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Full Length Research Paper

Chemically reacting Magnetohydrodynamics (MHD) boundary layer flow of heat and mass transfer past a low-heat-resistant sheet moving vertically downwards

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A theoretical study has been conducted to investigate the steady Magnetohydrodynamics (MHD) boundary layer flow past a low-heat-resistant sheet moving vertically downwards. The fluid is considered viscous, incompressible and electrically conducting. The non-linear coupled differential equations are solved numerically by applying Runge-Kutta integration scheme coupled with Newton-Raphson shooting technique. The results show that the velocity, temperature, and concentration profiles are appreciably influenced by the presence of the transverse magnetic field. Also, the effects of various parameters on the skin-friction, the Nusselt and the Sherwood numbers are discussed.

Key words: Natural convection; vertical plate; magnetohydrodynamics; boundary layer.

INTRODUCTION

Boundary layers formed across vertical surfaces are a common engineering problem in industry. Some practical areas of application include chemical coating of flat plates, hot rolling, wire drawing, metal and polymer extrusion processes. Many chemical engineering processes like metallurgical and polymer extrusion involve cooling of molten liquid. Some polymer fluids like Polyethylene oxide and polyisobutylene solution in cetane have better electromagnetic properties and can be regulated by external magnetic fields. A comprehensive review on the subject has been made by many authors including Nield and Bejan (1999), Ingham and Pop (1998, 2002), Bejan and Khair (1985), Trevisan and Bejan (1990) and Sakiadis (1961). Postelnicu (2004) numerically studied the influence of magnetic field on heat and mass transfer by natural convection from vertical surfaces in porous media by considering the Soret and Dufour effects while Anghel et al. (2000) analyzed the Dufour and Soret effects on free convection boundary layer over a vertical surface embedded in a porous medium. Furthermore, Alam and Rahman (2006) also investigated the Dufour and Soret effects on mixed convection flow past a vertical porous flat plate with variable suction.

Free convection on a vertical plate with uniform and constant heat flux in a thermally stratified micropolar fluid was presented by Chang and Lee (2008) whilst Vajravelu et al. (1993) and Crane (1970) investigated the convective heat transfer on a stretching sheet. Also, Gupta and Gupta (1977), Kays and Crawford (1993), Ibrahim and Makinde (2010a, 2010b) made significant contributions to the subject by considering various aspects of the problem of heat and mass transfer on stretching sheets.

Anwar et al. (2008) conducted a network numerical study on laminar free convection flow from a continuously-moving vertical surface in thermally-stratified non-Darcian high-porosity medium. Makinde (2005) earlier on presented computational results on boundary layer flow with heat and mass transfer past a

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Abbreviations: (MHD), Magnetohydrodynamics.

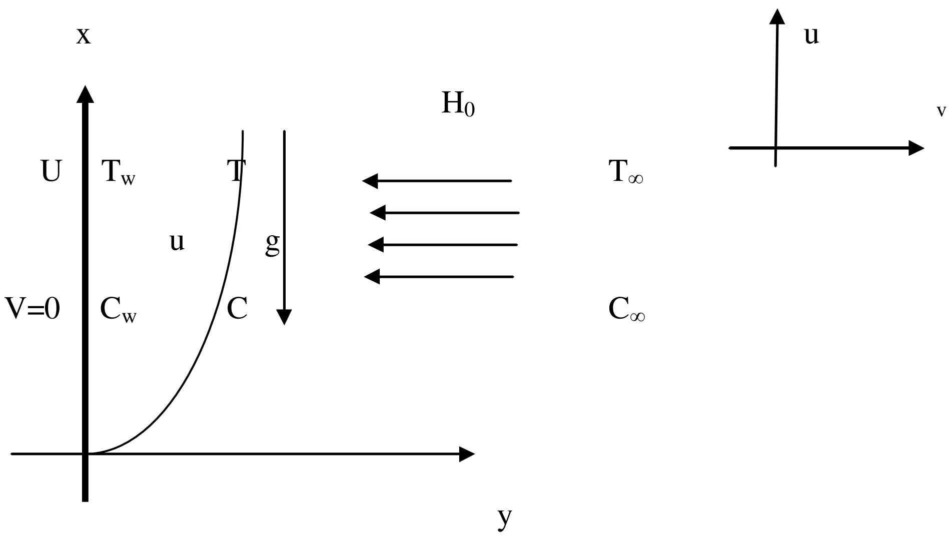

Figure 1. Flow configuration and coordinate system.

moving vertical porous plate. The effect of thermal radiation on heat and mass transfer of a variable viscosity fluid past a vertical porous plate permeated by transverse magnetic field was reported in Makinde and Ogulu (2008).

In the present study, the shooting technique is employed to analyze the behaviour of the boundary layer as the heated plate moves vertically downwards in a viscous fluid permeated by transverse magnetic field. The effects of various physical parameters on the velocity and temperature profiles as well as the skin-friction co-efficient, the Nusselt and Sherwood numbers are discussed.

Problem formulation

We consider the steady flow of a chemically reacting, incompressible and viscous fluid past a semi-infinite vertically moving flat plate, Figure 1. A uniform transverse magnetic field of magnitude (H_0) is applied in the presence of thermal buoyancy effect in the direction of y – axis. The magnetic Reynolds number is assumed to be small so that the induced magnetic field and the Hall effects are negligible. The wall temperature and concentration T and C are linear but varies along the plate with T_∞ and C_∞ as the ambient temperature and concentration respectively.

The governing equations for this problem are based on the conservation laws of mass, linear momentum, energy and chemical species concentration. With the assumptions stated above, the differential equations describing the physical dynamics of the boundary layer problem are written in Cartesian frame of reference as:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}-\frac{\sigma H_0^2}{\rho}u+g\beta_T(T-T_\infty)+g\beta_C(C-C_\infty), \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{\sigma H_0^2}{\rho c_p}u^2, \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-\gamma(C-C_\infty). \tag{4}$$

Subject to boundary conditions

$u=Bx, v=0, T=T_w=ax+T_\infty, C=C_w=bx+C_\infty$ at $y=0$

$$u\to 0, T\to T_\infty, C\to C_\infty \quad \text{as } y\to\infty \tag{5}$$

where respectively, *u* and *v* are the velocity components in the *x* and *y* directions, *T* and C are the fluid temperature and concentration, T_w and C_w are the wall surface temperature and concentration, T_∞ and C_∞ are the fluid temperature and concentration at a distant location from the surface, β is the thermal expansion coefficient, ν is the kinematic viscosity, α is the thermal diffusivity, D is the mass diffusivity, *a* and *b* are constants. In this study, we consider the case where the surface temperature and concentration $T_w(x)$ and $C_w(x)$ are greater than the ambient temperature T_∞ and concentration C_∞. Under these conditions, the free convective motion of the fluid is upward along the plate, as shown in Figure 1. In a reverse scenario, where the surface is colder than the ambient temperature and concentration, $T_w(x) < T_\infty$ and $C_w(x) < C_\infty$, the boundary layer profile remains the same but the direction is reversed, i.e. the fluid flow is downward, Yang et al. (1982).

