8371954 | 0.71318448 | - | 0.8371951 | 0.71318450 | 0.20065432 |
| 0.5 | 0.5 | 0.7725203 | 0.66570727 | - | 0.7725208 | 0.66570729 | 0.12908427 |
| 0.6 | 0.6 | 0.6691361 | 0.58748823 | - | 0.6691373 | 0.58748820 | 0.09087543 |

## Results and Discussion

In this section, the influence of various thermophysical parameters involved in the present problem in the flow field along with suction and chemical reaction are considered. The thermal Grashof number Gr is positive because of its application in cooling problems like cooling of electronic components and nuclear reactors.

### Effects of the fluid parameters on the velocity profile.

The effects of flow parameters on velocity profile are shown graphically in this section with the detailed discussions. Figures 2 to 10 show the effect of various thermophysical parameters in the flow field on the velocity profiles and the momentum boundary layer thickness. Generally, the fluid velocity is zero at the permeable stationary plate surface and increases to the prescribed free stream value satisfying the far field boundary condition. Increase in Grashof number Gr, Radiation parameter Ra, Eckert number Ec and velocity slip parameter $\lambda$ as in figures 4, 5, 7 and 9 increase the momentum boundary layer with all profiles asymptotically tending to the free stream value away from the plate thereby increasing the fluid motion in the boundary layer region adjacent to the plate surface. This may be due to the effects of additional heated fluid entering into the flow field by injection and decrease in fluid thermal diffusivity. Also, increase in suction parameter b>0, magnetic field parameter M, Prandtl number Pr, Schmidth number Sc and temperature jump parameter $\delta$ as in Figures 2, 3, 6, 8 and 10 decrease the momentum boundary layer thickness with all profiles tending asymptotically to the free stream value away from the plate and consequently increasing the fluid motion in the boundary layer region adjacent to the plate surface. This is because the electrically conducting fluid receives a push from the electromagnetic Lorentz force due to inclusion of magnetic field towards the permeable surface. The magnetic field has the potential to move the electrically conducting fluid forward in the microscale system.

