

Hydromagnetic Flow with Dufour and Soret Effects past a Vertical Plate Embedded in Porous Media

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Abstract

The effect of thermal diffusion and diffusion thermo on mixed convection MHD flow past a semi-infinite vertical porous plate embedded in a porous medium with viscous and Ohmic dissipation is investigated. The governing equations of the problem are transformed to ordinary differential equations using similarity variables and then solved numerically by the fourth-order Runge-Kutta-Fehlberg method with shooting technique. Numerical results showing the effects of various thermophysical parameters on the local skin-friction coefficient, the local Nusselt number and the local Sherwood numbers are presented in tables whilst graphical illustrations for the velocity, temperature and concentration profiles are presented and discussed quantitatively.

Keywords: Hydrodynamics; Hydromagnetic; Boundary layer; Mass Transfer; Heat Transfer; Mass Flux; suction.

1. Introduction

The combined effect of heat and mass transfer by free convection in porous media has attracted considerable attention in recent times due to its numerous engineering and geophysical applications. It is commonly observed in aerodynamic extrusion of plastic sheets, continuous filament extrusion from a dye, cooling of plates in water baths, and movement of fluid along threads traveling between feed and wind-up rolls. The pioneering works of Sakiadis (1961) attracted the interest of many researchers in the area of fluid dynamics. Crane (1970) investigated the two dimensional flow driven by stretching elastic flat sheets in their own plane with a velocity varying linearly from a fixed point.

A comprehensive review can be found in Nield and Bejan (1999), Ingham and Pop (1998, 2002), and Ibrahim and Makinde (2010a, 2010b, 2011a, 2011b). These researchers restricted their analysis to axisymmetric flow induced by stretching surfaces. Seini and Makinde (2012, 2013) investigated the effects of MHD, radiation and chemical reaction due to exponential stretching surface and also near stagnation -points on a vertical surface with slip whilst Seini (2013) recently investigated the flow over unsteady stretching surface with chemical reaction and non-uniform heat source. Many of these research works had neglected the effects of Dufour and Soret on the heat and mass transfer under the assumption that they were of smaller magnitude than that prescribed by the Fourier's and Fick's laws. Recent advances in heat transfer shows that Dufour effect is important in transport problems while Soret effect is influential in mass transfer phenomenon. The Soret effect, for instance, has been utilized for isotope separation and in a mixture between gases with very light molecular weight (H_2, He) and of medium molecular weight (H_2, air). According to Eckert and Drake (1972), dufour effect is of considerable magnitude and should not be neglected. There has been many investigations in hydrodynamics over the years focusing on this problem. Kafoussias and Williams (1995), Anghel *et al.* (2000), Postelnicu (2004), Alam et al. (2006) and the references there in, are readily cited for their contributions to the subject.

Alam et al. (2006) for instance, studied the Dufour and Soret effects on steady free convection and mass transfer past a semi-infinite vertical porous plate in a porous medium while Bég et al. (2009) numerically analyzed the Soret and Dufour effects on free convection MHD heat and mass transfer from a stretching surface to a saturated porous medium. Similarly, Tsai and Huang (2009) investigated the heat and mass transfer for Soret and Dufour effects on Hiemenz flow through a porous medium on stretching surfaces. Afify (2009) presented similarity solutions for MHD thermal-diffusion and diffusion-thermo on free convective heat and mass transfer over a stretching surface in relation to suction or injection. The hydromagnetic mixed convection flow with Soret and Dufour effects past a vertical plate embedded in a porous medium was investigated by Makinde (2011). Olanrewaju and Makinde (2011) then analysed the effect of thermal-diffusion and diffusion-thermo on chemically reacting MHD boundary layer flow of heat and mass transfer past a moving vertical plate with suction/injection.

In this paper, the hydromagnetic mixed convection heat and mass transfer past a semi-infinite vertical porous plate with Soret and Dufour effects is investigated. The flow is embedded in a fluid-saturated porous medium in the presence of Viscous and Ohmic heating since these parameters have significant contribution to convective transport processes. The nonlinearity of the basic equations modelling the flow and the additional mathematical difficulties associated with it requires the use of numerical methods. In the solution process, the systems of partial differential equations describing the flow are transformed to ordinary differential equations using similarity variables. The transformed dimensionless governing equations are solved numerically using the fourth-order Runge-Kutta-Fehlberg method with shooting technique. In section 2, the problem is formulated and similarity analysis presented. Section 3 presents the results and discussions while Section 4 concludes the paper.

2. Problem Formulation

Consider a two dimensional flow of an electrically conducting fluid past a vertical moving porous plate in a porous medium. A uniform transverse magnetic field (B_0) is applied along the y-axis. The magnetic Reynolds number is assumed to be small such that the induced magnetic field is neglected. The *x*-axis is taken in the direction of the main flow along the plate and the *y*-axis is normal to the plate. The velocity components in the x and y – axes are respectively *u* and *v*. The physical configuration of the problem is depicted in Fig 1.

Under the usual boundary layer assumptions together with Boussinesq's approximations, the governing equations describing the problem are:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\upsilon\frac{\partial^2 u}{\partial y^2}+g\beta_T(T-T_\infty)+g\beta_c(C-C_\infty)-\frac{\upsilon u}{K'}-\frac{\sigma B_0^2}{\rho}u, \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{D_m k_T}{c_s c_p}\frac{\partial^2 C}{\partial y^2}+\frac{\mu}{\rho c_p}\left(\frac{\partial u}{\partial y}\right)^2+\frac{\sigma B_0^2}{\rho c_p}u^2, \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_m\frac{\partial^2 C}{\partial y^2}+\frac{D_m k_T}{T_m}\frac{\partial^2 T}{\partial y^2}, \tag{4}$$

where *u* and *v* are the velocity components in the *x* and *y* directions respectively, υ is the kinematic viscosity, *g* is the acceleration due to gravity, ρ is the density, B_0 is the magnetic parameter, β_T is the coefficient of volume expansion, β_C is the volumetric coefficient of expansion with concentration. *T*, T_w and T_∞ are the temperature of the fluid inside the boundary layer, the plate temperature and the fluid temperature in the free stream, respectively. Similarly, *C*, C_w and C_∞ are the corresponding concentrations. Also, K' is the permeability of a porous medium, α is the thermal diffusivity, D_m is the coefficient of mass diffusivity, c_p is the specific heat at constant pressure, *Tm* is the mean fluid temperature, k_T is the thermal diffusion ratio and c_s is the concentration susceptibility. The boundary conditions for the problem are given as:

$$u=U_0,\ v=V(x),\ T=T_w,\ C=C_w,\ \text{as } y=0, \tag{5}$$
$$u\to 0,\ T\to T_\infty,\ C\to C_\infty,\ \text{as } y\to\infty,$$

where U_0 is the plate uniform velocity and *V*(*x*) is the suction/injection velocity at the plate surface. The variable plate surface suction/injection velocity is prescribed as

$$V(x)=-f_w\sqrt{\frac{U_0\upsilon}{2x}}, \tag{6}$$

where f_w is a constant with $f_w > 0$ representing the transpiration (suction) at the plate surface, $f_w < 0$ corresponds to injection and $f_w = 0$ for an impermeable surface. The stream function ψ satisfies the continuity equation (1) automatically with

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

We introduce the following similarity and dimensionless variables into equations (1) - (5);

$$\eta=y\sqrt{\frac{U_0}{2\upsilon x}},\ \psi=\sqrt{2vxU_0}\,f(\eta),\ v=\sqrt{\frac{\upsilon U_0}{2x}}(\eta f'-f),$$

$$\theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \quad \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty}, \quad u = U_0 f', \tag{8}$$

to obtain

$$f''' + ff'' + G_T\theta + G_C\phi - (K + M_x) f' = 0, \tag{9}$$

$$\theta'' + \Pr f\theta' + Du \Pr \phi'' + \Pr Ec(f'')^2 + \Pr M_x Ec(f')^2 = 0, \tag{10}$$

$$\phi'' + Scf\phi' + ScSr\,\theta'' = 0, \tag{11}$$

with

$$f'(0) = 1, \ f(0) = f_w, \ \theta(0) = 1, \ \phi(0) = 1 \ \text{at} \ \eta = 0,$$
$$f'(\infty) = 0, \ \theta(\infty) \to 0, \ \phi(\infty) \to 0 \ \text{as} \ \eta \to \infty \tag{12}$$

where the prime symbol denotes differentiation with respect to η and

$G_T = \dfrac{2g\beta_T (T_w - T_\infty) x}{U_0^2}$ (Thermal Grashof number),

$G_C = \dfrac{2g\beta_C (C_w - C_\infty) x}{U_0^2}$ (Concentration Grashof number),