Equations (1) to (4) admit self similar solutions of the form

$$\eta = y\sqrt{\frac{B}{\upsilon}}, \qquad \psi = x\sqrt{\nu B}\, f(\eta), \qquad \theta(\eta) = \frac{T - T_\infty}{T_o - T_\infty},$$
$$\phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty}, \tag{6}$$

where η, ψ, θ, and ϕ are respectively the dimensionless variables, the stream function, the dimensionless temperature and the dimensionless concentration. The stream function relates in the usual way to the velocity components as:

$$u = \frac{\partial \psi}{\partial y} \text{ and } v = -\frac{\partial \psi}{\partial x}. \tag{7}$$

The continuity equation of (1) is satisfied automatically.

Equations (2) to (4) are transformed to ordinary differential equations as follows:

$$f''' + ff'' - f'^2 - Haf' + Gr\theta + Gc\phi = 0, \tag{8}$$

$$\theta'' + \Pr f\theta' - \Pr \theta f' - Ha\Pr Ecf'^2 = 0, \tag{9}$$

$$\phi'' + Scf\phi' - Sc\phi f' - Sc\beta\phi = 0, \tag{10}$$

where $Ha = \frac{\sigma H_0^2}{\rho B}$ is the Hartmann number,

$G_r = \frac{g\beta_T (T_w - T_\infty)}{xB^2}$ is the thermal Grashof number,

$G_c = \frac{g\beta_c (C_w - C_\infty)}{xB^2}$ is the concentration Grashof number,

$\Pr = \frac{\nu}{\alpha}$ is the Prandtl number,

$Ec = \frac{x^2 B^2}{c_p (T_w - T_\infty)}$ is the Eckert number,

$Sc = \frac{\nu}{D}$ is the Schmidt number,

$\beta = \frac{\gamma}{B}$ is the reaction rate.

The primes indicate differentiation with respect to η. The boundary conditions (5) are also transformed to:

$$f'(0) = 1, f(0) = 0, \theta(0) = 1, \phi(0) = 1, \text{ on } \eta = 0$$

$$f'(\eta) \to 0, \theta(\eta) \to 0, \phi(\eta) \to 0 \text{ as } \eta \to \infty \tag{11}$$

The physical quantities of interest are the skin friction parameter (τ), the Nusselt number (Nu) and the Sherwood number which can be computed easily. These quantities are defined in dimensionless terms as:

$$\tau = f''(0), \; Nu = -\theta'(0) \text{ and } Sh = -\phi'(0). \tag{12}$$

Numerical procedure

The system of ordinary differential equations (8), (9) and (10) with boundary conditions in (11) are solved numerically using the forth order Runge–Kutta integration scheme with a modified version of the Newton–Raphson shooting technique. The resulting higher order ordinary differential equations are reduced to first order differential equations by letting:

$$f = x_1, \quad f' = x_2, \quad f'' = x_3, \quad \theta = x_4, \quad \theta' = x_5, \quad \phi = x_6,$$
$$\phi' = x_7. \tag{13}$$

Thus, the corresponding first order differential equations are

$$\begin{aligned}
x_1' &= x_2, \\
x_2' &= x_3, \\
x_3' &= -x_1x_3 + x_2^2 + Hax_2 - Grx_4 - Gcx_6, \\
x_4' &= x_5, \\
x_5' &= -\Pr x_1x_5 + \Pr x_2x_4 + \Pr HaEcx_2^2, \\
x_6' &= x_7, \\
x_7' &= -Scx_1x_7 + Scx_2x_6 + Sc\beta x_6,
\end{aligned} \tag{14}$$

Table1. Computations showing the variation in local skin friction, Nusselt number and Sherwood number for Sc = 0.24.

Ha	Gr	Gc	Pr	Ec	B	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0	0.1	0.1	0.71	0.1	0.1	-0.8672315153	0.845372426	0.4538848758
1.0	0.1	0.1	0.71	0.1	0.1	-1.3040411834	0.769606228	0.3968458010
2.0	0.1	0.1	0.71	0.1	0.1	-1.6363224533	0.7152561700	0.3637592785
3.0	0.1	0.1	0.71	0.1	0.1	-1.914170216	0.6748301664	0.3417321548
0.1	1.0	0.1	0.71	0.1	0.1	-0.3839658694	0.95276174188	0.5268684571
0.1	2.0	0.1	0.71	0.1	0.1	0.11763577749	1.02373066746	0.5739990411
0.1	3.0	0.1	0.71	0.1	0.1	0.57540541047	1.07621858633	0.6081067643
0.1	0.1	1.0	0.71	0.1	0.1	-0.5036924009	0.91055575959	0.4901999207
0.1	0.1	2.0	0.71	0.1	0.1	-0.0963335838	0.96454281127	0.521869527
0.1	0.1	3.0	0.71	0.1	0.1	0.28056792190	1.0063088977	0.5462127475
0.1	0.1	0.1	1.00	0.1	0.1	-0.9249676483	1.03144243794	0.4442962139
0.1	0.1	0.1	5.00	0.1	0.1	-0.9469422732	2.5856233329	0.4402201913
0.1	0.1	0.1	7.10	0.1	0.1	-0.9502609122	3.1264076966	0.4399339618
0.1	0.1	0.1	0.71	1.0	0.1	-0.9514562137	3.282065838	0.4397836153
0.1	0.1	0.1	0.71	2.0	0.1	-0.9527820463	3.4548206835	0.43961672419
0.1	0.1	0.1	0.71	3.0	0.1	-0.9541054829	3.62736701503	0.43945000226
0.1	0.1	0.1	0.71	0.1	1	-0.9664432051	3.1207006382	0.66834955297
0.1	0.1	0.1	0.71	0.1	3	-0.9791178642	3.1163155824	0.97930723624

subject to the following initial conditions:

$$x_1(0)=0,\quad x_2(0)=1,\quad x_3(0)=s_1,\quad x_4(0)=1,$$
$$x_5(0)=s_2,\ x_6(0)=1,\ x_7(0)=s_3 \tag{15}$$

In the shooting method, the unspecified initial conditions s_1, s_2 and s_3 are assumed and equation (14) integrated numerically as an initial valued problem to a given terminal point. The accuracy of the assumed missing initial condition is checked by comparing the calculated value of the dependent variable at the terminal point with its given value there. If a difference exists, improved values of the missing initial conditions must be obtained and the process is repeated. The computations were done by a written program which uses a symbolic and computational computer language MAPLE, Heck (1993). A step size of $\Delta\eta$ = 0.001 was selected to be satisfactory for a convergence criterion of 10^{-7} in nearly all cases. The maximum value of η_∞ to each group of parameters *Ha*, Ec, *Gr*, Gc and *Pr* are determined when the values of unknown boundary conditions at η = 0 not changed to successful loop with error less than 10^{-7}.

