Original Article

Bulletin of Pure and Applied Sciences.
Vol. 37E (Math & Stat.), No.2, 2018.P.507-518
Print version ISSN 0970 6577
Online version ISSN 2320 3226
DOI: 10.5958/2320-3226.2018.00055.3

MHD CONVECTIVE FLOW THROUGH VERTICAL PLATE IN POROUS MEDIUM WITH VARIABLE PROPERTIES OF HEAT AND MASS TRANSFER

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Received on 29.05.2018, Accepted on 26.10.2018

Abstract

The present paper concerns with the effects of variable viscosity and thermal conductivity on an unsteady two dimensional laminar flow of a viscous incompressible electrically conductive fluid over a semi infinite vertical plate. The impact of chemical reaction, internal heat generation and Soret effect are considered. The fluid viscosity is assumed as a linear function of temperature. The basic governing non linear partial differential equations are transformed into a system of ordinary differential equations and solved by perturbation technique. Analytical solution deduced here is found to depend on many physical parameters including the Hartmann number M, Prandtl number Pr, Grashof number Gr, modified Grashof number Gm and Schmidt number Sc. The velocity, temperature and concentration fields are graphically discussed to observe the effects of parameters entering in the problem. The expressions for skin friction, Nusselt number and Sherwood number are derived. Finally a thorough discussion of different results is presented.

Keywords: Radiation, Porous medium, Thermal conductivity, MHD, Heat generation, and Soret effect.

1. INTRODUCTION

The subject of magneto hydrodynamics has attracted the attention of a large number of research scholars due to its diverse applications in several problems of technological importance. The ionized gas or plasma can be made to interact with the magnetic field and can frequently alter heat transfer and friction characteristics on the bounding surface. Heat transfer by thermal radiation is assuming greater importance when we are concerned with space applications, higher operating temperatures and also power engineering. In astrophysics and geophysics, it is mainly applied to study the stellar and solar structures, interstellar matter, radio propagation through the ionosphere, etc. In engineering, the problem assumes greater significance in MHD pumps, MHD journal bearings, etc. Recently, it is of great interest to study the effects of magnetic field and other participating parameters on the temperature distribution and heat transfer when the fluid is not only an electrical conductor but also when it is capable of emitting and absorbing thermal radiation. The flow of Newtonian electrically - conducting fluids is also of great interest in high speed aerodynamics, astronomical plasma flows, MHD boundary layer control, MHD accelerator technologies and the applications are many from the view of science and technology. Free convection flow involving coupled heat and mass transfer occurs frequently in several areas of chemical engineering and manufacturing process sectors. Free convection arises in the fluid when temperature changes cause density variation leading to buoyancy forces acting on the fluid elements. The study of heat and mass transfer to chemical reacting MHD free convection flow with radiation effects on a vertical plate has received a growing interest during the last decades. Chamkha [1] analyzed an unsteady, MHD convective, viscous incompressible, heat and mass transfer along a semi-infinite vertical porous plate in the presence of transverse magnetic field, thermal and concentration buoyancy effects. Das and Jana [2] studied heat and mass transfer effects on unsteady MHD free convection flow near a moving vertical plate in porous medium. Sharma [3] investigated the effect of periodic heat and mass transfer on the unsteady free convection flow past a vertical flat plate in slip flow regime when suction velocity oscillates in time. Muthucumaraswamy and Meenakshisundaram [4] examined theoretical study of chemical reaction effects on vertical oscillating plate with variable temperature. Osman et al. [5] developed analytical solution for thermal radiation and chemical reaction effects on unsteady MHD convection through porous media with heat source. Prasad et al. [6] investigated thermal radiation effects on magnetohydrodynamic free convection heat and mass transfer from a sphere in a variable porosity regime. Anjalidevi and Kandasamy [7] analyzed the effects of a chemical reaction heat and mass transfer on MHD flow past a semi-infinite plate. Kumar and Reddy [8] studied radiation and chemical reaction effects on MHD flow fluid over an infinite vertical oscillating porous plate. Ramana Reddy et al. [9] investigated thermal diffusion and chemical reaction effects on unsteady MHD dusty viscous flow. Alam et al. [10] studied the problem of free convection heat and mass transfer flow past an inclined semi-infinite heated surface of an electrically conducting and steady viscous incompressible fluid in the presence of magnetic field and heat generation. Anghel et al. [11] examined Dufour and Soret effects on free convection boundary-layer over a vertical surface embedded in a porous medium. Sengupta and Sen [12] investigated free convective heat and mass transfer flow past an oscillating plate with heat generation, thermal radiation and thermo-diffusion effects. Cess [13] observed the interaction of thermal radiation with free convection heat transfer. Rao and Viswanatha [14] studied Soret and Dufour effects on hydromagnetic heat and mass transfer over a vertical plate in a porous medium with a convective surface boundary condition and chemical reaction. Subhakar and Gangadhar [15] examined Soret and Dufour effects on MHD free convection heat and mass transfer flow over a stretching vertical plate with suction and heat source/sink. Ibrahim [16] studied unsteady MHD convective heat and mass transfer past an infinite vertical plate embedded in a porous medium with radiation and chemical reaction under the influence of Dufour and Soret effects. Bhavana et al. [17] observed the Soret effect on free convective unsteady MHD flow over a vertical plate with heat source. Muthucumaraswamy and Ganesan [18] examined effects of suction on heat and mass transfer along a moving vertical surface in the presence of chemical reaction. Reddy and Reddy [19] studied radiation effects on MHD combined convection and mass transfer flow past a vertical porous plate embedded in a porous medium with heat generation. Chaudhary and Jha [20] examined the effects of chemical reactions on MHD micropolar fluid flow past a vertical plate in slip-flow regime. Few other studies are also reported [21-26].