$K = \dfrac{2\upsilon x}{K' U_0}$ (Permeability parameter),

$\Pr = \dfrac{\upsilon}{\alpha}$ (Prandtl number),

$Sc = \dfrac{\upsilon}{D_m}$ (Schmidt number),

$Sr = \dfrac{D_m k_T (T_w - T_\infty)}{\upsilon T_m (C_w - C_\infty)}$ (Soret number),

$Du = \dfrac{D_m k_T (C_w - C_\infty)}{\upsilon c_s c_p (T_w - T_\infty)}$ (Dufour number),

$M_x = \dfrac{2\sigma H_0^2 x}{\rho U_0}$ (Magnetic field parameter),

$Ec = \dfrac{U_0^2}{c_p (T_w - T_\infty)}$ (Eckert Number)

The quantities of practical importance in this study with respect to engineering and industrial applications are the local skin friction coefficient, local Nusselt number and the local Sherwood number which are defined as follows:

$$C_f = \frac{\tau_w}{\rho U_0^2}, \ Nu = \frac{x q_w}{k(T_w - T_\infty)}, \ Sh = \frac{x q_m}{k(C_w - C_\infty)}, \tag{13}$$

where τ_w is the plate surface shear stress, q_w is the surface heat flux and q_m is the surface mass flux, which are given by;

$$\tau_w = \mu \left.\frac{\partial u}{\partial y}\right|_{y=0}, \ q_w = -k \left.\frac{\partial T}{\partial y}\right|_{y=0}, \ q_m = -D_m \left.\frac{\partial C}{\partial y}\right|_{y=0}. \tag{14}$$

Substituting equation (14) into equation (13), we obtain

$$\mathrm{Re}_x^{1/2} C_f = f''(0), \ \mathrm{Re}_x^{-1/2} Nu = -\theta'(0), \ \mathrm{Re}_x^{-1/2} Sh = -\phi'(0), \tag{15}$$

where $Re_x = U_0 x/\upsilon$ is the local Reynolds number. The set of equations (9) - (11) subject to the boundary conditions (12) were solved numerically by the Runge–Kutta–Fehlberg method with the shooting technique. Both the velocity, temperature and concentration profiles were obtained and used to compute the local skin-friction coefficient, the local Nusselt number and the local Sherwood number from equation (15).

3. Results and Discussions

In solving the problem, the value of Prandtl number (Pr) is taken equal to *0.71*, which corresponds physically to air. The value of Schmidt number (Sc) is chosen as *0.22*, which represents hydrogen at approximately $T_m = 25^0 C$ at a pressure of 1 *atm*, whilst the value of Eckert number (Ec) is taken to be 0.1. Furthermore, the values of Dufour number (Du) and Soret number (Sr) are chosen in such a way that their product is a constant provided that the mean temperature *Tm* is kept constant as well. Finally, the values of thermal Grashof number (G_T), concentration Grashof number (G_C), suction/injection parameter (f_w) and permeability parameter *K* are chosen arbitrarily.

Table 1 presents a comparison of computational results from our study with similar results obtain by Alam et al. (2006) for the local skin friction coefficient, local Nusselt number and the local Sherwood number. The table shows a perfect agreement between our results and that reported earlier, thus validating the numerical procedure.

Table 2 presents numerical results for various controlling parameters on the local skin friction co-efficient, the local Nusselt number and the local Sherwood number. It is clear that increasing the magnetic field parameter has the effect of increasing the local skin friction co-efficient due to the presence of Lorenz force induced by the magnetic field. The rate of heat transfer, which is proportional to the local Nusselt number is observed to decrease whilst the rate of mass transfer increase with increasing magnetic field parameter. A similar observation is made for the permeability parameter (K).

The suction parameter is observed to increase the local skin friction co-efficient and the local Nusselt number but decrease the local Sherwood number. It is further observed that both the thermal and solutal Grashof numbers have similar effects on the local skin friction coefficient as well as the local Nusselt and Sherwood numbers. Both parameters decrease the local skin friction co-efficient but increase the local Nusselt numbers and the local Sherwood numbers. Finally, increasing the Dufour number (Du) which is inversely related to the Soret number (Sr) has the effect of increasing both the local skin friction coefficient and the local Sherwood numbers but decreases the local Nusselt numbers.

Graphical results depicting the effects of various thermophysical parameters involved in the problem are presented in fig (2) - (22).

A) Velocity Profiles

The effect of varying the magnetic parameter on the velocity profile is illustrated in Fig 2. It is clear that the presence of the magnetic field results in a reduction of the velocity profiles in the boundary layer region as a consequence of the induced force, the Lorenz force, caused by the magnetic field. The Prandtl number is observed to have the same effect as the magnetic parameter, (see Fig 3). In Figs 4 and 5, the effect of both thermal and concentration Grashof numbers are illustrated. It is observed that increasing either of these parameters increases the velocity profiles particularly near the surface where a high overshoot is recorded.

Fig 6 depicts the effect of decreasing the Dufour number (Du) whilst increasing the Soret number (Sr) on the velocity profile. The velocity profiles are observed to increase with decreasing Dufour number but increasing Soret number, and vice versa. Conversely, suction and permeability parameters have the effect of decreasing the velocity profiles for obvious reasons as shown in Fig 7 and 8.

B) Temperature Profiles

Figs 9 – 15 illustrate the temperature profiles for various parameter variations. It is clear from these figures that apart from the magnetic parameter (Fig 9) and the permeability parameter (Fig 15), which increase the thermal boundary layer, all other parameters including the Prandtl number (Fig 10), the thermal Grashof number (Fig 11), the concentration Grashof number (Fig 12), the Dufour and Soret numbers (Fig 13) and suction parameter (Fig 14) reduces the thermal boundary layer.

C. Concentration Profiles

The effect of parameter variation on the concentration profiles are depicted in Figs 16 to 22. It is observed that the magnetic parameter (Fig 16), the Prandtl number (Fig 17), Soret and Dufour numbers (Fig 20) as well as permeability parameter (Fig 22) increases the concentration boundary layer. The thermal and concentration Grashof numbers (Figs 18 and 19) as well as the suction parameters (Fig 21) are observed to decrease the concentration boundary layer.

4. Conclusion

The Dufour and Soret effect on a hydromagnetic flow with heat and mass transfer past a continuously moving semi-infinite vertical porous plate in a porous medium permeated by a transverse magnetic field have been investigated. The study numerically considered the hydrogen-air mixture as a non-chemical reacting fluid pair. The results show that the velocity, temperature and the concentration fields are appreciably influenced by the Dufour and Soret numbers. It is noted that both permeability of the medium and the magnetic field together with fluid suction influence the flow structure. We conclude that for fluids with medium molecular weight (H_2, air), the Dufour and Soret effects should not be neglected.

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Table 1: Comparison of Skin-friction coefficient, Nusselt number and Sherwood number for $G_T = 10$, Gc = *4*, *fw = 0.5*, K = 0.3, Pr = 0.71, *Mx* = 0, Ec = 0 and Sc = 0.22

		$f''(0)$		$-\theta'(0)$		$-\phi'(0)$	
Du	Sr	Alam et al. (2006)	Present Study	Alam et al. (2006)	Present Study	Alam et al. (2006)	Present Study
0.030	2	6.2285	6.22933	1.1565	1.15640	0.1531	0.153205
0.037	1.6	6.1491	6.15001	1.1501	1.15001	0.2283	0.228403
0.05	1.2	6.0720	6.07293	1.1428	1.14265	0.3033	0.303335
0.075	0.8	6.0006	6.00160	1.1333	1.13316	0.3781	0.378167
0.150	0.4	5.9553	5.95636	1.1157	1.11555	0.4540	0.454027

Table 2: Effects of parameter variation on the local skin-friction coefficient, local Nusselt number and local Sherwood number when Pr = 0.71, Ec = 0.1 and Sc = 0.22