RESULTS AND DISCUSSION

Numerical and graphical results are obtained for heat and mass transfer of chemically reacting fluid pasts a moving vertical flat plate in the presence of magnetic field and chemical reaction. These results illustrate the influence of thermal and solutal Grashof numbers (Gr, Gc), Prandtl number (Pr), magnetic field parameter (Ha), Schmidt number (Sc), and Eckert number (Ec), on the velocity, temperature and the concentration profiles.

Computational results

The results illustrate the influence of the thermal Grashof number (Gr), the solutal Grashof number (Gc), the Prandtl number (Pr), the Schmidt number (Sc) and the magnetic parameter (Ha) on the skin friction coefficient as well as the rate of heat and mass transfers at the plate surface. The value of *Pr* is taken to be 0.71 and 7.1 which corresponds to air and water respectively.

Table 1 shows the numerical results for various parameter variations. It is observed that the magnitude of the skin friction coefficient at the surface of the plate increases with increasing values of the Hartmann number

Table 2. Comparison of non-dimensional wall velocity gradient $F''(0)$ for various values of the Hartmann number (Ha) when Pr = Sc = Ec = Gr = Gc = 0.

Ha	**0.0**	**0.5**	**1.0**	**1.5**	**2.0**
Takhar et al. (1986)	-1.0	-1.22	-1.41	-1.58	-1.73
Yih (1999).	-1.0	-1.2247	-1.4142	-1.5811	-1.7321
Abdelkhalek (2009).	-1.0	-1.2356	-1.4156032	-1.58212	-1.73342
Present study	-1.0	-1.22474	-1.4142136	-1.5811388	-1.7320508

Table 3. Comparison of non-dimensional wall temperature gradient for various values of the Prandtl number for Ha = Sc = Ec = Gr = Gc = 0.

Pr	**0.72**	**1**	**3**	**10**	**100**
Grubka et al. (1985)	0.8086	1.0	1.9237	3.7207	12.294
Ali (1994).	0.8058	0.9961	1.9144	3.7006	-
Yih (1999).	0.8086	1.0	1.9237	3.7207	12.294
Abdelkhalek (2009).	0.80865	1.0	1.9246	3.7216	12.29453
Present study	0.808834	1.0	1.923679	3.7206712	12.294081

(Ha). However, both the Nusselt and Sherwood numbers, which represent the heat and mass transfer rates at the plate surface, respectively decrease with increasing values of the Hartmann number (Ha). Furthermore, increasing the thermal and solutal Grashof numbers increases the skin friction coefficient, the Nusselt and Sherwood numbers. Similarly, increasing the Prandtl number (Pr) increases the local skin friction coefficient and the Nusselt number but decreases the Sherwood number.

It is also noted that increasing the values of the Eckert number increases the skin friction co-efficient and the Nusselt numbers while decreasing the Sherwood number. Finally, the reaction rate parameter is observed to increase the skin friction parameter and the Sherwood numbers while reducing the Nusselt numbers for obvious reasons.

Tables 2 and 3 compared our results with previous results reported by Grubka et al. (1985), Ali (1994), Yih (1999) and Abdelkhalek (2009), which showed a perfect agreement.

Effects of parameter variation on velocity profiles

The effects of various parameters on velocity profiles in the boundary layer region are depicted in Figures 2 to 6. It is observed that the velocity starts from a maximum value of 1 at the plate surface and decreases exponentially to a free stream value of zero located far away from the plate surface, satisfying the far field boundary conditions for all parameter values. In Figures 3 and 4, the buoyancy force parameters, (Gr) and (Gc) enhanced the fluid velocity thereby increasing the boundary layer thickness. The velocity profile started at one on the plate surface and increased to a peak value before decreasing to the free stream value of zero some distance away from the plate in both cases.

Moreover, it is interesting to note in Figure 2 that the effect of increasing magnetic field parameter (Ha) is to decrease the velocity profiles throughout the boundary layer region. A resistive force called the Lorentz force was introduced into the fluid due to the presence of the transverse magnetic field. This type of force slowed down the fluid velocity as shown in Figure 2. Figures 5 and 6 showed the influence of increasing the Schmidt number and Prandtl number on the velocity profiles. Increasing the Schmidt number caused a reduction in the velocity profile where as increasing the Prandtl number decreased the velocity profile.

Effect of parameter variation on temperature profiles

It was observed from Figures 7 to 11 that, the fluid temperature attained a maximum value at the plate surface and decreased exponentially to the free stream zero value away from the plate. In Figure 7, the thermal boundary layer thickness increased when the strength of the applied magnetic field was increased. Figures 8 and 9 showed that the thermal boundary layer decreased with the buoyancy force parameters, Gr and Gc. The influence of Prandtl number (Pr) and the Schmidt number were shown in Figures 10 and 11. The temperature profiles