2. MATHEMATICAL FORMULATION

In a situation of two dimensional unsteady laminar natural convection flows of a viscous, incompressible, electrically conducting, radiating fluid past an impulsively started semi-infinite vertical plate in the presence of transverse magnetic field with viscous dissipation is considered. The fluid is assumed to be gray, absorbing emitting but non-scattering. The x^* - axis is taken along the plate in the upward direction and the y^*- axis is taken normal to it. The fluid is assumed to be slightly conducting and hence the magnetic Reynolds number is much less than unity and the induced magnetic field is negligible in comparison with the transverse applied magnetic field. Initially, it is assumed that the plate and the fluid are at the same temperature T_∞^* and concentration level C_∞^* everywhere in the fluid. At time $t^*>0$, the plate starts moving impulsively in the vertical direction with constant velocity u_0 against the gravitational field. Also, the temperature of the plate and the concentration level near the plate are raised to T_w^* and C_w^*, respectively and are maintained constantly thereafter. It is assumed that the concentration C^* of the diffusing species in the binary mixture is very less in comparison to the other chemical species, which are present and hence the Soret and Dufour effects are negligible. It is also assumed that there is no chemical reaction between the diffusing species and the fluid. Then, under the above assumptions, in the absence of an input electric field, the governing boundary layer equations with Boussinesq's approximation are

Continuous equation

$$\frac{\partial u^*}{\partial x^*}+\frac{\partial v^*}{\partial y^*}=0 \quad (1)$$

Momentum conservation

$$\frac{\partial u^*}{\partial t^*}+u^*\frac{\partial u^*}{\partial x^*}+v^*\frac{\partial u^*}{\partial y^*}= g\beta(T^*-T^*_\infty)+g\beta^*(C^*-C^*_\infty)+v^*\frac{\partial^2 u^*}{\partial y^{*2}}-\frac{\sigma\beta_0^2}{\rho}u^*-\frac{v}{k^1}u^* \quad (2)$$

Energy conversation

$$\frac{\partial T^*}{\partial t^*}+u^*\frac{\partial T^*}{\partial x^*}+v^*\frac{\partial T^*}{\partial y^*}=\alpha\frac{\partial^2 T^*}{\partial y^{*2}}-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial y}+\frac{v^*}{cp}\left(\frac{\partial u^*}{\partial y^*}\right)^2+\frac{Q}{\rho C_p}(T^*-T^*_\infty) \quad (3)$$

Species conservation

$$\frac{\partial C^*}{\partial t^*}+u^*\frac{\partial C^*}{\partial x^*}+v^*\frac{\partial C^*}{\partial y^*}=D\frac{\partial^2 C^*}{\partial y^{*2}}-K_r^1(C^*-C^*_\infty)+D_1\frac{\partial^2 T^*}{\partial y^{*2}} \quad (4)$$

The initial and boundary conditions are as follows:

$$t\le 0, u=0, v=0 \quad T^*=T^*_\infty \quad C^*=C^*_\infty \ \forall y$$

$$t*>0, u*=u_0 e^{a^*t^*}, T*= Tw*+\in(T^*_w-T^*_\infty)ent, C*=C_W*+\in(C^*_w-C^*_\infty)e^{n^*t^*}$$

$$\text{at } y^*=0 \quad u*=0, T*\to T_\infty, C^*\to C^\infty \text{ at } y^*\to\infty \quad (5)$$

Thermal radiation is assumed to be present in the form of a unidirectional flux in the *y* -direction i.e., q_r(transverse to the vertical surface). By using the Roseland approximation, the radioactive heat flux q_r is given by

$$q_r=-\frac{4\sigma_s}{3k_c}\frac{\partial T^{*4}}{\partial y^*} \quad (6)$$

where, σ_s is the Stefan-Boltzmann constant and k_c – the mean absorption coefficient. In the Roseland approximation, the present analysis is limited to optically thick fluids. If temperature differences within the flow are sufficiently small, then equation (6) can be linearized by

expanding T^{*4} into the Taylor series about T^*_∞, which, after neglecting higher order terms, takes the form

$$T^{*4}=4T^{*3}_\infty-T^{*4}_\infty \quad (7)$$

In view of (6) and (7), (3) reduces to

$$\frac{\partial T^*}{\partial t^*}+u^*\frac{\partial T^*}{\partial x^*}+v^*\frac{\partial T^*}{\partial y^*}=\alpha\frac{\partial^2 T^*}{\partial y^{*2}}+16\frac{\sigma_s T^{*3}}{3k_c c_p\rho c_p}\frac{\partial^2 T^*}{\partial y^{*2}}+\frac{v^*}{cp}\left(\frac{\partial u^*}{\partial y^*}\right)^2 \quad (8)$$