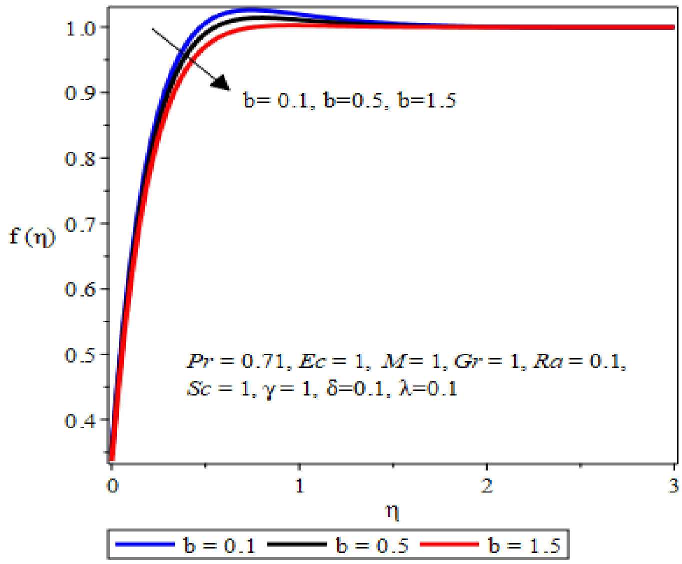


**Fig. 2: Effect of Suction parameter b>0 on velocity**

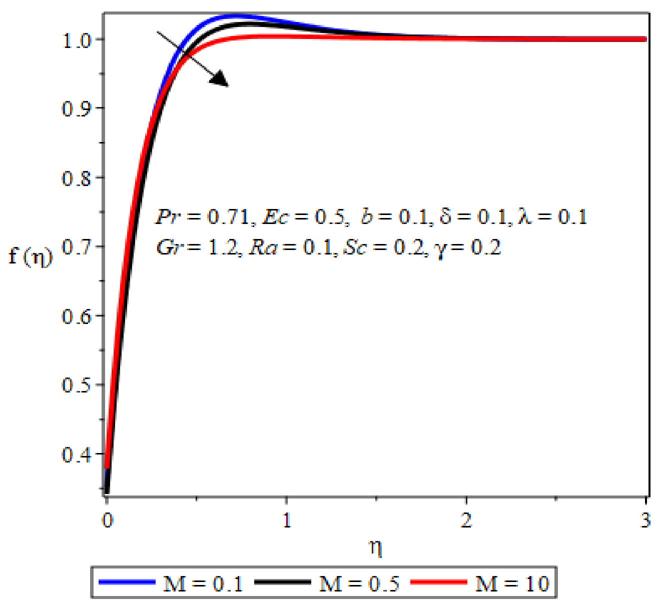


**Fig.3: Effect of Magnetic field parameter M on velocity**

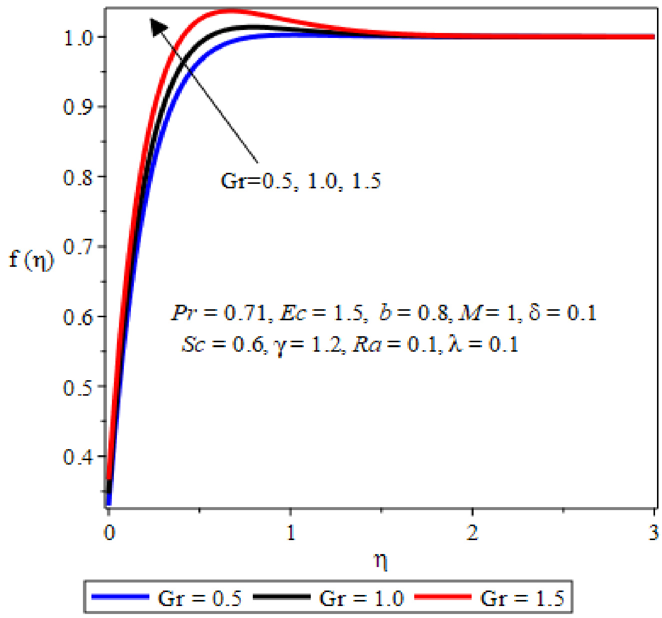


**Fig. 4: Effect of Grashof number Gr on velocity**

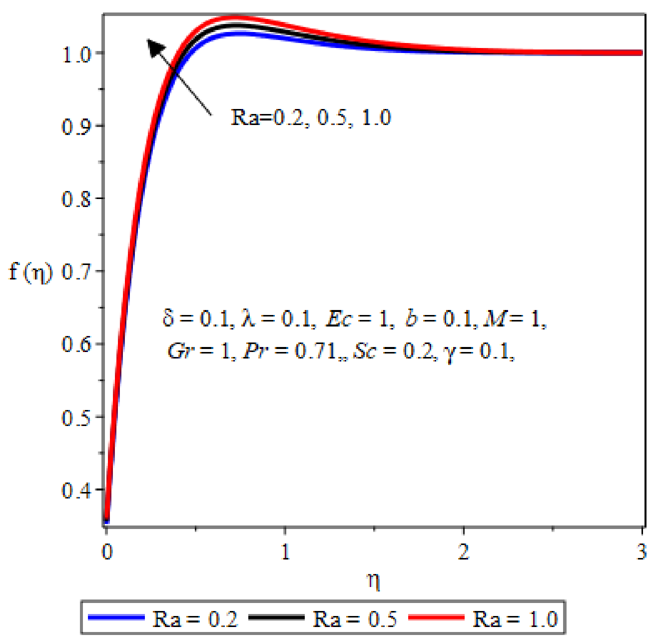


**Fig. 5: Effect of Radiation parameter Ra on velocity**

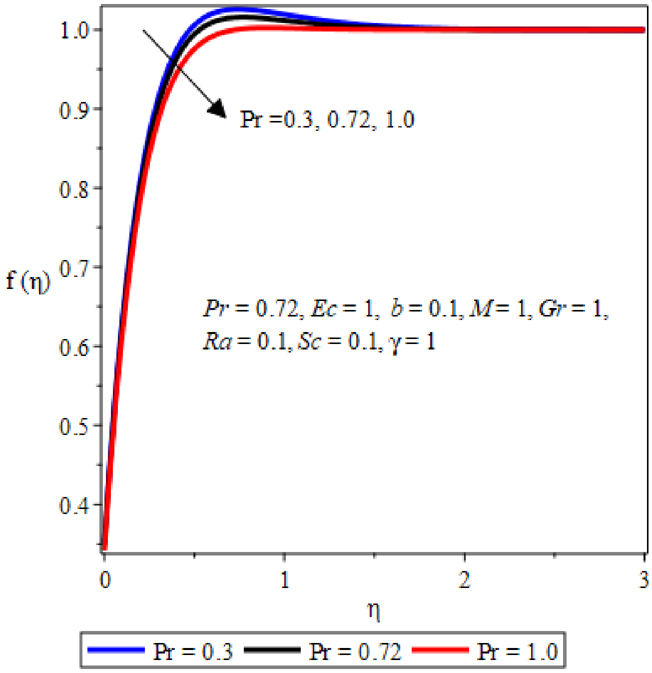


**Fig.6: Effect of Prandtl mumber Pr on velocity**

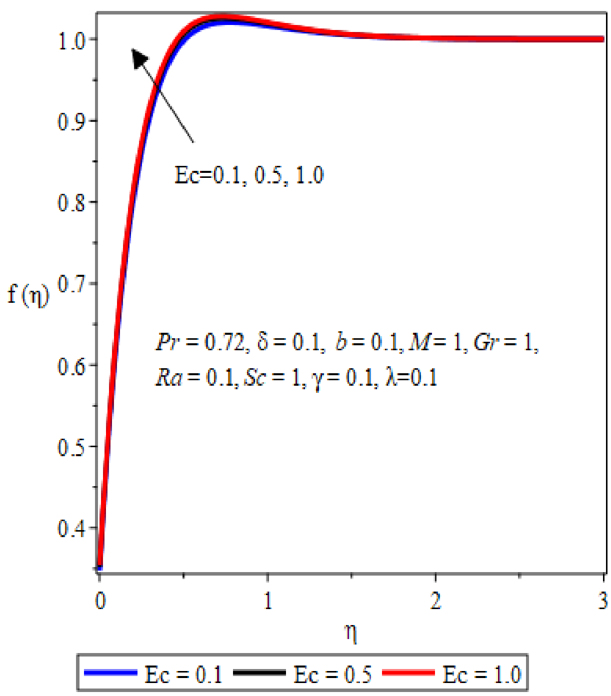


**Fig. 7: Effect of Eckert number Ec on velocity**

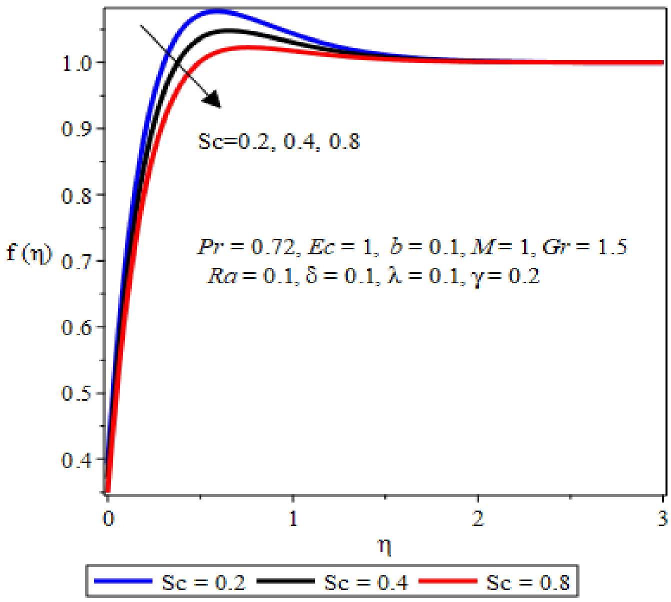


**Fig. 8: Effect of Schmidth number Sc on velocity**

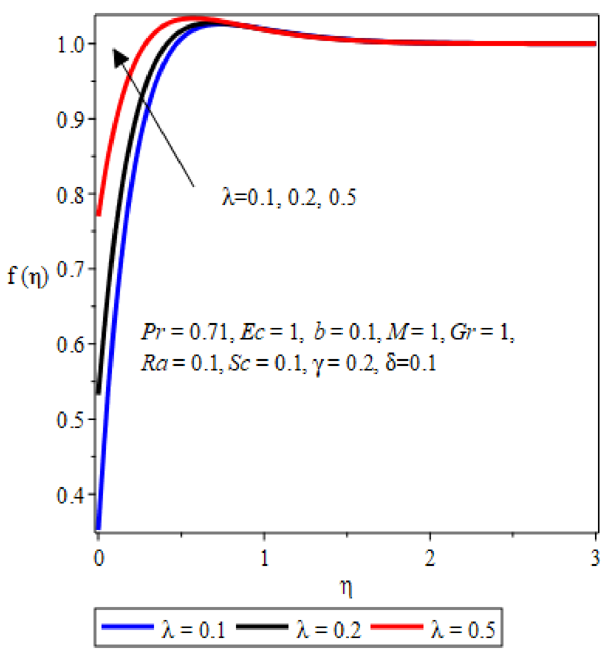


**Fig. 9: Effect of velocity slip parameter $\lambda$ on velocity**

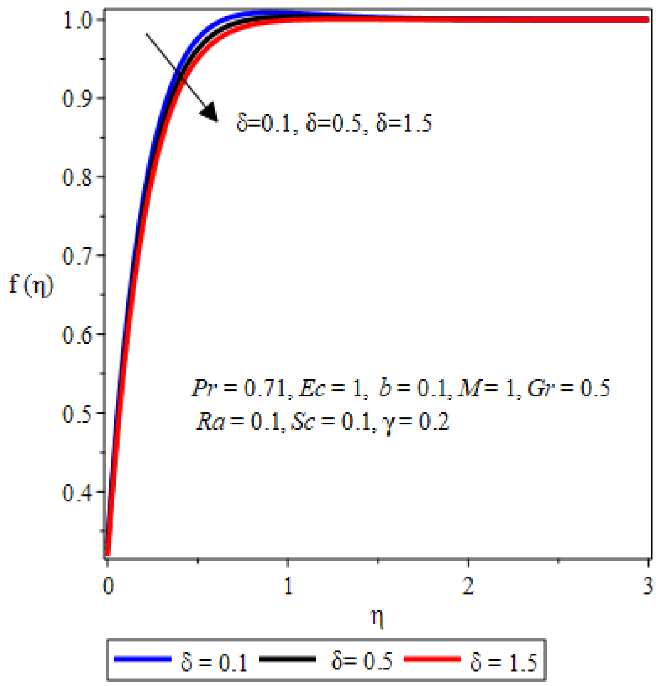


**Fig.10: Effect of temperature jump $\delta$ on velocity**

**Effects of the fluid parameters on the temperature profiles.**

The effects of flow parameters on temperature profiles are shown graphically in this section with the detailed discussions. Figures 11 to 19 show the effect of various thermophysical parameters in the flow field on the temperature profiles and the momentum boundary layer thickness. The fluid temperature is highest at the plate surface and decreases exponentially to the free stream zero value satisfying the prescribed far field boundary condition. Increase in magnetic parameter M, Grashof number Gr, radiation parameter Ra and Eckert number Ec give rise to the fluid temperature and the thermal boundary layer thickness of the fluid. The presence of Joule or Lorentz heating due to the presence of magnetic field, absorption of heat by the fluid from the plate surface and viscous dissipation effect also serve as additional heat source to increase fluid temperature. Increase in suction parameter b>0, Prandth number Pr, Schmidth number Sc, velocity slip parameter $\lambda$ and temperature jump parameter $\delta$ also decrease the fluid temperature and the thermal boundary layer thickness threby deceasing the plate surface temperature which leads to convective cooling of the plate surface.