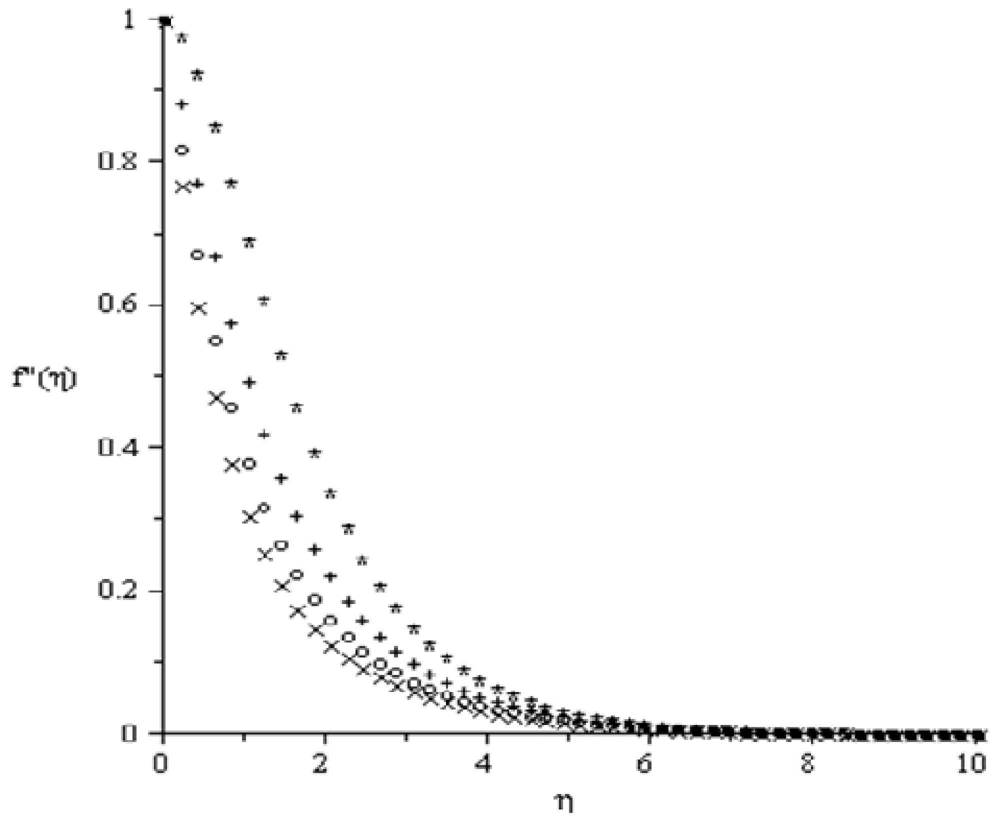

Figure 2. Velocity profile for Pr = 0.71, Gr = 1, Gc = 1, Sc = 0.24, Ec = 1.

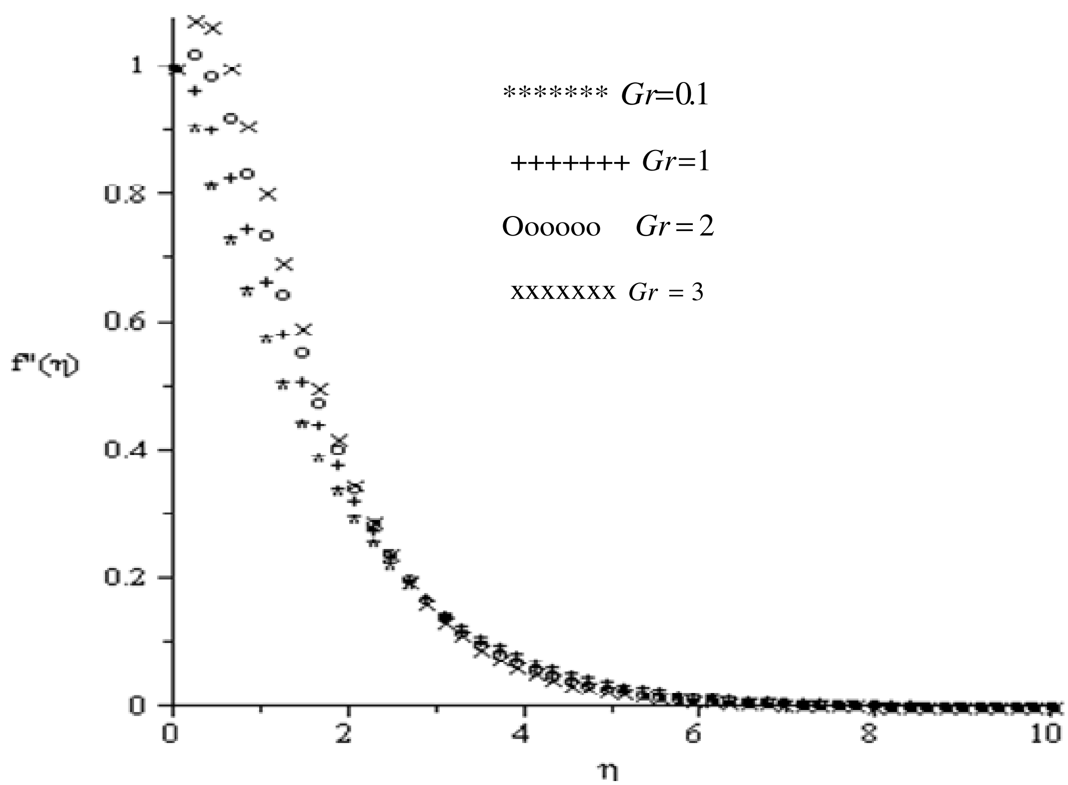

Figure 3. Velocity profile for Pr = 0.71, Ha = 0.1, Gc = 1, Sc = 0.24, Ec = 1.

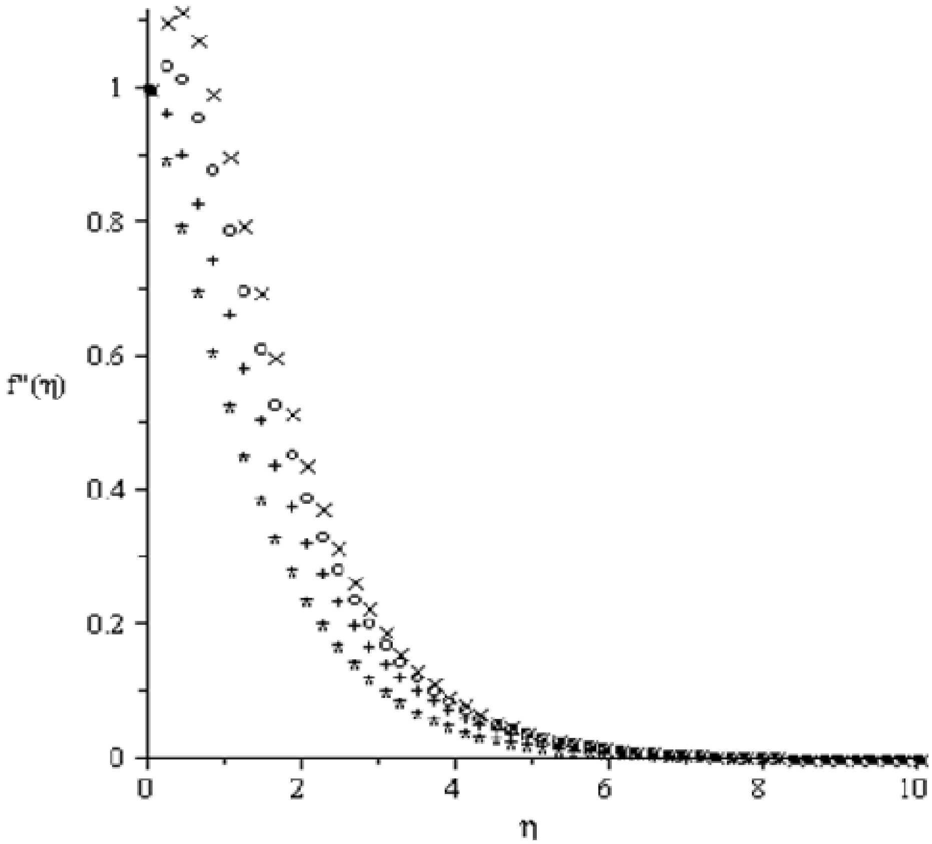

Figure 4. Velocity profile for Gr = 0.1, Pr = 0.71, Sc = 0.24, Ec = 0.1, Ha = 0.1.