The non-dimensionless quantities introduced in these equations are defined as

$$x=\frac{x^*u_0}{v}, y=\frac{y^*u_0}{v}, t=\frac{t^*u_0^2}{v}, k_r=\frac{k_r^1}{u_0^2}, u=\frac{u^*}{u_0}, v=\frac{v^*}{u_0}, r=\frac{vg\beta(T^*_w-T^*_\infty)}{u_0^2}, G_m=\frac{vg\beta^*(T^*_w-T^*_\infty)}{u_0^2}$$

$$N=\frac{k_ck}{4\sigma_{s}T^{*3}_\infty}, M=\frac{\sigma\beta_0^2 v}{u_0^2}, \theta=\frac{T^*-T^*_\infty}{T^*_w-T^*_\infty}, \emptyset=\frac{C^*-C^*_\infty}{C^*_w-C^*_\infty}, K=\frac{k^1u_0^2}{v}, p_r=\frac{v}{\alpha}, s_c=\frac{v}{D}, \quad (9)$$

In a situation where only one dimensional flow is considered, the above set of equations (1), (2), (8) and (4) are reduced to the following non-dimensional form:

$$\frac{\partial v}{\partial y}=0 \Longrightarrow v=-v_0 \text{ (where } v_0=1) \quad (10)$$

$$\frac{\partial u}{\partial t}-\frac{\partial u}{\partial y}=G_r\theta+Gm\emptyset+\frac{\partial^2 u}{\partial y^2}-(M+\frac{1}{K})u \quad (11)$$

$$\frac{\partial\theta}{\partial t}-\frac{\partial\theta}{\partial y}=\frac{1}{p_r}(1+\frac{4}{3N})\frac{\partial^2\theta}{\partial y^2}+Q\theta \quad (12)$$

$$\frac{\partial\emptyset}{\partial t}-\frac{\partial\emptyset}{\partial y}=\frac{1}{s_c}\frac{\partial^2\emptyset}{\partial y^2}-K_r\emptyset+s_0\frac{\partial^2\theta}{\partial y^2} \quad (13)$$

The corresponding initial and boundary conditions are as follows:

$$t\le 0, U=0, T=0, C=0 \ \forall y$$

$$u=e^{at}, \theta=1+\in e^{nt}, \varphi=1+\in e^{nt} \text{ at } y=0 \quad (14)$$

$$u=0, \theta\to 0, \varphi\to 0 \text{ as } y\to 0$$

Solution of the Problem:

In order to solve the equations (11) - (13) with respect to the boundary conditions (14) for the flow, let us take

$$u(y,t)=u_0(y)+\in u_1(y)e^{nt} \quad (15)$$

$$\theta(y,t)=\theta_0(y)+\in\theta_1(y)e^{nt} \quad (16)$$

$$\emptyset(y,t)=\emptyset_0(y)+\in\emptyset_1(y)e^{nt} \quad (17)$$

Substituting the equations (15) - (17) into the equations (11) – (13), we obtain:

$$u_0''+u_o'-(M+\frac{1}{K})u_0=-[G_r\theta_0+G_m\emptyset_0] \quad (18)$$

$$u_1''+u_1'-(n+M+\frac{1}{K})u_1=-[G_r\theta_1+G_m\emptyset_1] \quad (19)$$

$$\theta_0''+\theta_0^1K_2+Q\theta_0K_2=0 \quad (20)$$

$$\theta_1''+K_3\theta_1'+K_3(Q-n)\theta_1=0 \quad (21)$$

$$\emptyset_0''+S_c\emptyset_0^1-S_cK_r\emptyset_0=-S_cS_0\theta_0'' \quad (22)$$

$$\emptyset_1''+S_c\emptyset_1^1-S_c(K_r+n)\emptyset_1=-S_cS_0\emptyset_1'' \quad (23)$$

where prime (′) denotes ordinary differentiation with respect to y. The corresponding boundary conditions can be written as

$u_0 = 0,\ \ T_0 = 1, T_1 = 1,\ C_0 = 1,\ \ C_1 = 0$ at $y = 0$,

$u_0 = 0,\ \ T_0 = 0, T_1 = 0,\ C_0 = 1,\ \ C_1 = 1$ as $y \to \infty$ (24)

Solving the equations (19) – (23) under the boundary conditions (24), we obtain the velocity, temperature and concentration distribution in the boundary layer as:

$u(y,t) = e^{at} + A_7 e^{-m_5 y} + A_1 e^{-m_1 y} + A_2 e^{-m_3 y} + \in e^{nt}\{ A_9 e^{-m_6 y} + A_8 e^{-m_2 y} + A_5 e^{-m_4 y} \}$

$\theta(y,t) = e^{-m_1 y} + \in e^{nt} e^{-m_2 y}$

$\emptyset(y,t) = -m_1 e^{-m_1 y} - m_2 \in e^{nt} e^{-m_2 y}$

where $m_1 = \frac{k_2 + \sqrt{K_2^2 - 4QTk}}{2}$, $m_2 = \frac{k_3 + \sqrt{K_3^2 - 4(Q-n)k_3}}{2}$, $m_3 = \frac{S_c + \sqrt{S_c^2 + 4k_r s_c}}{2}$, $m_4 = \frac{S_c + \sqrt{S_c^2 + 4(n+k_r)}}{2}$