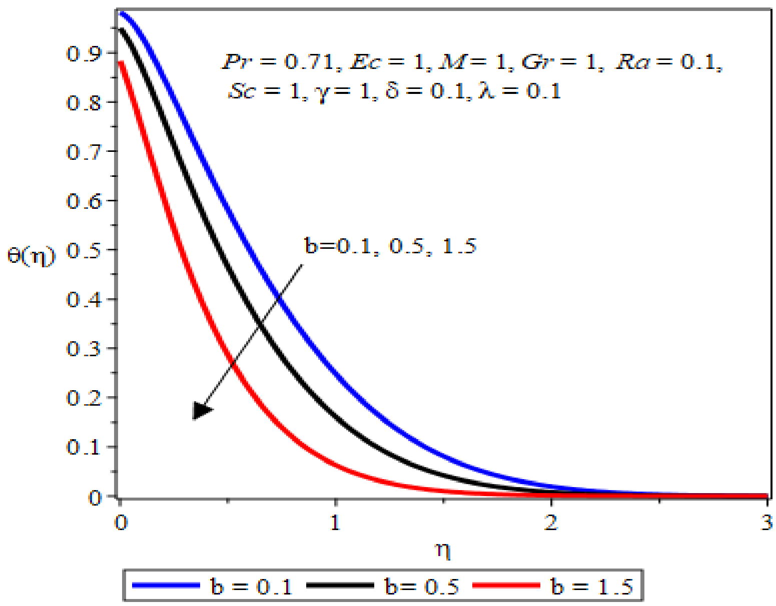


**Fig. 11: Effect of suction b>0 on the temperature**

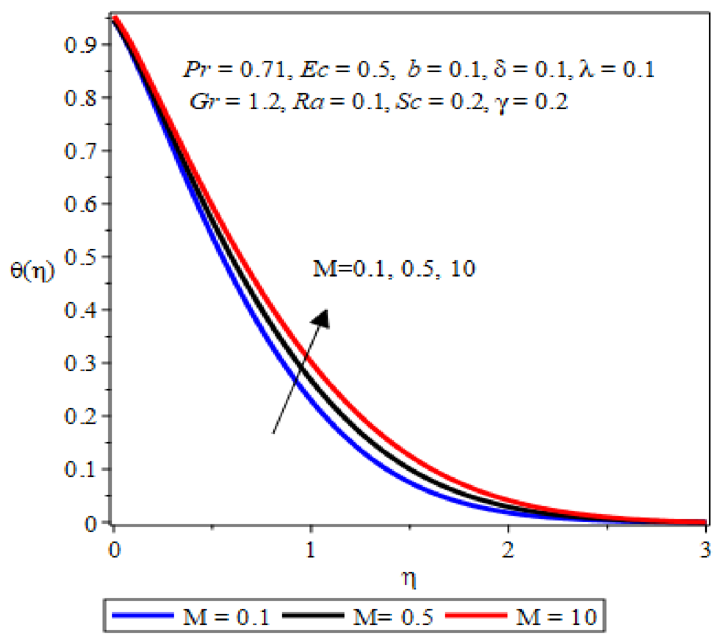


**Fig. 12: Effect of Magnetic field parameter M on the temperature**

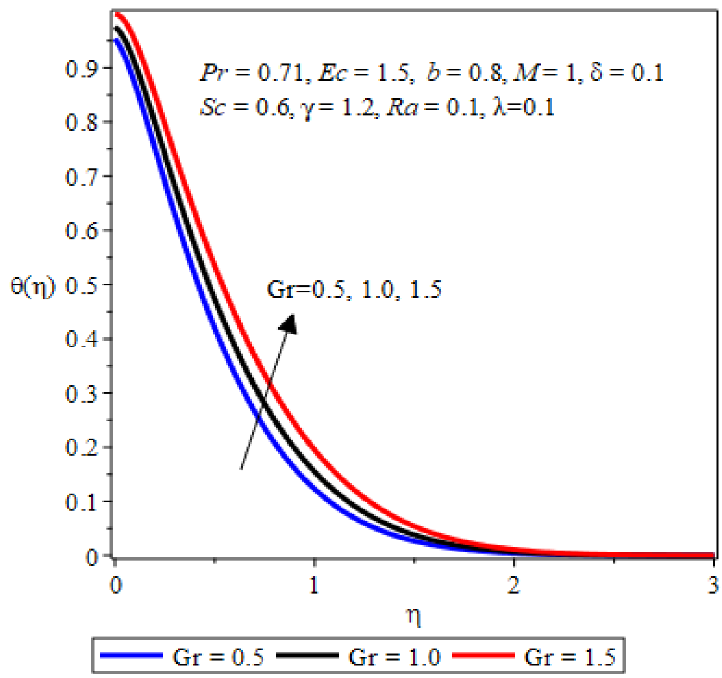


**Fig. 13: Effect of Grashof number Gr on temperature**

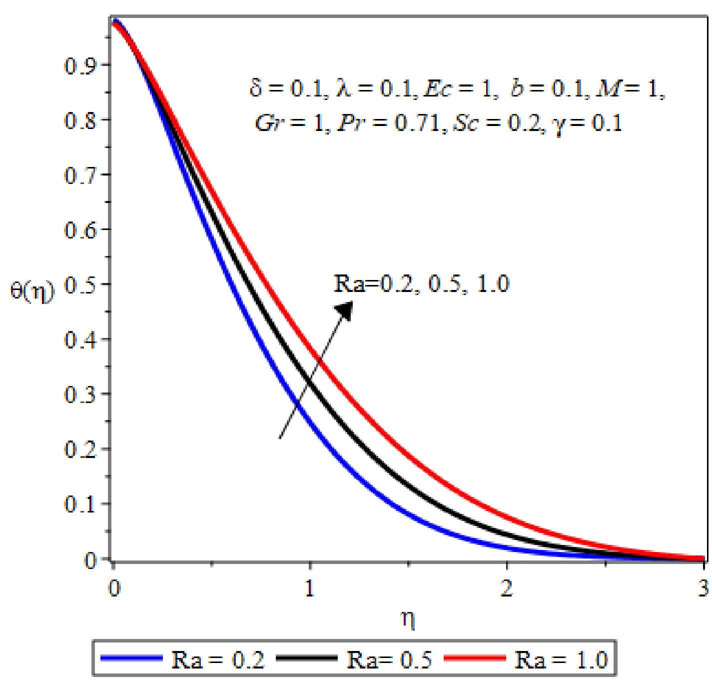


**Fig. 14: Effect of radiation parameter Ra on temperature**

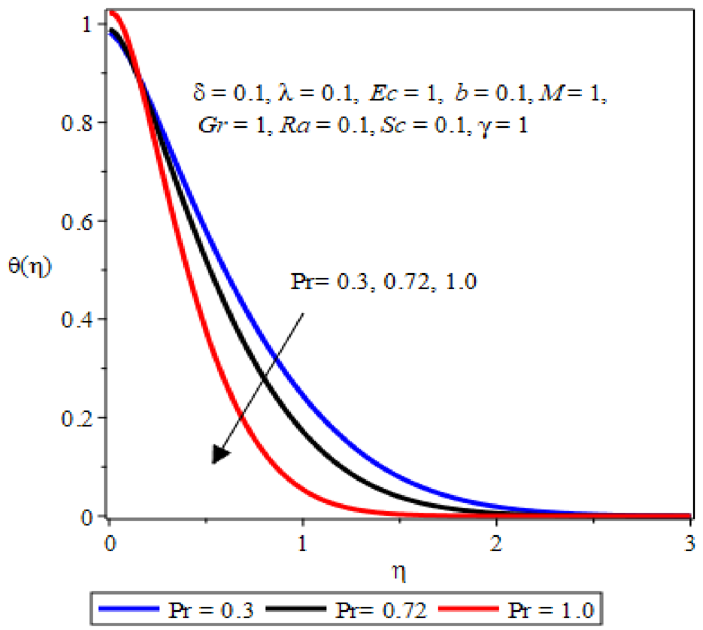


**Fig. 15: Effect of Prandtl number Pr on temperature**

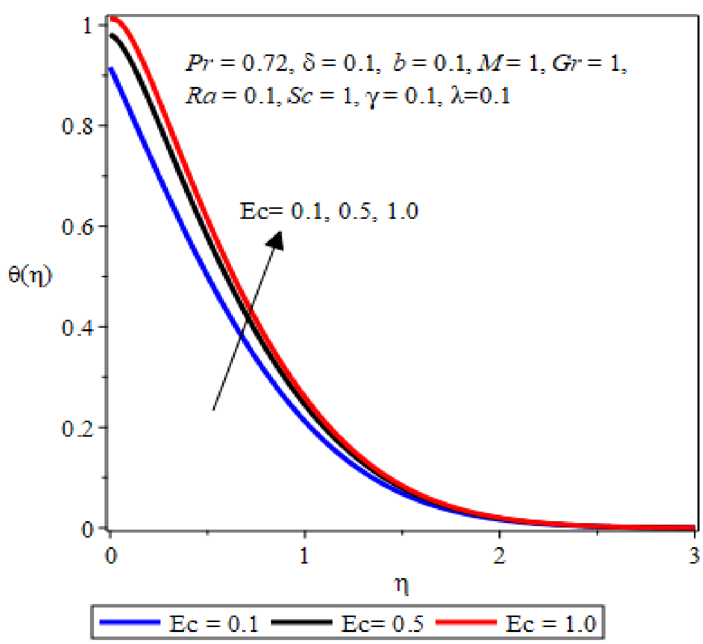


**Fig. 16: Effect of Eckert number Ec on temperature**

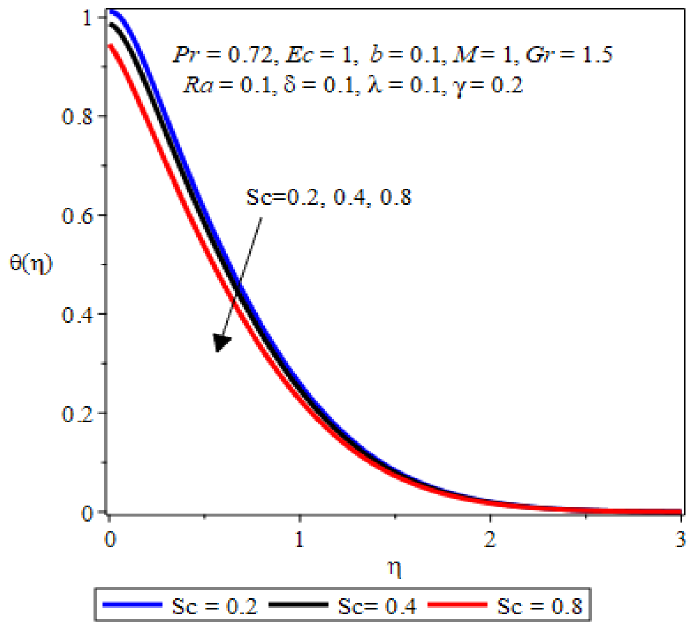