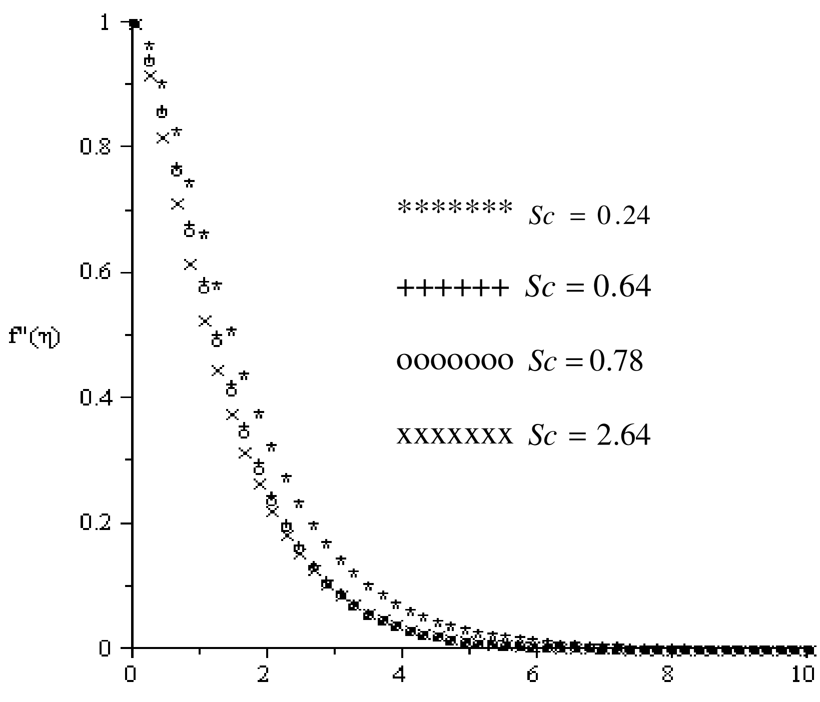

Figure 5. Velocity Profile for Ha = 0.1, Gr = 1, Gc =1, Ec = 1, Pr = 0.71,

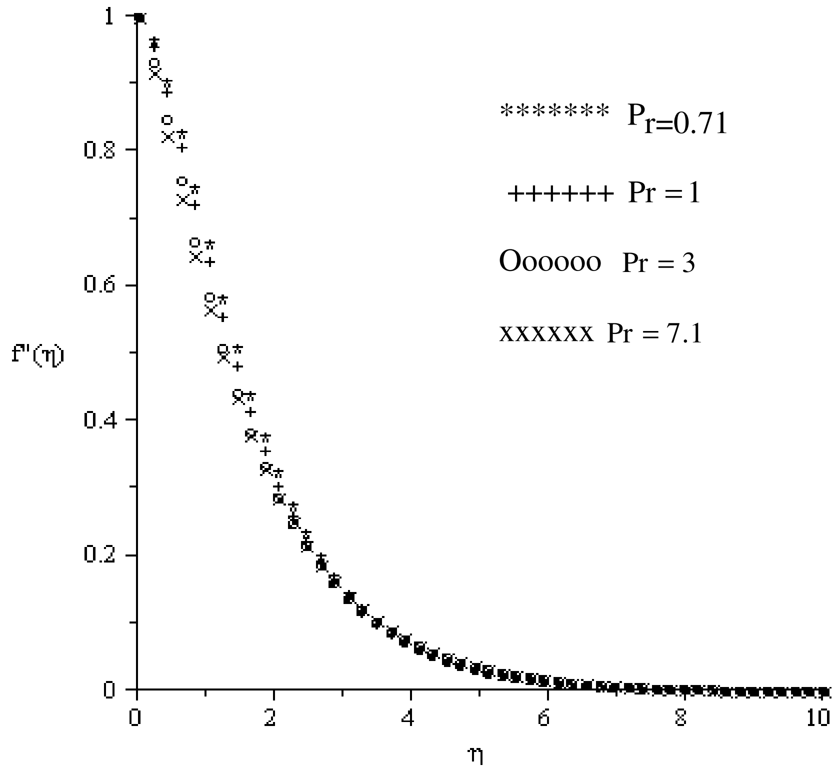

Figure 6. Velocity profile for Gr = 1, Gc = 1, Sc = 0.24, Ec = 1, Ha = 0.1.

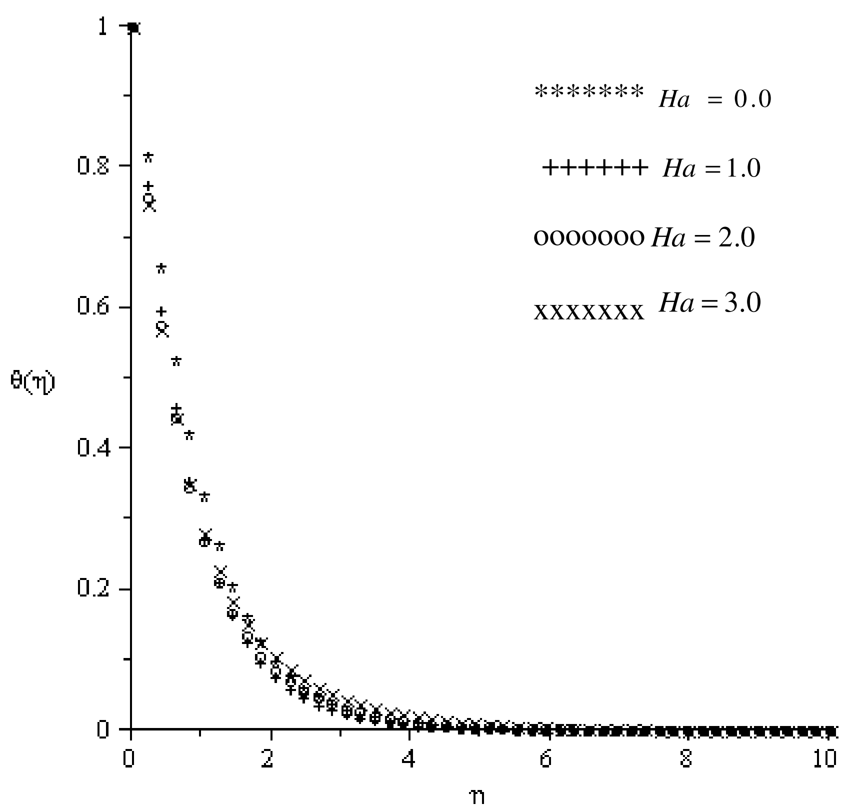

Figure 7. Temperature profile for Pr = 0.71, Gr =1, Gc = 1, Sc = 0.24, Ec = 0.1.