M_x	K	f_w	G_T	Gc	Du	Sr	$-f''(0)$	$-\theta'(0)$	$-\phi'(0)$
0	0.1	0.1	0.1	0.1	0.03	2	0.5225365	0.5666191	0.0653688
1	0.1	0.1	0.1	0.1	0.03	2	1.1033257	0.4339862	0.0681926
2	0.1	0.1	0.1	0.1	0.03	2	1.4933974	0.3511663	0.0794370
1	0.5	0.1	0.1	0.1	0.03	2	1.2731642	0.4071620	0.0678918
1	1.0	0.1	0.1	0.1	0.03	2	1.4590866	0.3786500	0.0693253
1	0.1	0.5	0.1	0.1	0.03	2	1.3296735	0.6304819	0.0283776
1	0.1	1.0	0.1	0.1	0.03	2	1.6553486	0.9036972	0.0239712
1	0.1	0.1	1	0.1	0.03	2	0.5878207	0.5109070	0.0773490
1	0.1	0.1	2	0.1	0.03	2	0.0666503	0.5565948	0.0905220
1	0.1	0.1	0.1	1	0.03	2	0.3605773	0.5641660	0.1181872
1	0.1	0.1	0.1	2	0.03	2	-0.3663646	0.6102922	0.1606354
1	0.1	0.1	0.1	0.1	0.05	1.2	1.10772199	0.4296848	0.1277673
1	0.1	0.1	0.1	0.1	0.15	0.4	1.11163430	0.4184908	0.1869470