$m_5 = \frac{1 + \sqrt{1 + 4(M + \frac{1}{k})}}{2}$, $A_1 = \frac{G_m K_4 - G_r}{m_1^2 - m_1 - \left(M + \frac{1}{k}\right)}$, $A_2 = \frac{-G_m(1 + K_4)}{m_3^2 - m_3 - \left(M + \frac{1}{k}\right)}$, $A_3 = \frac{s_0 s_c m_2^2}{m_2^2 + m_2 s_c - (n + k_r) s_c}$

$A_4 = \frac{-G_r}{m_2^2 - m_2 - K_1}$, $A_5 = \frac{-G_m A_3}{m_4^2 - m_4 - K_1}$, $A_6 = \frac{G_m}{m_2^2 - m_2 - K_1}$, $A_7 = -(A_1 + A_2) A_8 = (A_4 + A_6) A_9 = -(A_5 + A_8) A = \frac{s_0 s_c m_1^2}{m_1^2 + m_1 s_c - (k_r) s_c}$, $K_1 = n + M + \frac{1}{k}$, $K_2 = \frac{1}{p_r}\left(1 + \frac{4}{3N}\right)$, $K_3 = \frac{1}{K_2}$.

Skin-friction, Nusselt number and Sherwood number:

The dimensionless shearing stress on the surface of a body due to the fluid motion, known as skin-friction and defined by the Newton's law of viscosity and other quantities are given below:

$$\tau = \left(\frac{\partial u}{\partial y}\right)_{y=0} = -[(A_7 m_5 + A_1 m_1 + A_2 m_3) + \in e^{nt}(A_8 m_6 + A_9 m_2 + A_5 m_4)$$

$$N_u = \left(\frac{\partial \theta}{\partial y}\right)_{y=0} = -m_1 - \epsilon m_2 e^{nt}$$

$$S_h = \left(\frac{\partial \emptyset}{\partial y}\right)_{y=0} = -(1 + A) m_3 + A m_1 + A_3 (m_2 - m_4)$$

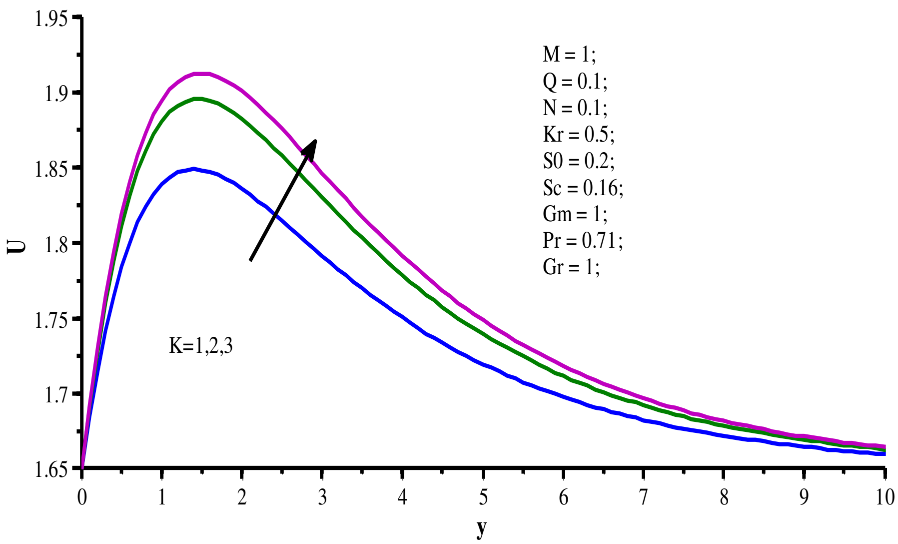

Fig. 1: Effect of permeability parameter on velocity.