**Fig. 17: Effect of Schmidth number Sc on temperature**

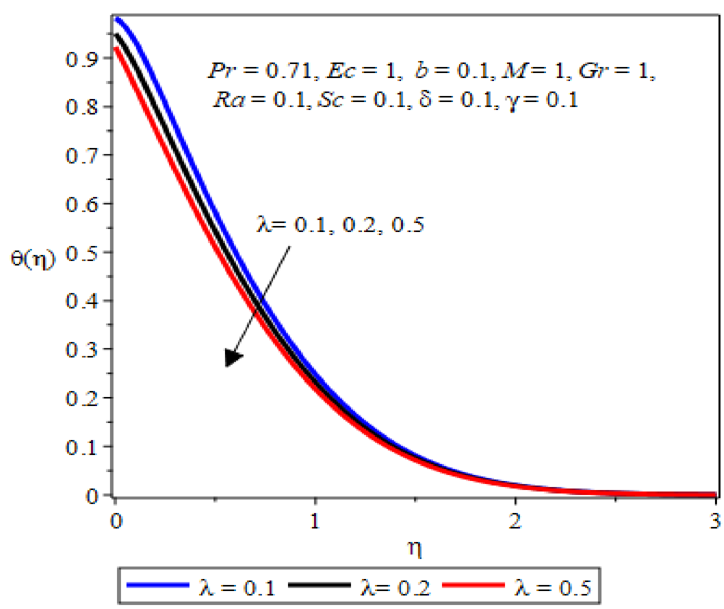


**Fig. 18: Effect of velocity slip parameter $\lambda$ on temperature**

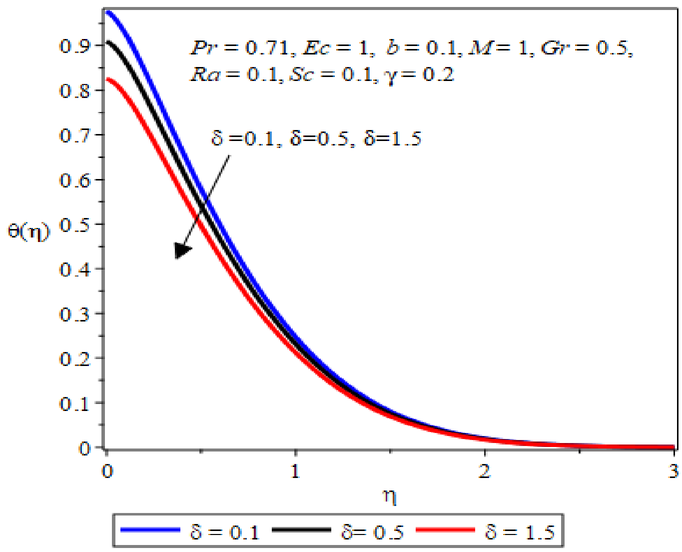


**Fig. 19: Effect of temperature jump parameter $\delta$ on temperature**

**Effects of the fluid parameters on the concentration profiles.**

The effects of flow parameters on cocentration profiles are shown graphically in this section with the detailed discussions. The fluid concentration is highest at the surface and decreases exponentially to free stream zero value satisfying