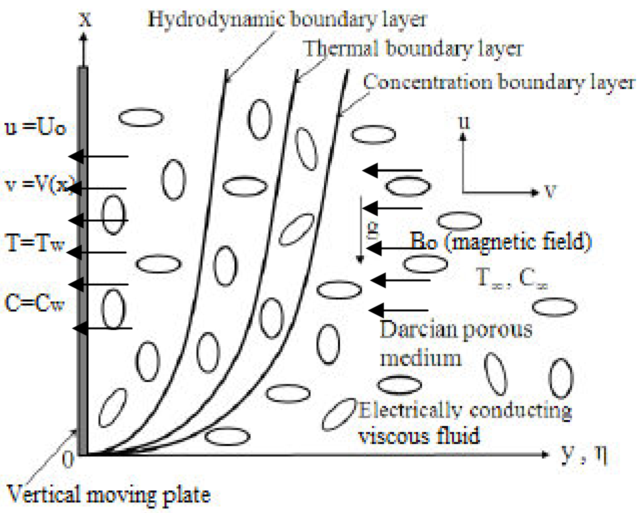

Fig. 1: Physical Configuration of the problem

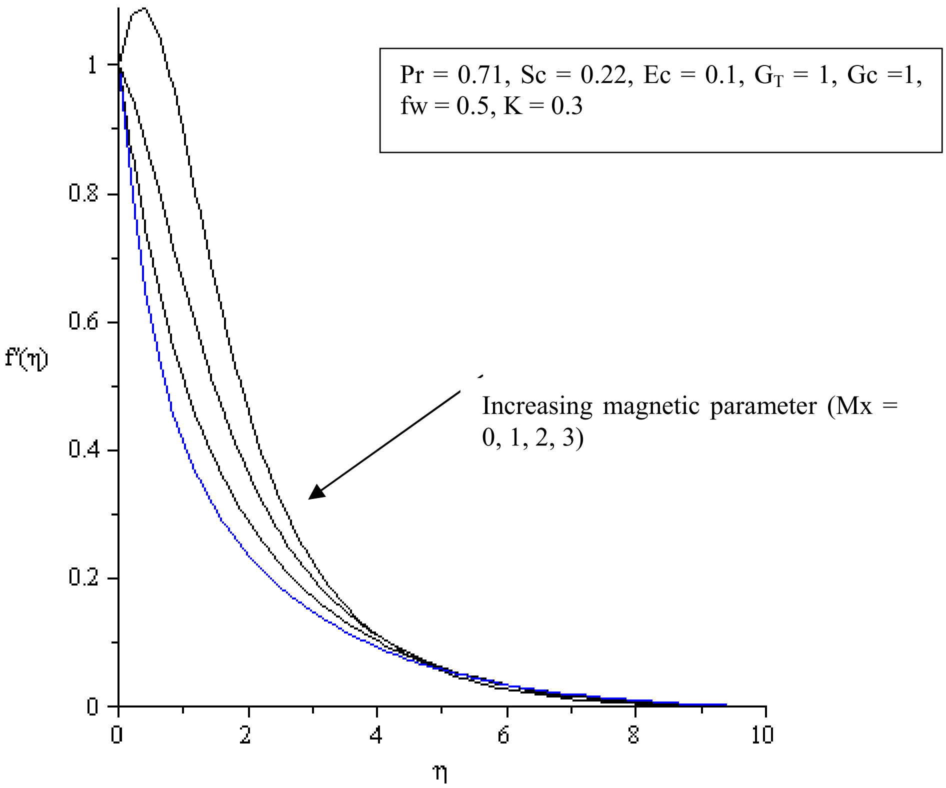

Fig. 2: Velocity Profiles for varying values of Mx

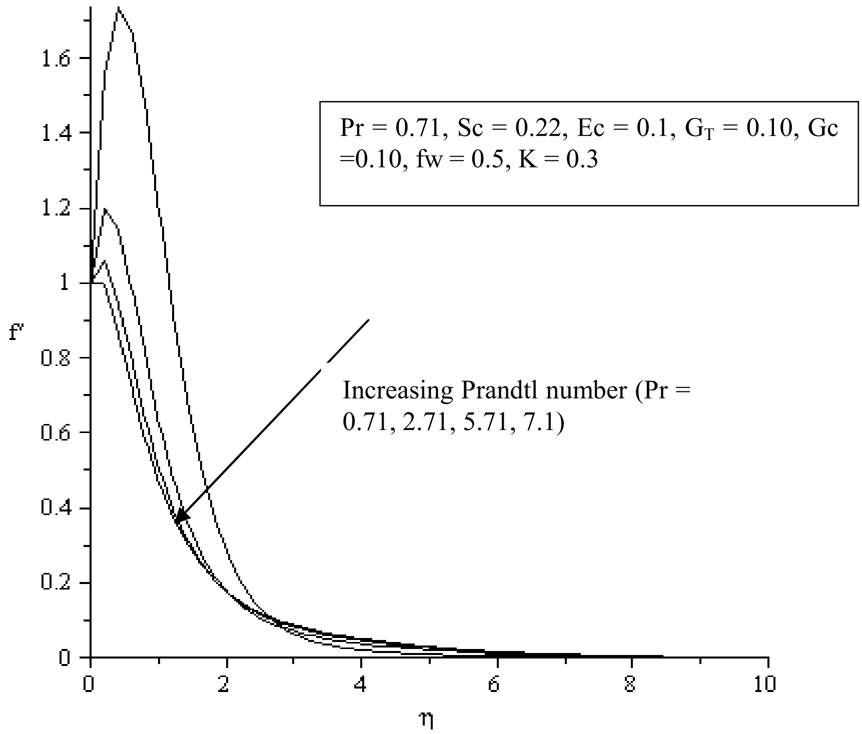

Fig. 3: Velocity Profiles for varying values of Prandtl number

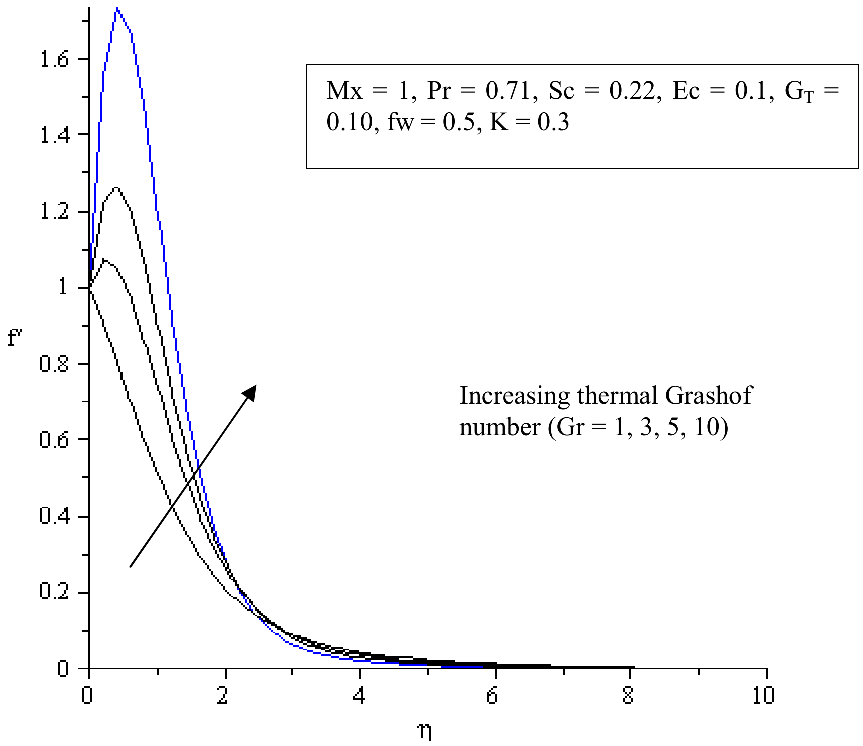

Fig. 4: Velocity Profiles for varying values of Thermal Grashof number

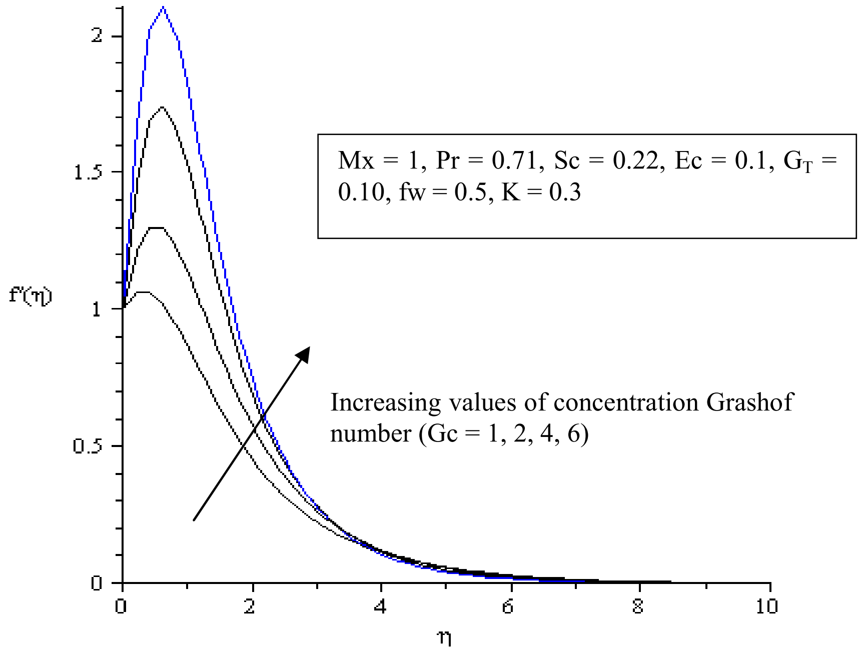

Fig. 5: Velocity Profiles for varying values of concentration Grashof number