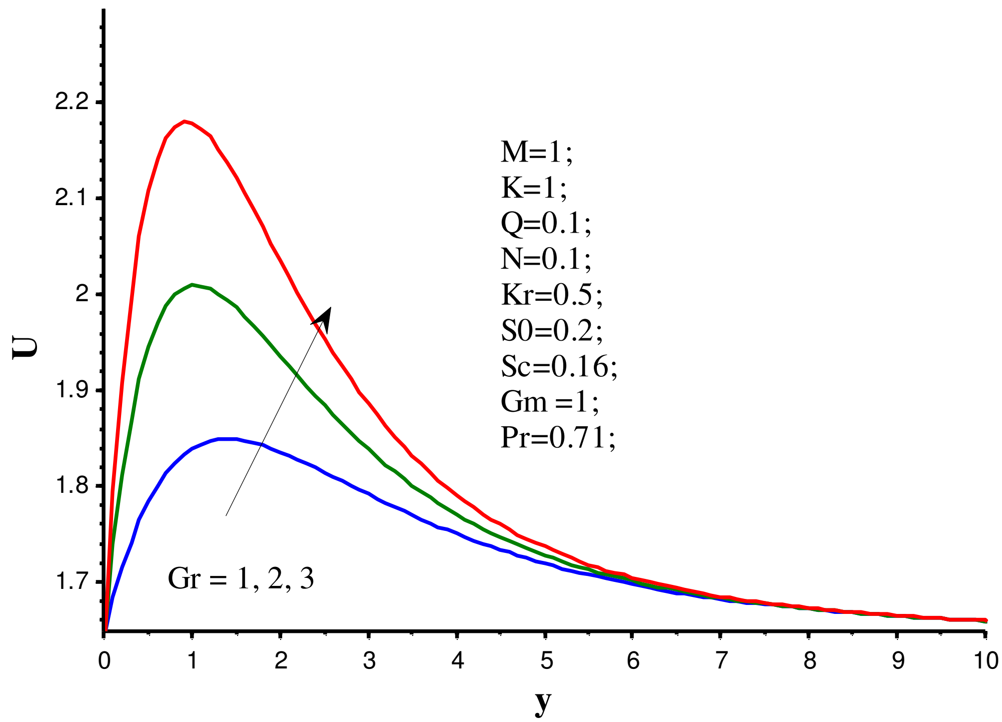

Fig. 2: Effects of Grashof number on velocity profiles.

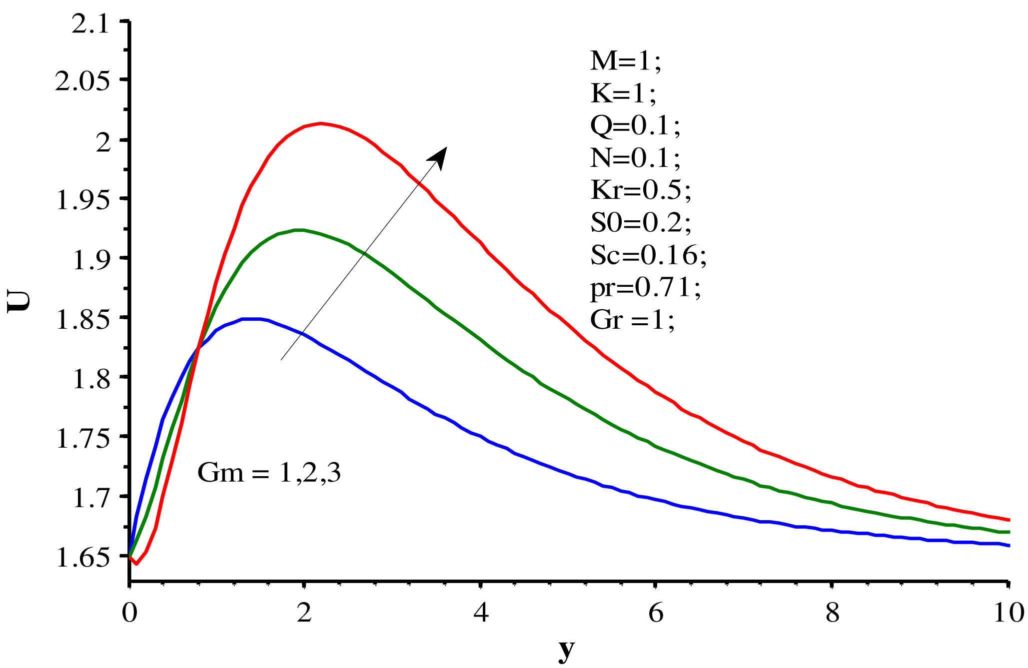

Fig. 3: Effect of modified Grashof number on velocity profiles.

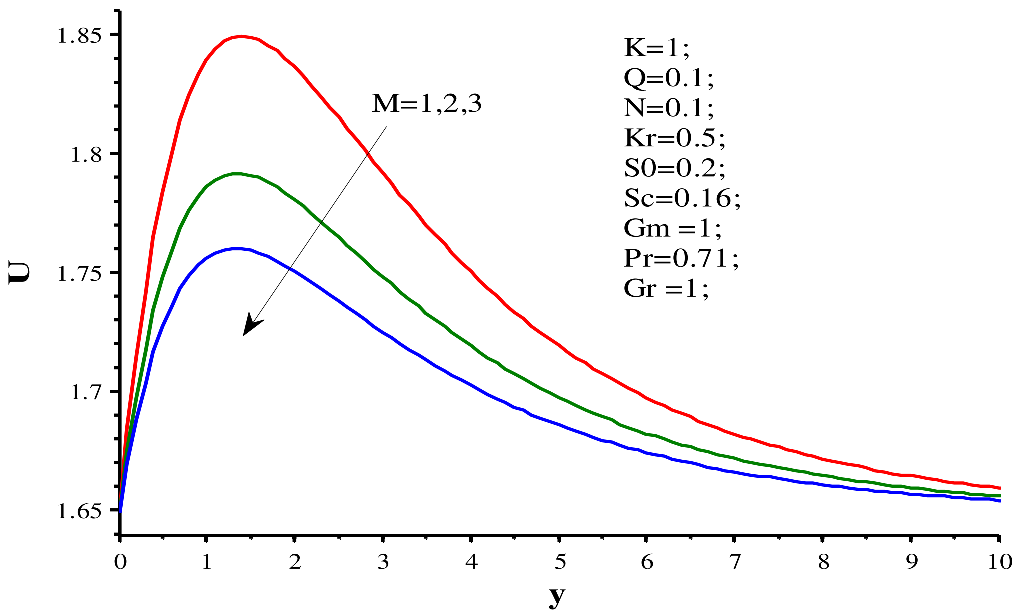

Fig. 4: Effect of magnetic parameter on velocity profiles.