the prescribed far field boundary condition. Increase in Grashof number Gr as shown in Figure 21 increase the concentration of the fluid since the Grashof number increase the temperature and mass diffusivity of the fluid. Increase in suction parameter b>0, radiation parameter Ra, Prandtl number Pr, Schmidth number Sc and chemical reaction parameter $\delta$ as shown in Figures 20, 22 and 23 also decrease the concentration of the fluid due to convective cooling

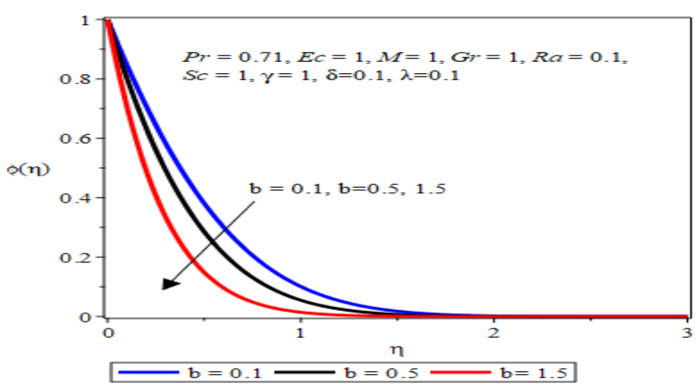


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**Fig. 20: Effect of Suction parameter b>0 on concentration**