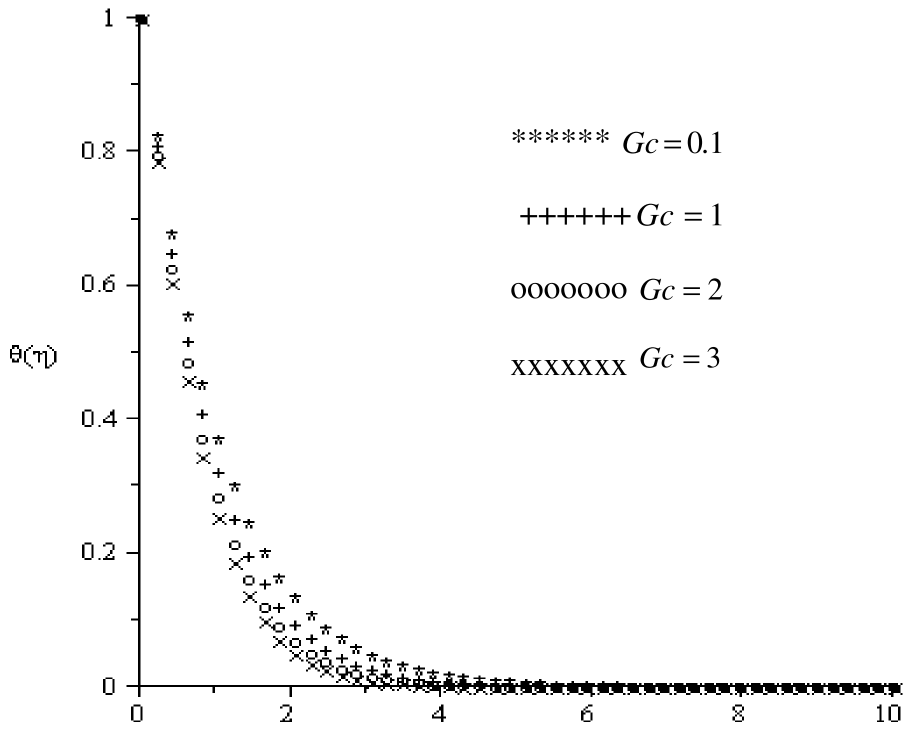

Figure 8. Temperature profile for Gr = 1, Ha = 0.1, Pr = 0.71, Ec = 1, Sc = 0.24.

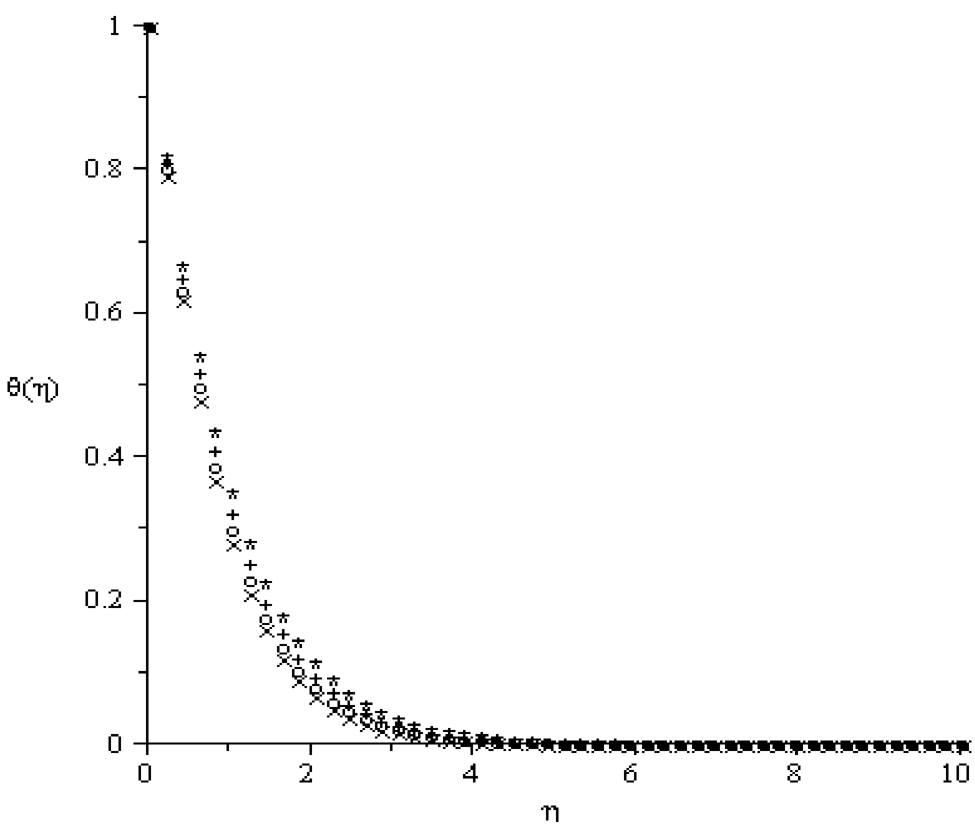

Figure 9. Temperature profile for Sc = 0.24, Ha = 0.1, Gc = 1, Ec = 1, Pr = 0.71.

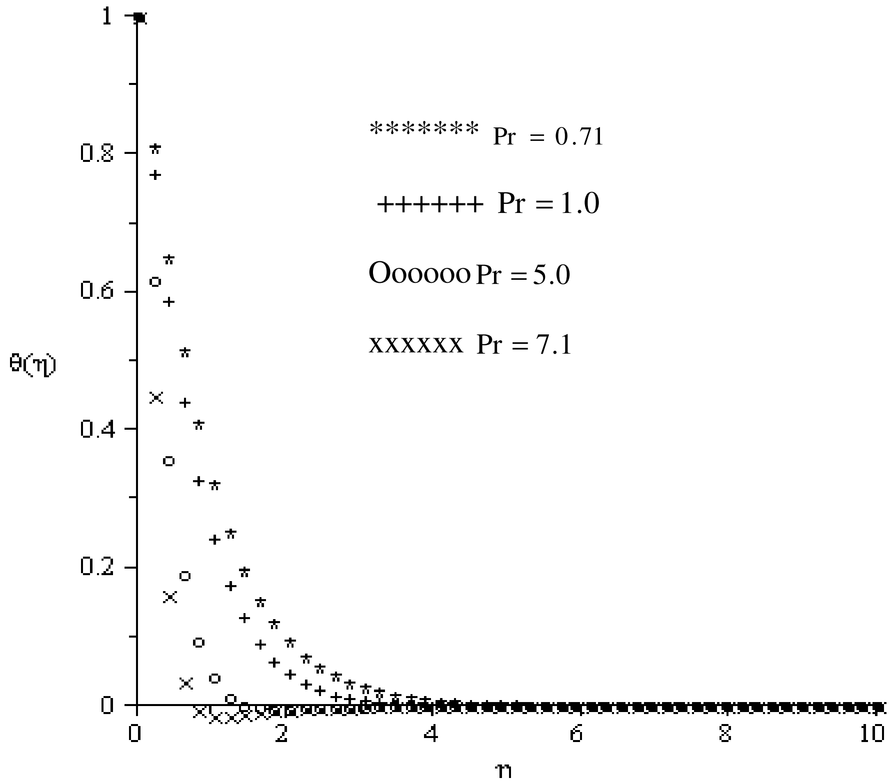

Figure 10. Temperature profile for Gr = 1, Ha = 0.1, Gc = 1, Ec = 1, Sc = 0.24.