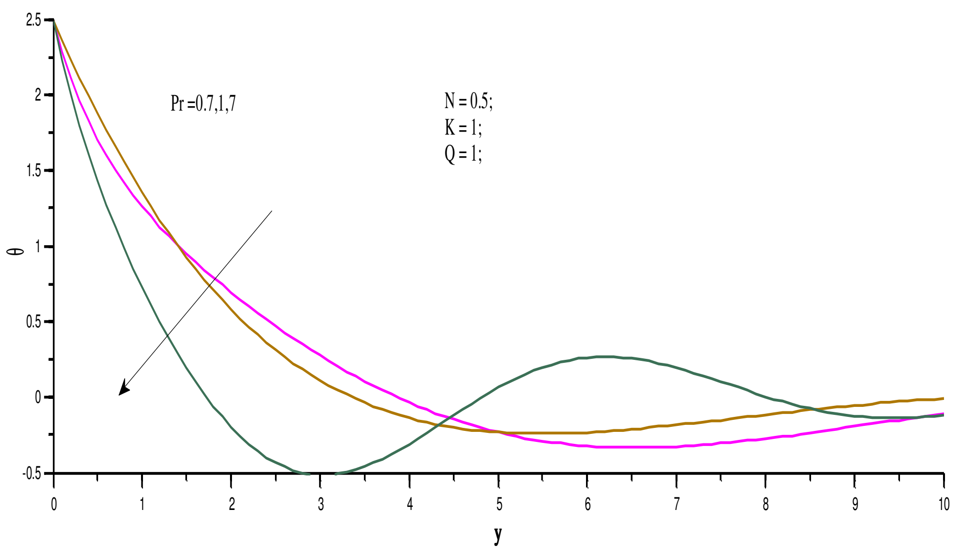

Fig. 5: Effect Prandntl number on temperature profiles.

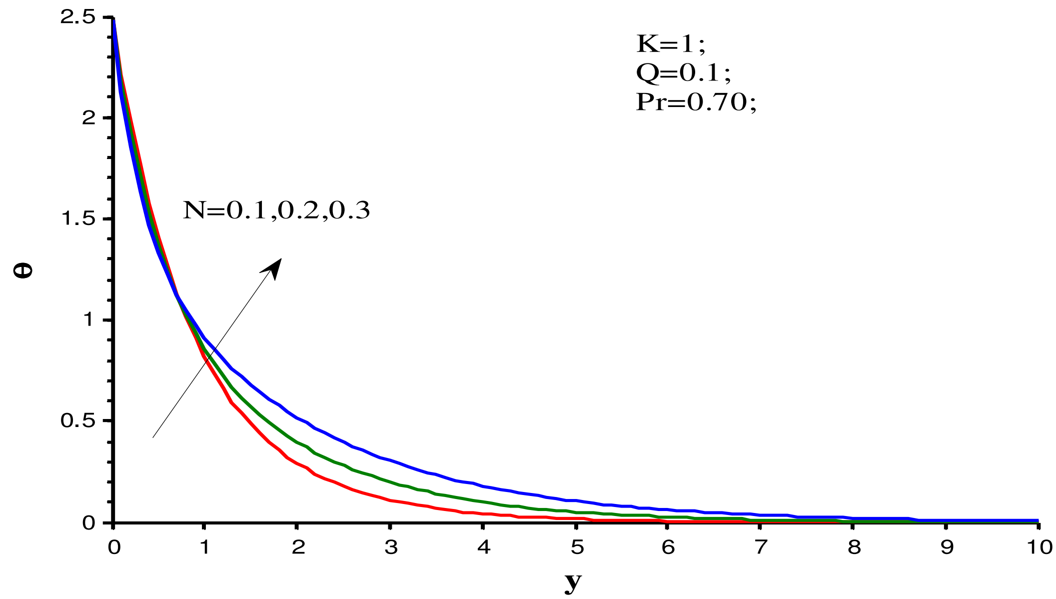

Fig. 6: Effect radiation parameters on temperature profiles.

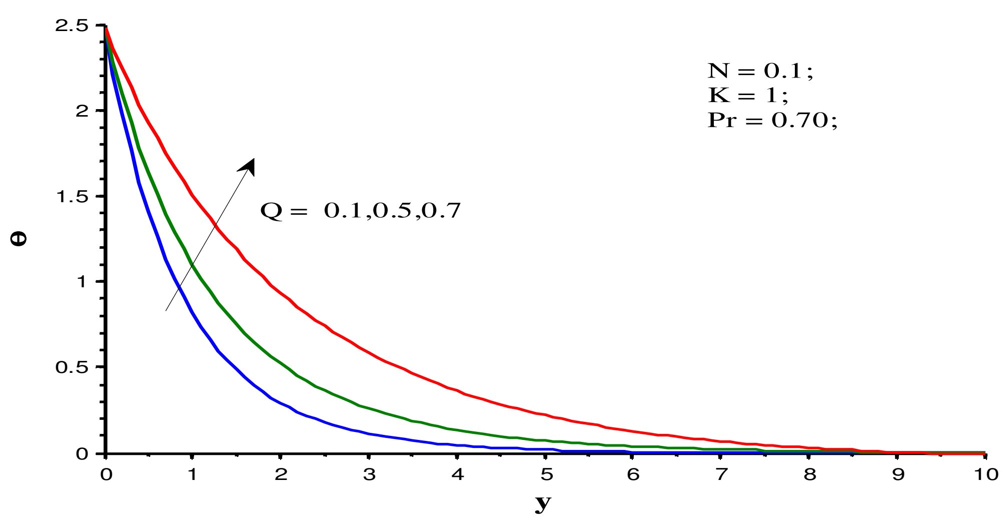

Fig. 7: Effect of heat generation parameter on temperature profiles.