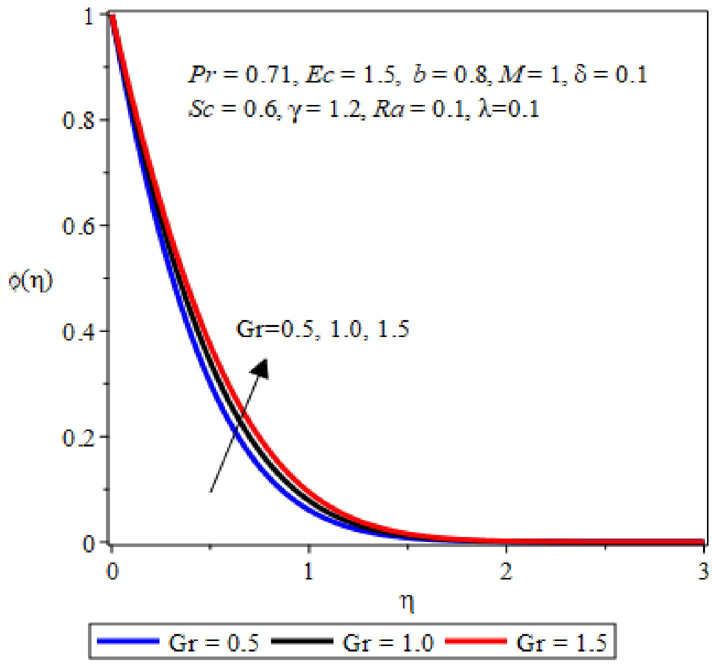


**Fig. 21: Effect of Grashof number Gr on concentration**

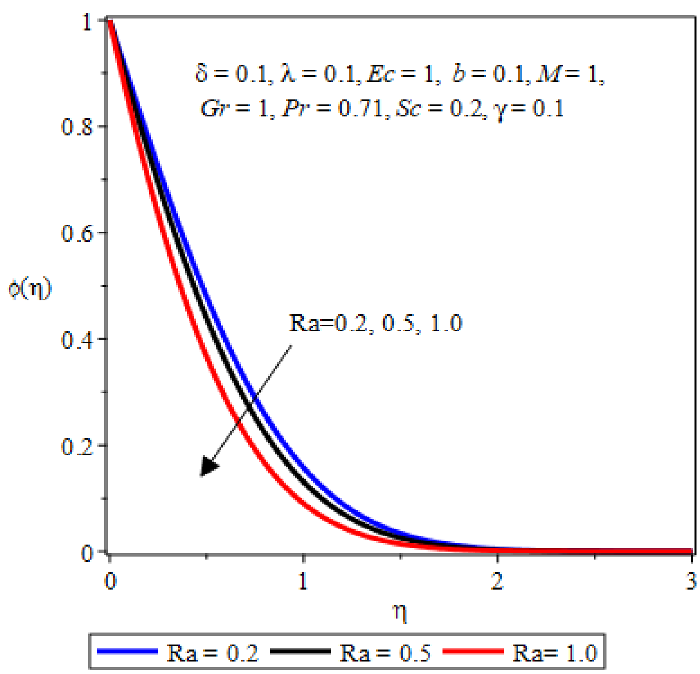


**Fig. 22: Effect of radiation parameter Ra on concentration**

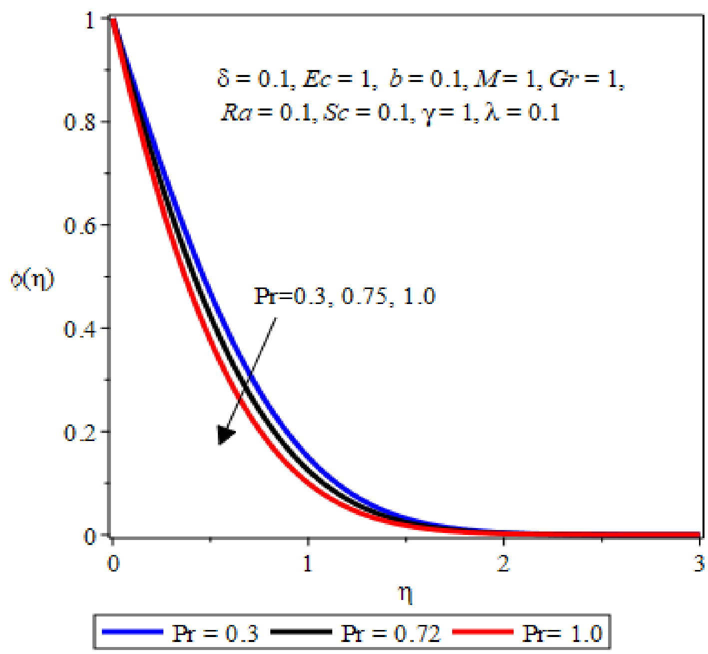


**Fig. 23: Effect of Prandtl number Pr on concentration**

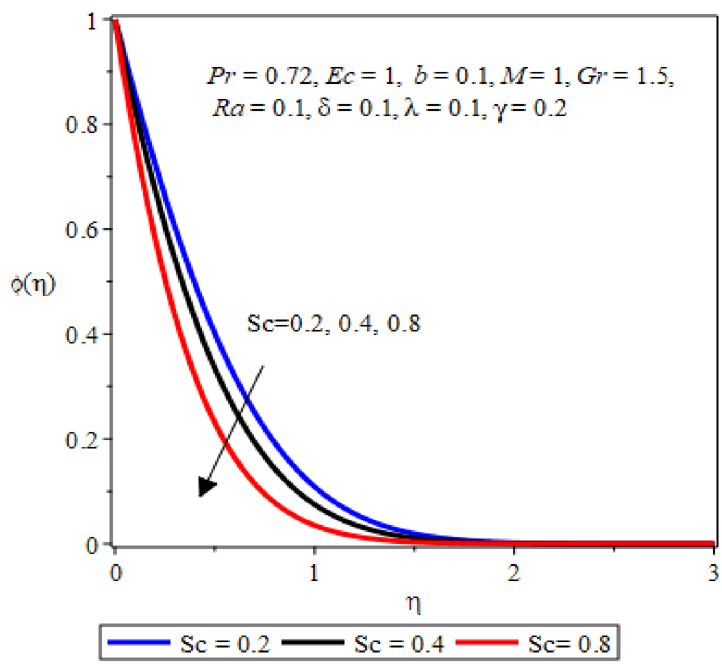


**Fig. 24: Effect of Schmidth number Sc on concentration**

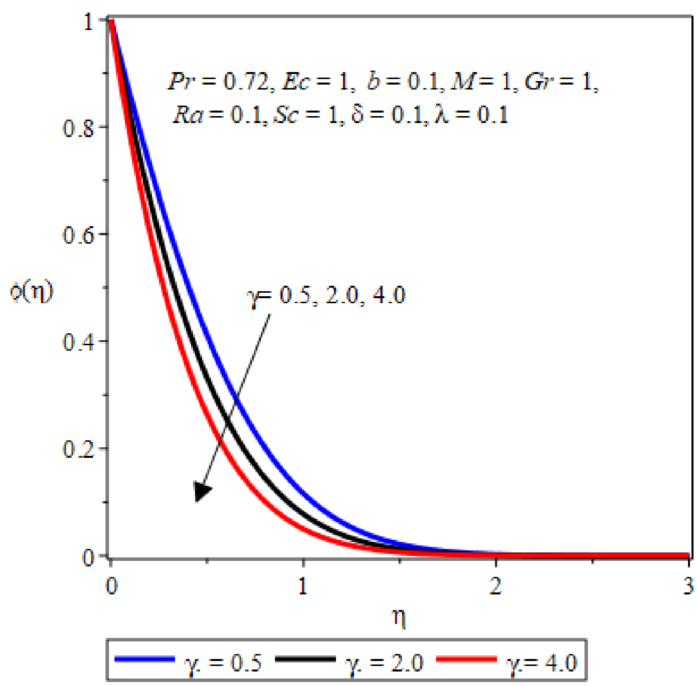


**Fig. 25: Effect of chemical reaction parameter $\gamma$ on concentration**

**Conclusion**

The work investigates numerically an unsteady magnetydrodynamic (MHD) boundary layer flow problem over a permeable surface with suction and chemical reaction. Using similarity variables, the modeled partial differential equations for the problem were transformed into a set of coupled nonlinear ordinary differential equations and the boundary value problem was solved numerically using the shooting technique coupled with Runge-Kutta-Fehlberg integration scheme. Graphical results are presented for the fluid velocity, temperature and concentration profiles. The results show that:

- The fluid velocity and momentum boundary layer thickness increase with increase in Grashof number Gr, radiation parameter Ra, Eckert number Ec and velocity slip parameter where all profiles are asymptotically tending to the free stream value away from the plate due to additional heated fluid entering the flow field by injection and decrease in thermal diffusivity.
- The fluid velocity is zero at the permeable stationary plate surface and increases to the prescribed free stream value satisfying the far field boundary condition.