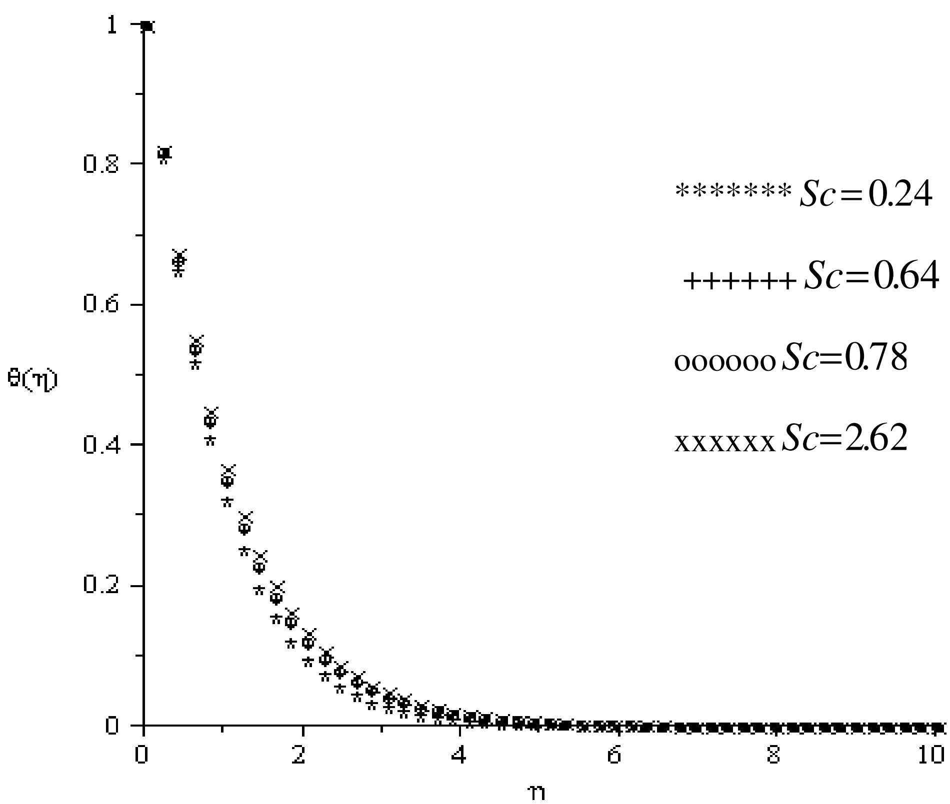

Figure 11. Temperature profile for Gr = 1, Ha = 0.1, Gc = 1, Ec = 1, Pr = 0.71

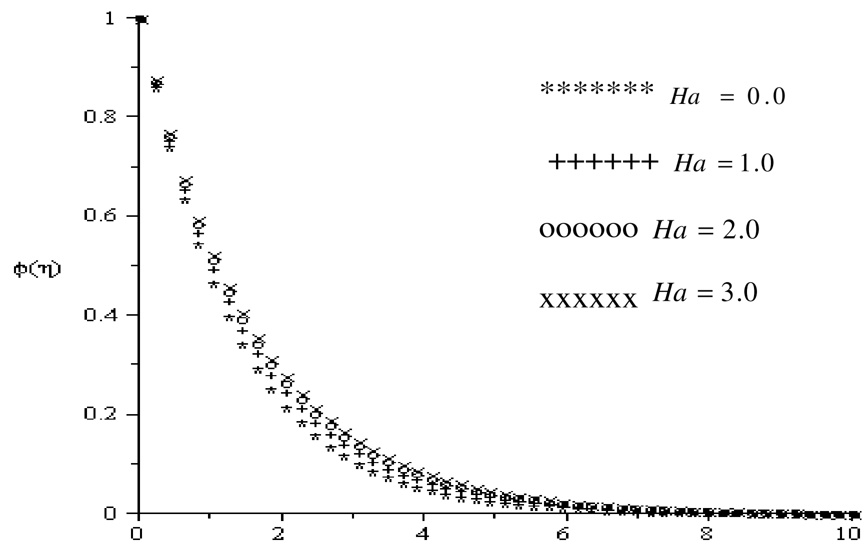

Figure 12. Concentration Profile for Gr = 1, Gc = 1, Pr = 0.71, Sc = 0.24, Ec = 1.

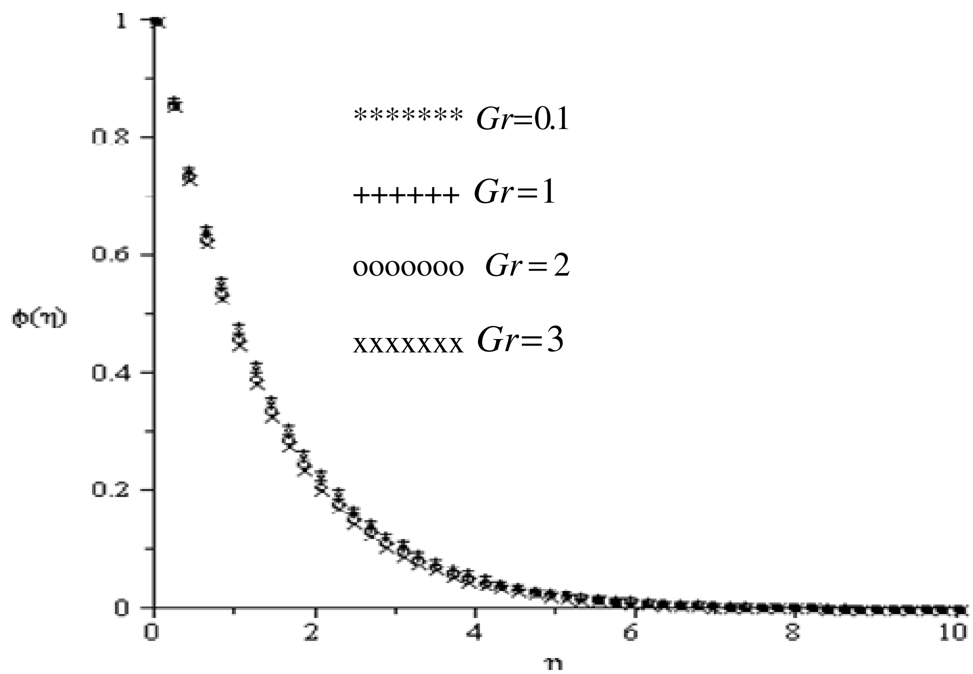

Figure 13. Concentration Profile for Ha = 0.1, Pr = 0.71, Gc = 1, Ec = 1, Sc = 0.24.

were observed to decrease when the Prandtl number was increased but increased when the Schmidt number increases.