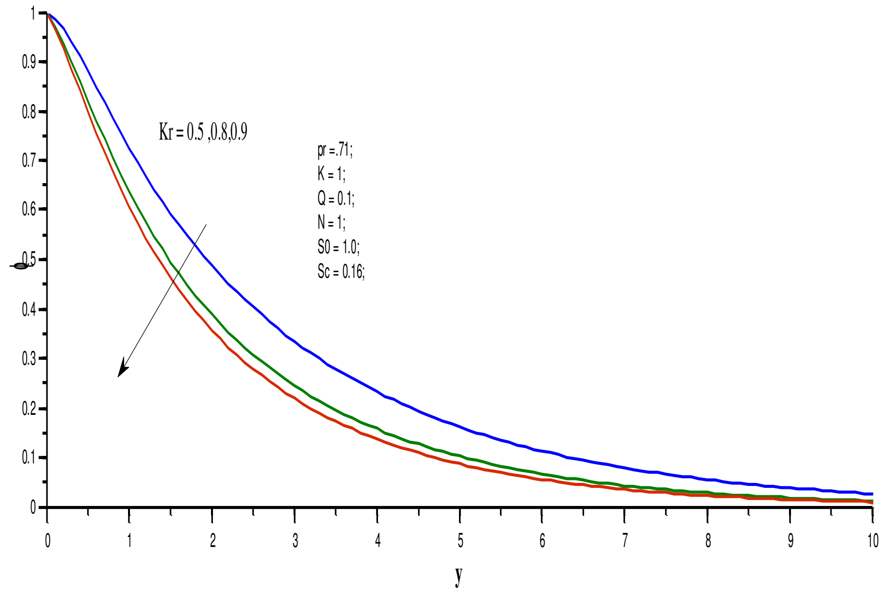

Fig. 8: Effect of chemical reaction parameter on concentration.

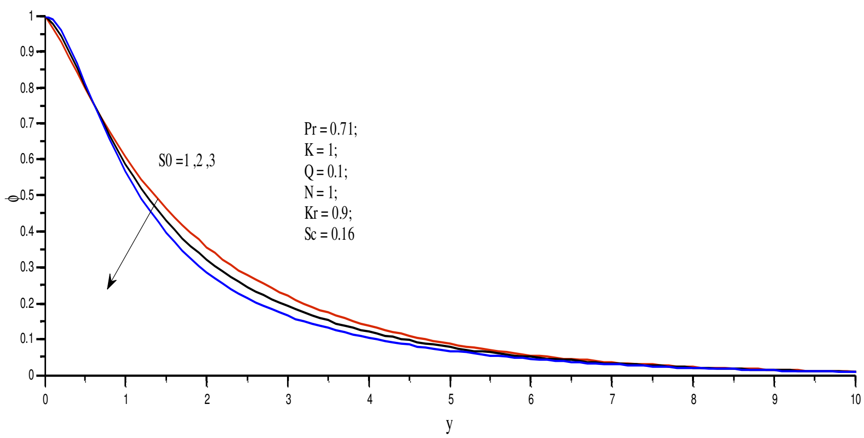

Fig. 9: Effect of Soret number on concentration

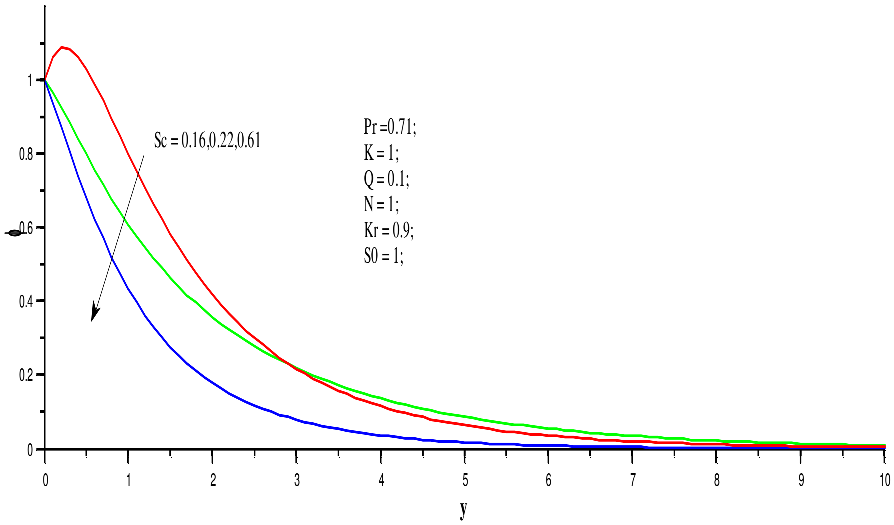

Fig.10: Effect of Schimdt number on concentration.