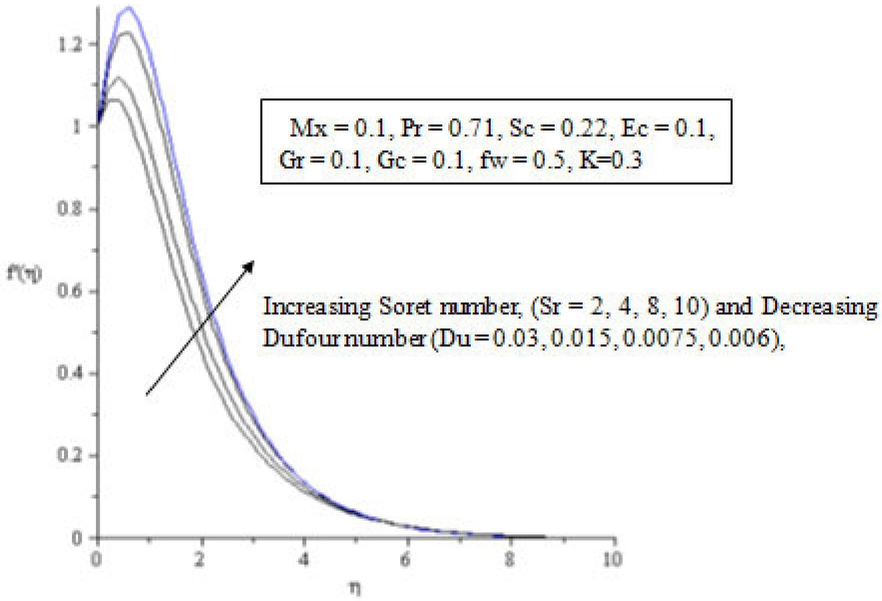

Fig. 6: Velocity Profiles for varying values of Dufour and Soret numbers

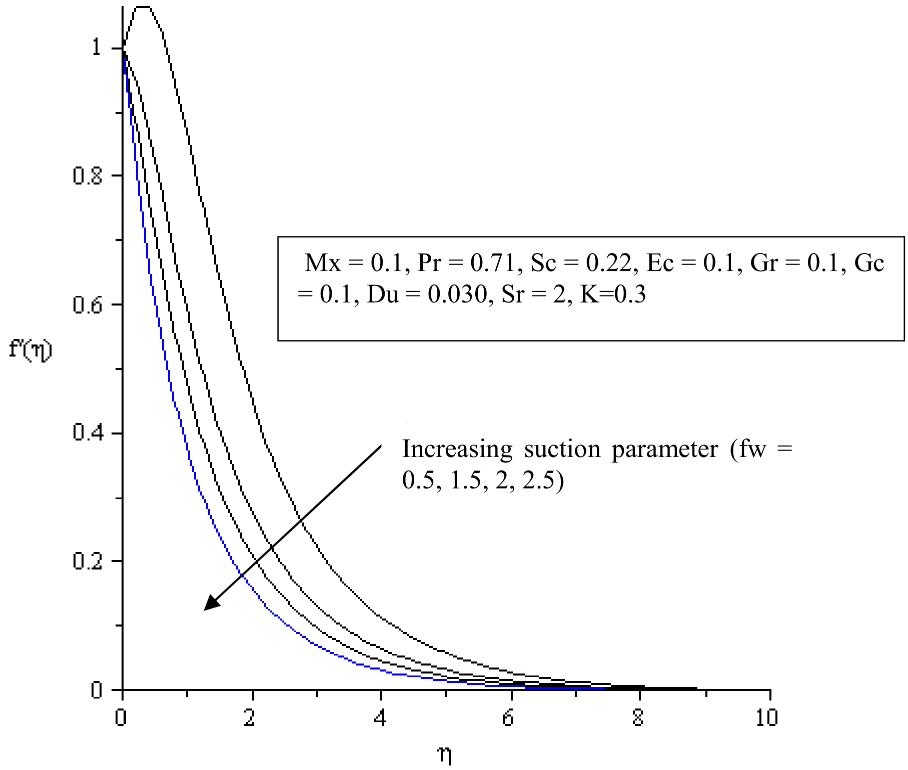

Fig. 7: Velocity Profiles for varying values of suction parameter

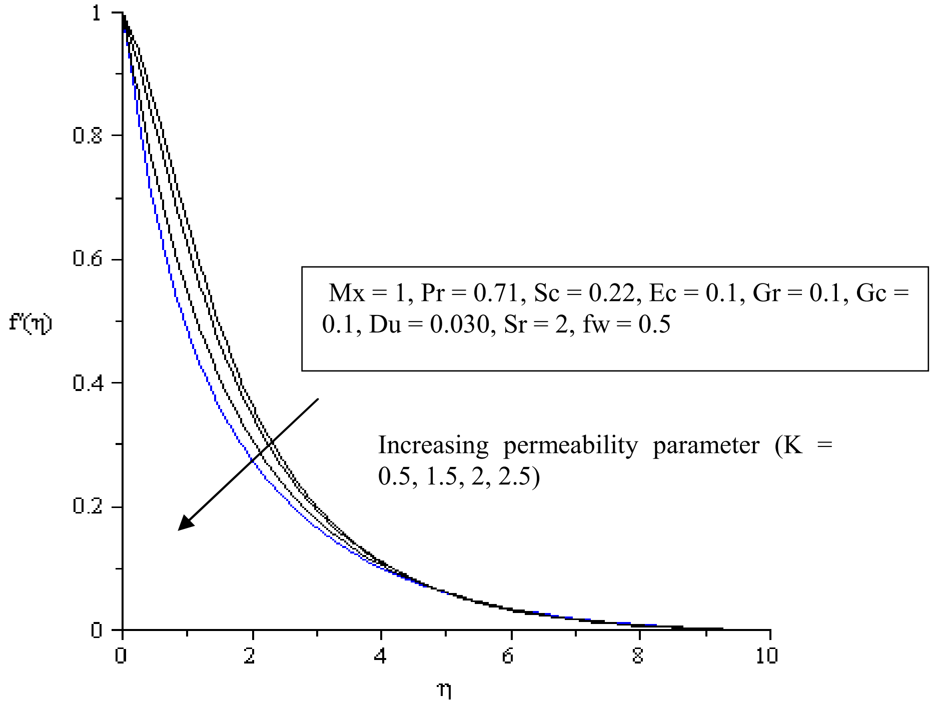

Fig. 8: Velocity Profiles for varying values of permeability parameter

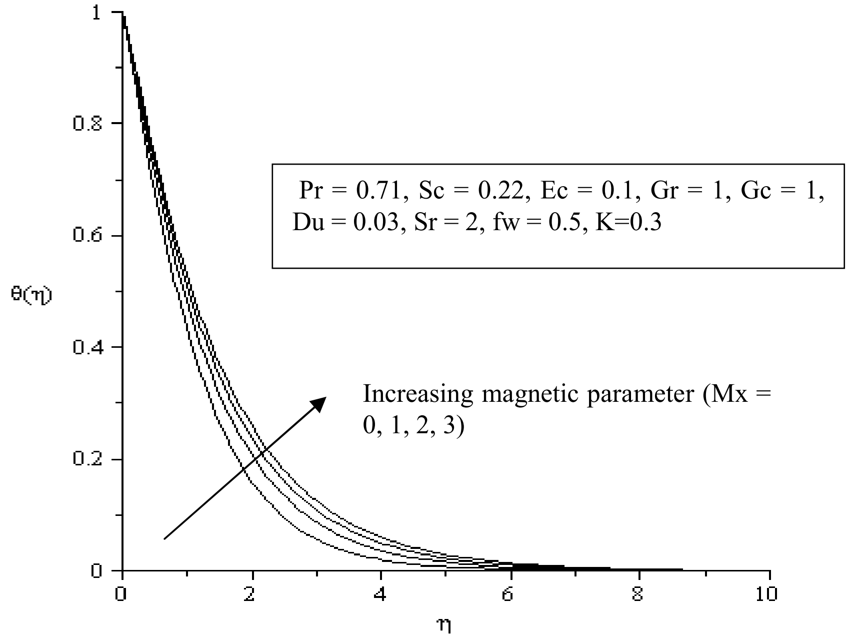

Fig. 9: Temperature Profile for varying Magnetic parameter

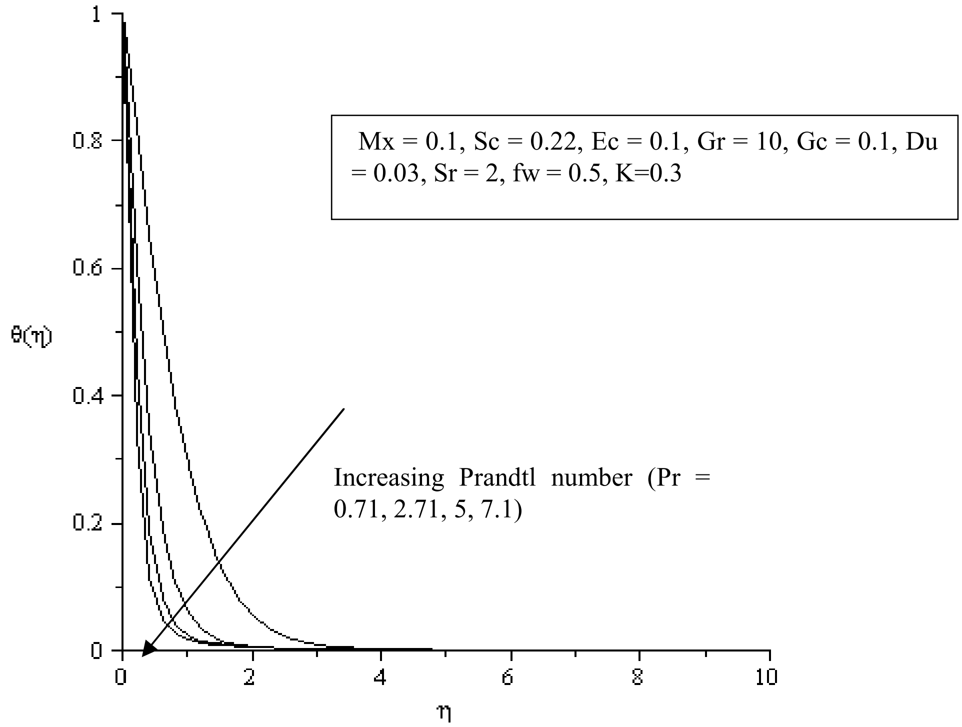

Fig. 10: Temperature profiles for varying Prandtl numbers