- The fluid velocity and momentum boundary layer thickness decreases with increase in suction parameter b>0, magnetic field parameter M, Prandth number Pr, Schmidth number Sc and chemical reaction parameter $\delta$ where all profiles are tending asymptotically to the free stream value away from the plate because the electrically conducting fluid receives a push from the electromagnetic Lorentz force due to the inclusion of magnetic field.
- The fluid temperature is highest at the surface and decreases exponentially to the free stream zero value satisfying

the prescribed far field boundary condition.

- A rise in fluid temperature and thermal boundary layer thickness can be attributed to increase in magnetic field parameter M, Grashof number Gr, radiation parameter Ra and Eckert number Ec due to the presence of Joule or Lorentz heating (as a result of the presence of magnetic field), absorption of heat by the fluid from the plate surface and viscous dissipation effect which serve as heat source to increase the fluid temperature.
- The fluid temperature and thermal boundary layer thickness decrease with increase in suction parameter b>0, Prandtl number Pr, Schmidth number Sc, velocity slip parameter $\lambda$ and chemical reaction parameter $\delta$ due to convective cooling of the plate surface.
- The fluid concentration is highest at the surface and decreases exponentially to free stream zero value satisfying the prescribed far field boundary condition.
- The concentration of the fluid increase with increase in Grashof number due to increase in the temperature (which increase the concentration of the fluid) and mass diffusivity of the fluid.
- The fluid concentration decreases with increase in suction parameter b>0, radiation parameter Ra, Prandtl number Pr, Schmidth number Sc and chemical reaction parameter $\delta$ due to convective cooling of the plate surface.

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