3. RESULTS AND DISCUSSION

The effects of the various parameters on the velocity, temperature and concentration such as Schmidt number, Nusselt number, skin-friction profiles, heat generation, chemical reaction, Soret effect, magnetic parameter, Grashof number, modified Grashof number, permeability parameter, etc. are discussed qualitatively and graphically. In Fig.1 the effect of permeability parameter on the velocity profiles is presented. This figure shows that as the permeability parameter increases the velocity profile increases. In figures 2 and 3 the effects of Grashof number and modified Grashof number on velocity profiles are plotted. These figures show that as the Grashof number and modified Ggrashof number increases, the velocity profiles increase.

Fig. 4 predicts the effect of magnetic parameter on velocity profiles. This figure indicates that as the magnetic parameter increases, the velocity profile decreases. In Fig. 5 the effect of Prandntl number on the temperature profile is described. This figure shows that as the Prandntl number increases the temperature profiles decrease. Figures 6 and 7 illustrate the effects of radiation parameter and heat source parameter on the temperature profiles. From these figures it is clear that the temperature increases with the increase in radiation parameter and heat source parameter. Figures 8-10 are the effects of Schmidt number, Soret number and chemical reaction respectively. These figures show that concentration decreases with increase of Schmitd number, Soret number and chemical reaction. From the table it is noticed that, Skin friction enhances with increasing values of Grashof number whereas the reverse nature is found under the influence of Prandtl number. Raising the values of modified Grashof number leads to a decrease in Prandtl number where as Nusslet number and Sherwood numbers remain the same. Nusslet number and Sherwood number decreases with an increase in the magnetic number and Prandtl number where as the reverse phenomenon is observed in case of Nusslet number. Skin friction decreases with increasing Schmidt number whereas, reverse nature is observed in case of Sherwood number, but the Nusslet number remains the same.

Table 1: Effects of Schmidt number Nusselt number Sharehood Number for different values of Gr, Gm, M, Pr, Sc, Kr, N, K,Q:

Gr	Gm	M	Pr	Sc	Kr	N	K	Q	Cf	Nu	Sh
1	1	1	0.5	0.22	0.71	1	1	1	0.7804	-5.0240	0.3511
2	1	1	0.5	0.22	0.71	1	1	1	-3.7601	-5.0240	0.3511
3	1	1	0.5	0.22	0.71	1	1	1	-8.3007	-5.0240	0.3511
4	2	2	0.5	0.22	0.71	1	1	1	5.1401	-5.0240	0.3511
5	3	2	0.5	0.22	0.71	1	1	1	1.8980	-5.0240	0.3511
6	4	2	0.5	0.22	0.71	1	1	1	-1.8441	-5.0240	0.3511
7	4	3	0.5	0.22	0.71	1	1	1	-1.6189	-5.0240	0.3511
8	4	4	0.5	0.22	0.71	1	1	1	-1.4615	-5.0240	0.3511
9	4	5	0.5	0.22	0.71	1	1	1	-1.3440	-3.7742	0.0901
11	4	5	0.80	0.22	0.71	1	1	1	-0.9297	-3.4518	0.0461
12	4	5	0.95	0.22	0.71	1	1	1	-0.0442	-3.0477	0.0776
13	4	5	0.95	0.45	0.71	1	1	1	-0.6325	-3.0477	-0.1958
14	4	5	0.95	0.72	0.71	1	1	1	-0.5775	-3.0477	-0.5033
15	4	5	0.95	0.91	0.71	1	1	1	-0.4936	-3.0477	-0.7724
16	4	5	0.95	0.91	0.8	1	1	1	-0.5595	-3.0477	-0.8512
17	4	5	0.95	0.91	0.9	1	1	1	-0.6195	-3.0477	-0.9344
18	4	5	0.95	0.91	0.9	2	1	1	-0.9778	-4.2846	0.2176
19	4	5	0.95	0.91	0.9	3	1	1	-0.0148	-5.5822	1.4218
20	4	5	0.95	0.91	0.9	4	1	1	-0.10081	-6.9209	2.6527
21	4	5	0.95	0.91	0.9	4	2	1	-1.0784	-6.7595	2.5126
22	4	5	0.95	0.91	0.9	4	3	1	-1.1087	-6.5891	2.3650
23	4	5	0.95	0.91	0.9	4	4	1	-1.1284	-6.4077	2.2082
25	4	5	0.95	0.91	0.9	4	4	0.9	-1.0127	-6.6682	2.2987
26	4	5	0.95	0.91	0.9	4	4	0.5	-0.5639	-7.3275	2.6322
27	4	5	0.95	0.91	0.9	4	4	0.1	-0.0387	-7.8293	2.9509

4. CONCLUSIONS

The effects of variable viscosity and thermal conductivity on unsteady two dimensional laminar flow of a viscous incompressible electrically conductive fluid over a semi-infinite vertical plate are studied. The outcomes of this study are as follows:

(i) Velocity increases for increasing values of Grashof number, modified Grashof number and permeability of the porous medium, where as it shows opposite effect in the case of magnetic parameter.
(ii) Temperature decreases for the increasing values of Prandtl number but it has the reverse tendency in the case of radiation parameter and heat source parameter.
(iii) Concentration boundary layer decreases for increasing values of Schmidt number and chemical reaction parameter. Of course it shows a different phenomenon in the case of Soret number.

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