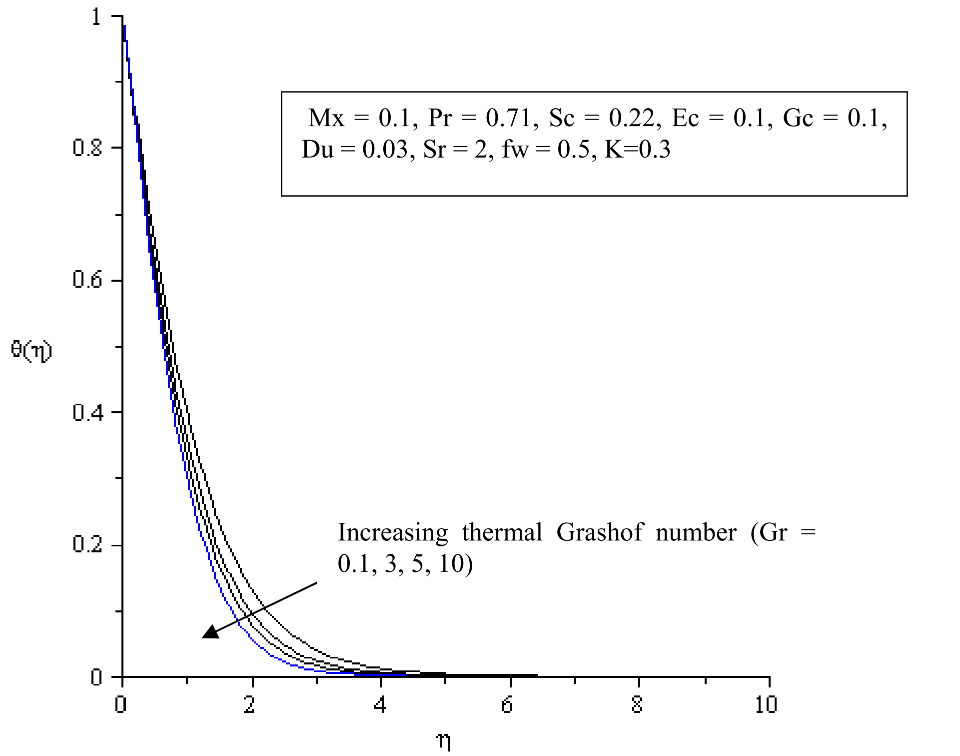

Fig. 11: Temperature Profiles for varying thermal Grashof number

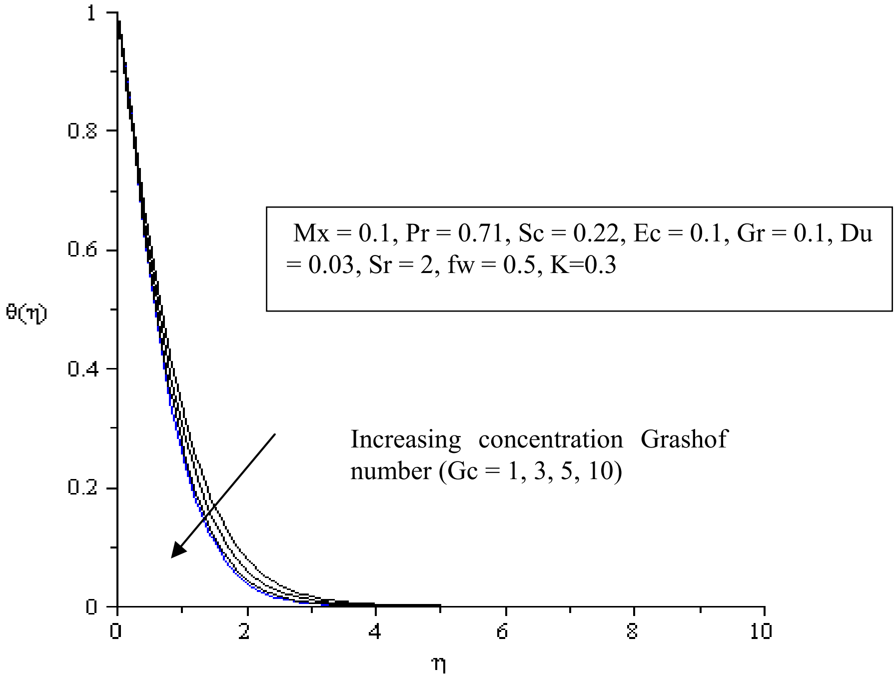

Fig. 12: Temperature Profiles for varying concentration Grashof number

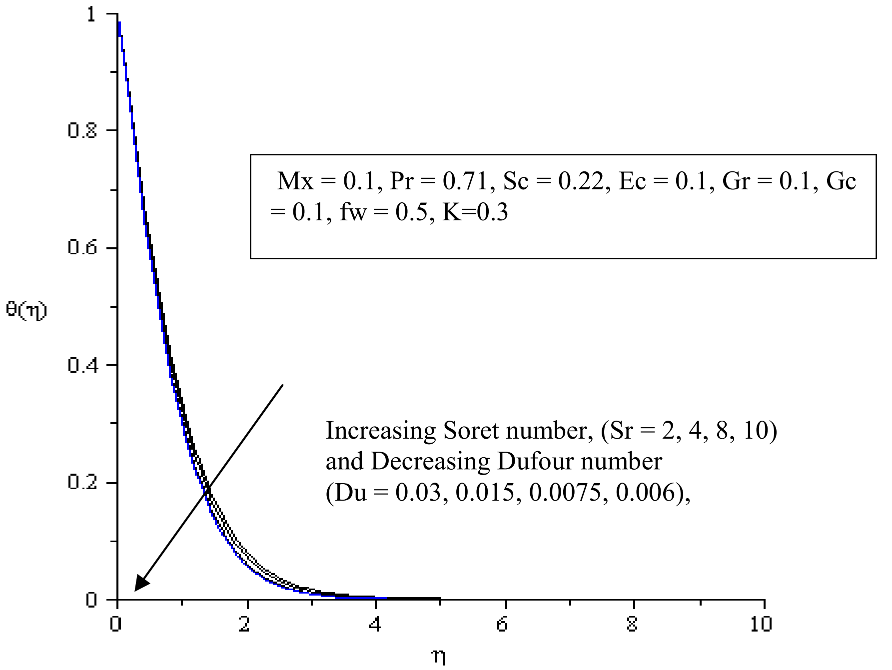

Fig. 13: Temperature Profiles for varying values of Dufour and Soret numbers

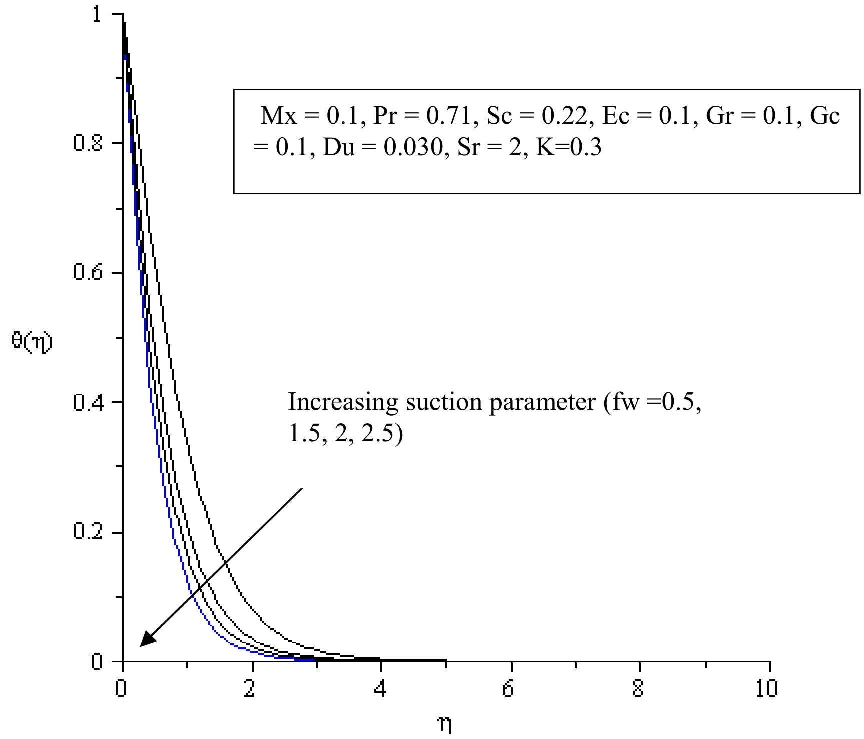

Fig. 14: Temperature Profiles for varying values of suction parameter

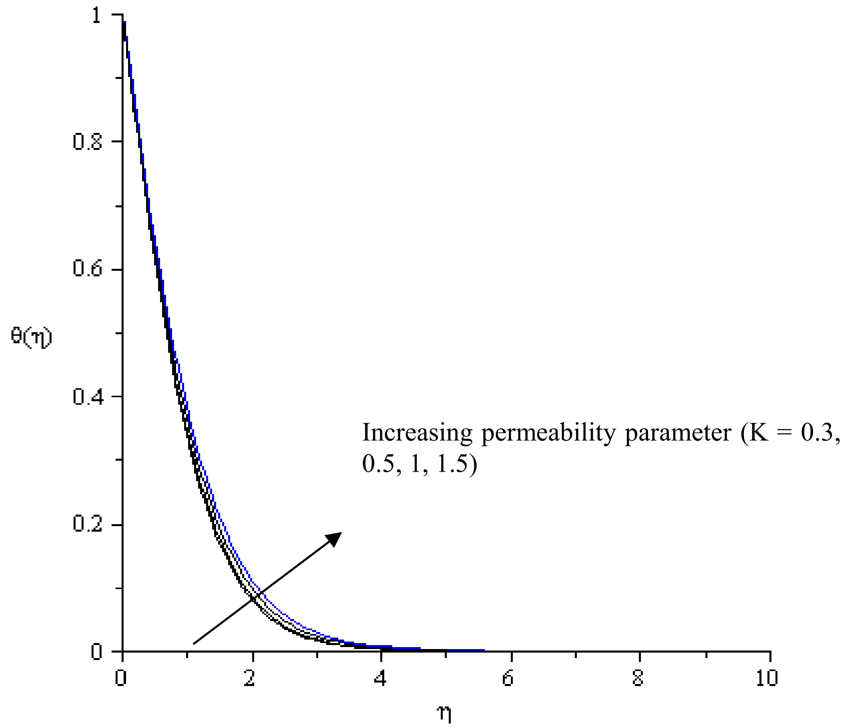