Effect of parameter variation on concentration profiles

Generally, the species concentration in the fluid had a maximum value at the plate surface and decreased exponentially to the free stream zero value away from the plate. This was observed in Figures 12 to 15. The solutal boundary layer was observed to increase with increasing magnetic field strength in Figure 12, whilst in Figures 13 and 14, it was observed to decrease with increasing buoyancy force parameters, (Gr) and (Gc). It was further observed that increasing the Schmidt number reduced the concentration boundary layer as shown in Figure 15.

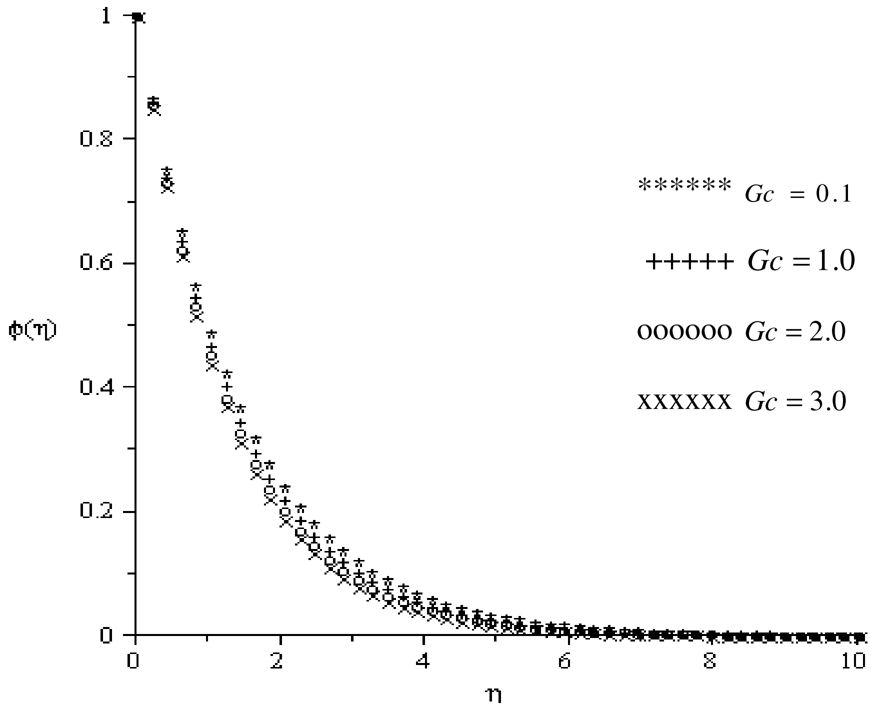

Figure 14. Concentration Profile for Ha = 0.1, Pr = 0.71, Gr = 1, Ec = 1, Sc = 0.24.

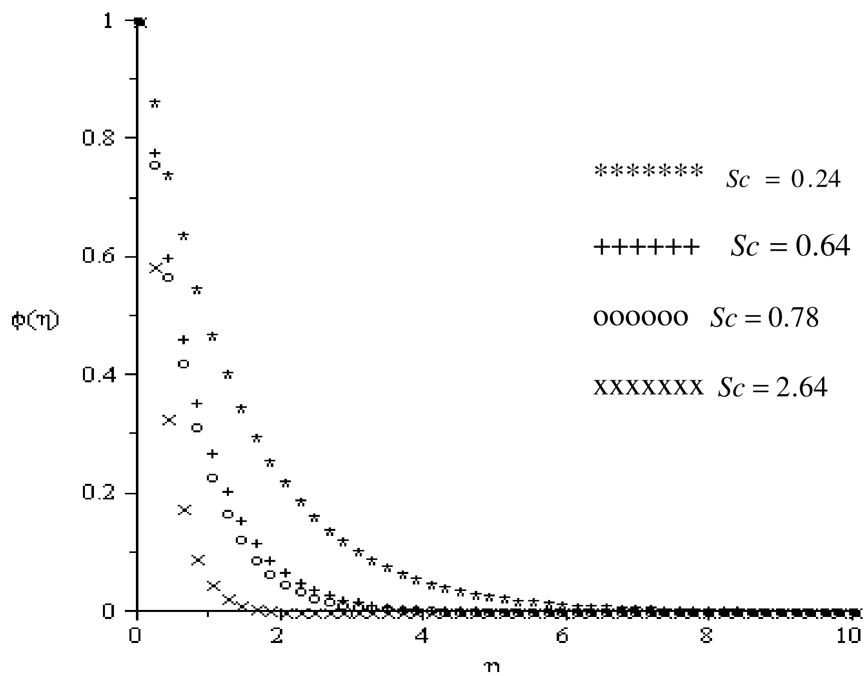

Figure 15. Concentration Profile for Ha = 0.1, Gr = 1, Gc = 1, Ec = 0.1, Pr = 0.71.

Conclusion

In this study, the effect of magnetic field strength on the cooling of a low-heat-resistant plate moving vertically downwards in electrically conducting and chemically reacting fluid was investigated. The nonlinear and coupled governing differential equations were solved numerically using the forth order Runge-Kutta shooting method. Numerical results were presented whilst the velocity, temperature and concentration profiles illustrated graphically and analyzed. It was observed generally that velocity decreases while temperature and concentration profiles increased with magnetic parameter. Furthermore, increased in buoyancy force parameters increased the fluid velocity but decreased the temperature due to convective cooling.

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Nomenclature		***Greek symbols***	
T_w	Wall temperature	η	Similarity variable
(u, v)	Velocity components	ψ	Stream function
(x, y)	Coordinate axes	θ	Dimensionless temperature
H_0	Magnetic field strength	μ	Dynamic viscosity
Gr	Temperature Grashof number	α	Thermal Conductivity
Pr	Prandtl number	β	Thermal Expansion Co-efficient
σ	Electrical conductivity	ν	Kinematic viscosity
g	Acceleration due to gravity	ρ	Fluid density
T_∞	Temperature away from the surface		
C_p	Specific heat capacity at constant pressure		
f	Dimensionless stream function		
U	Plate velocity		