Fig. 15: Temperature Profiles for varying values of the permeability parameter

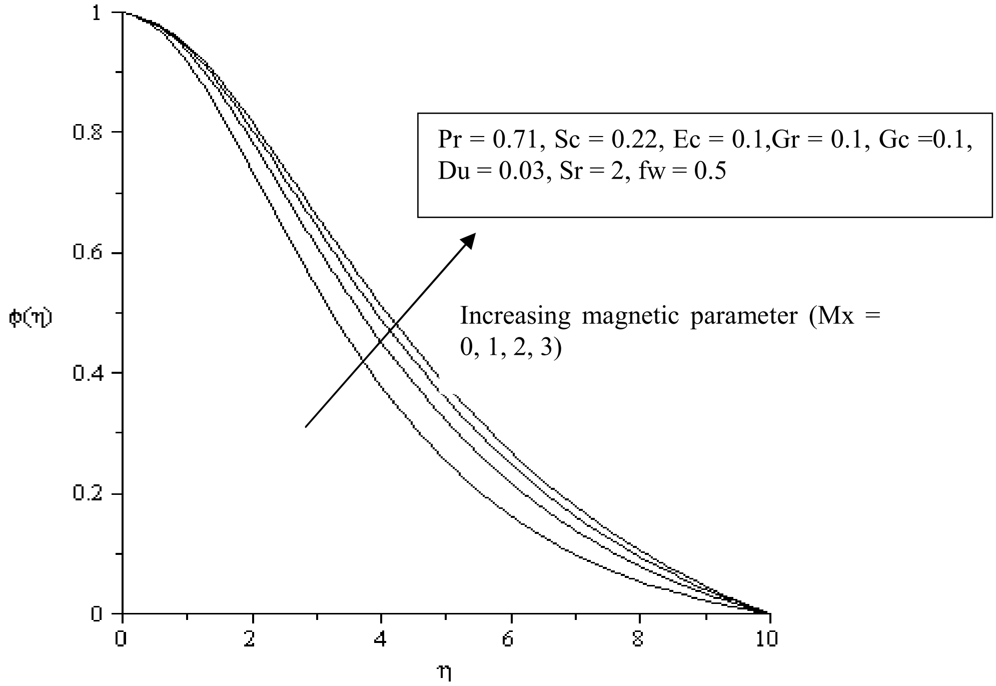

Fig. 16: Concentration Profiles for varying magnetic parameter

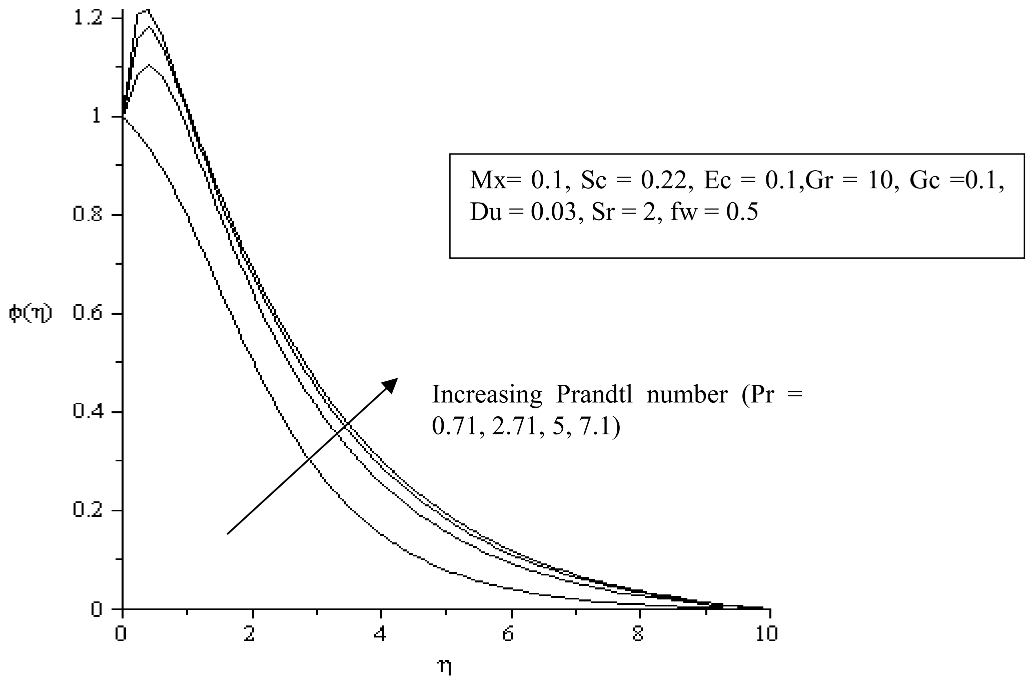

Fig. 17: Concentration Profiles for varying values of the Prandtl number

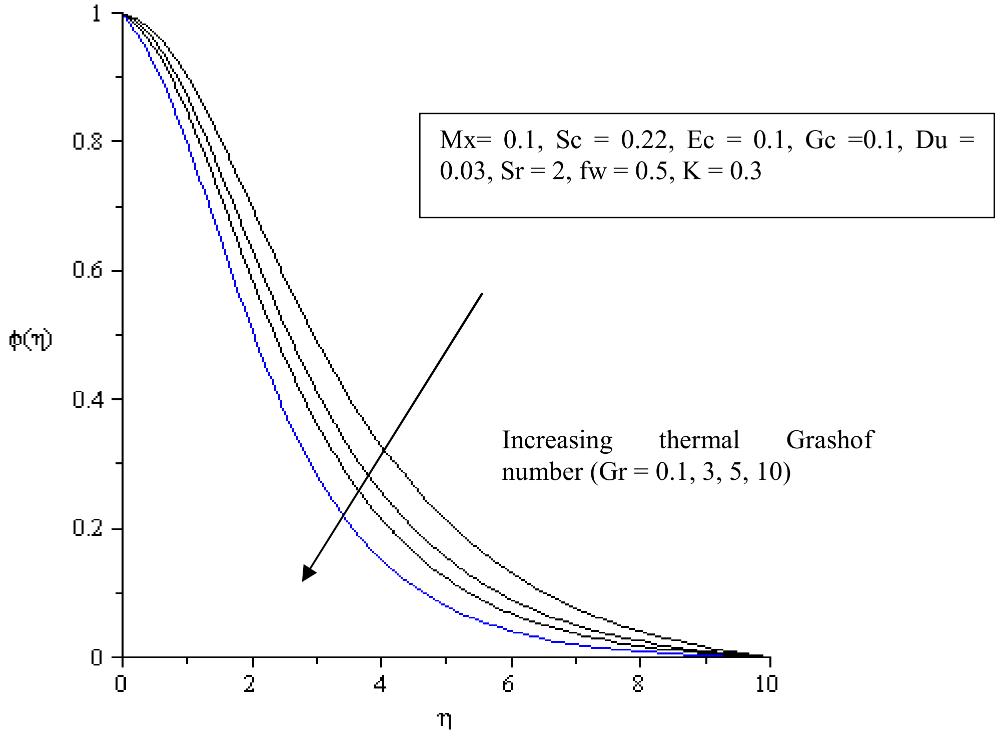

Fig. 18: Concentration Profiles for varying values of thermal Grashof number

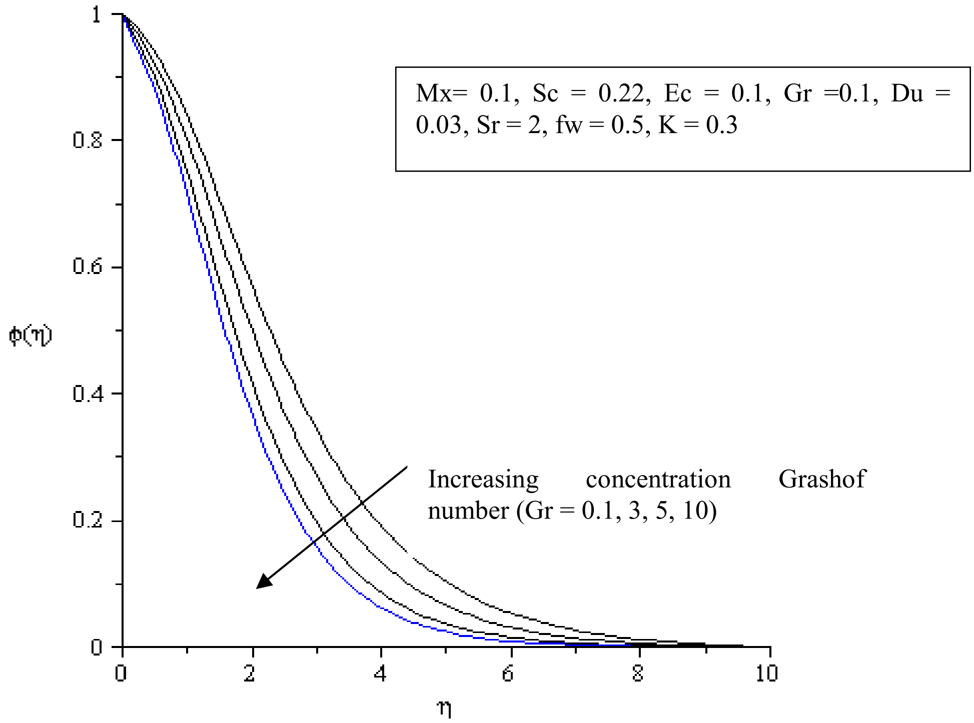

Fig. 19: Concentration Profiles for varying values of concentration Grashof number

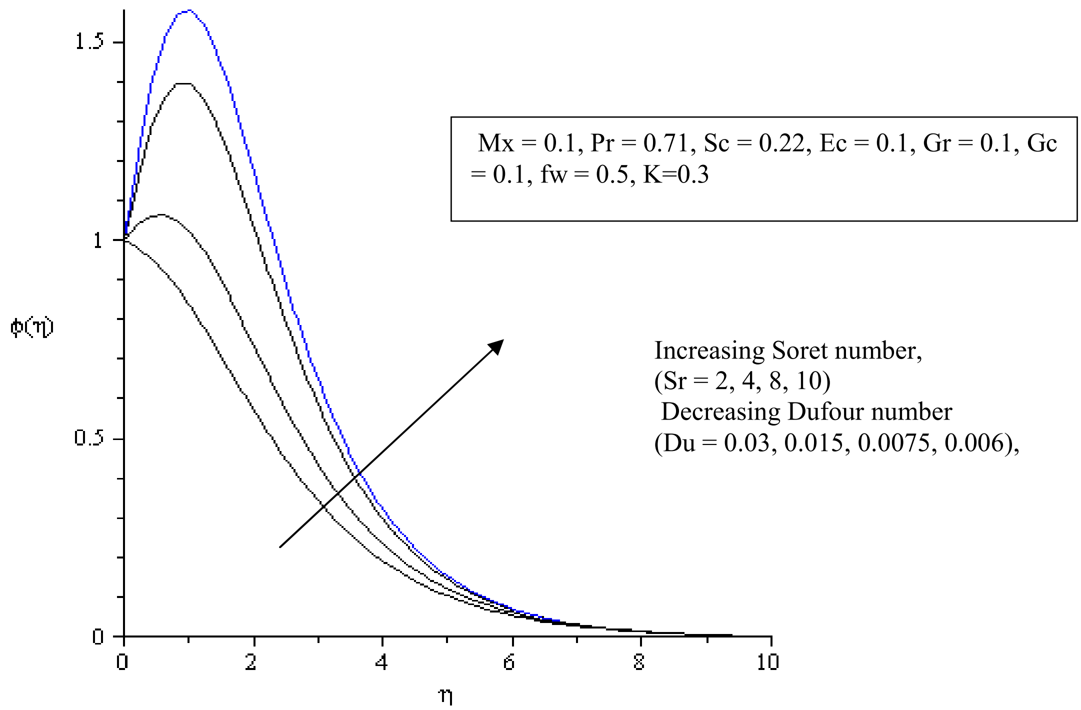

Fig. 20: Concentration Profiles for varying values of Dufour and Soret numbers

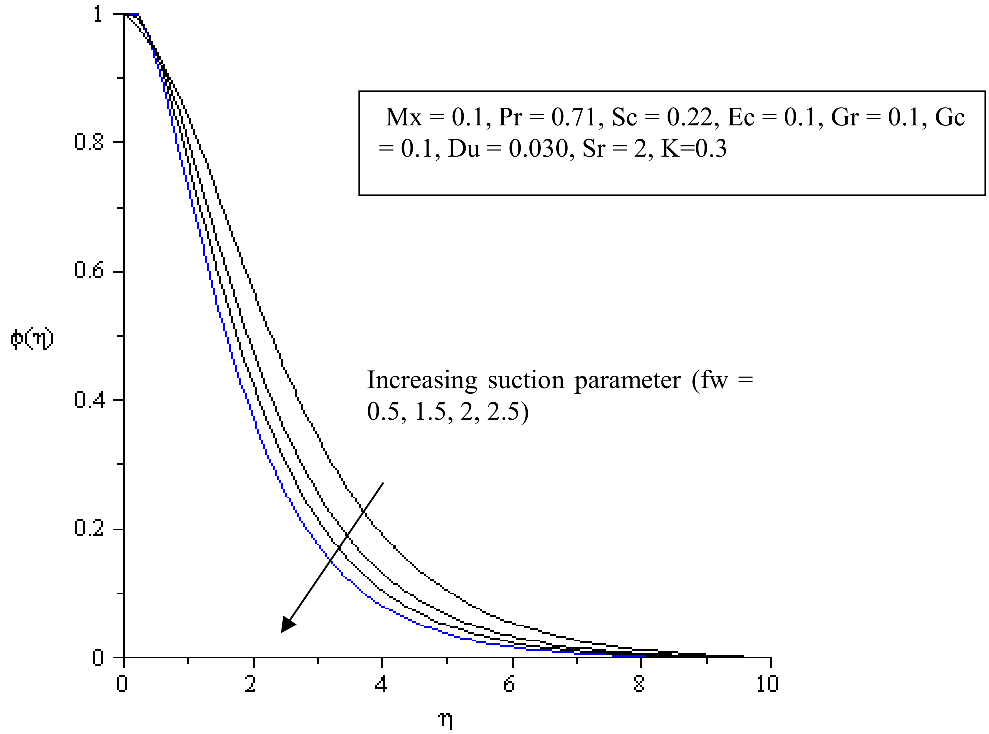

Fig. 21: Concentration Profiles for varying values of suction parameter

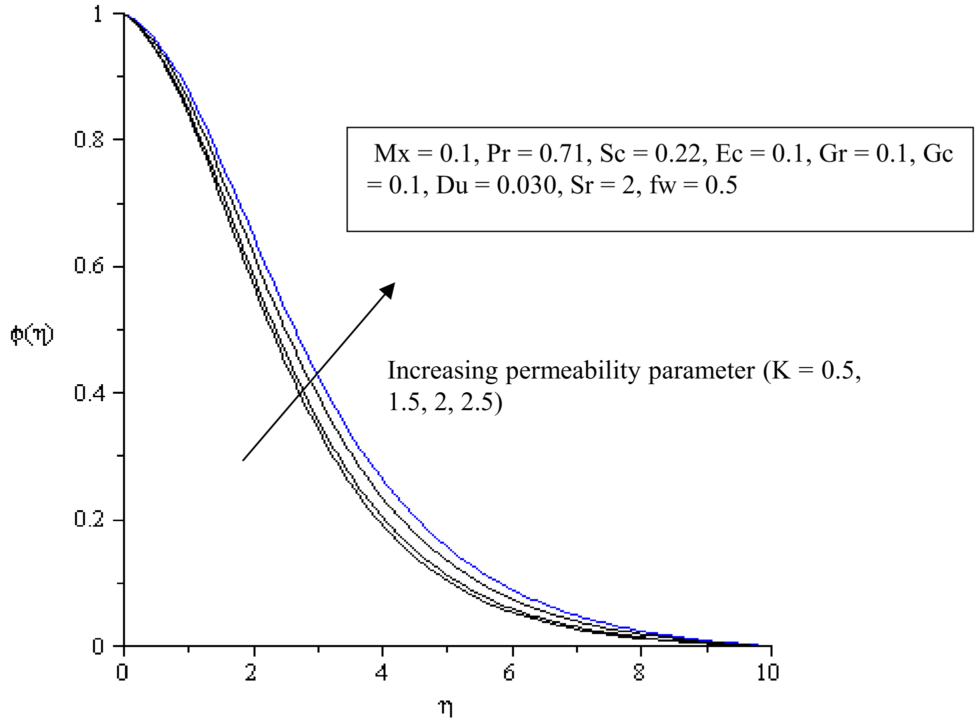

Fig. 22: Concentration Profiles for varying values of the Permeability parameter

Nomenclature:

x, y	Cartesian Coordinates variables
u, v	Velocity components in the x- and y- coordinate axes
g	Acceleration due to gravity,
B_0	Magnetic parameter
β_T	Volumetric coefficient of expansion with temperature,
β_C	Volumetric coefficient of expansion with concentration,
T	Fluid temperature,
T_w	Plate surface temperature,
T_∞	Temperature of fluid medium far away from the plate surface,
C	Fluid concentration,
C_w	Plate surface concentration,
C_∞	Concentration of the fluid medium far away from the plate surface,
K'	Permeability of the porous medium,
D_m	Coefficient of mass diffusivity,
c_p	Specific heat capacity at constant pressure,
Tm	Mean fluid temperature,
k_T	Thermal diffusion ratio,
c_s	Concentration susceptibility,
U	Plate uniform velocity,
$V(x)$	Suction/injection velocity at the plate,
G_T	Thermal Grashof number,
Gc	Concentration Grashof number,
K	Permeability parameter,
Pr	Prandtl number,
Sc	Schmidt number,

Sr	Soret number,
Du	Dufour number,
E_c	Eckert Number,
q_w	Surface heat flux,
q_m	Surface mass flux,
Mx	Magnetic parameter
Re_x	Local Reynolds number,
C_f	Local skin friction coefficient,
Nu_x	Local Nusselt number,
Sh_x	Local Sherwood number,

Greek Symbols

η	Dimensionless coordinate variable
ρ	Fluid density,
υ	Kinematic viscosity,
α	Thermal diffusivity,
τ_w	Plate surface shear stress,
ψ	Dimensionless stream function
ϕ	Dimensionless concentration,
θ	Dimensionless temperature,

Subscribes

w	Wall conditions
∞	Conditions at infinity