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Diffusion Thermo Effects on MHD Convective Flow Past a Semi-Infinite Vertical Moving Plate Embedded in a Porous Medium in the Presence of Chemical Reaction, Radiation and Heat Source

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Abstract
The study of MHD flow in a porous medium is receiving worldwide attention because of its numerous applications in cooling of electronic systems, chemical catalytic reactors and thermal insulating engineering etc. The study of radiation heat transfer is very useful in nuclear power plants, missile satellites and space vehicles. In the present work the free convection heat and mass transfer flow of a Newtonian, viscous electrically conducting and heat generation/absorption fluid over a continuously vertical permeable surface in the presence of radiation, a first order homogeneous chemical reaction and Dufour effect have been studied.. The governing equations of motion have been solved by Perturbation technique. Graphical results for velocity, temperature and concentration profiles of both phases based on the analytical solutions are presented and discussed. The results show that the concentration decreases as the Schimdt number Sc increases. Velocity within the boundary layer is observed to decrease as the chemical reaction γ increases and it increases with an increase in the values of Heat parameter S. Increment in the thermal radiation parameter N and the magnetic field parameter M result in reduction of velocity. It has also been deduced that as the Radiation parameter increases, the skin friction decreases and the Nusselt number increases.

Keywords: heat and mass transfer, chemical reaction, dufour number, skin friction, magnetohydodynamic (mhd) and thermal diffusion

INTRODUCTION

The study of unsteady Magnetohydrodynamic mixed convection flow in a porous medium has received much attention in recent time owing to diverse new technological developments in modern metallurgical and metal-working processes. Convective heat and mass transfer in porous media has also been a subject of great interest for the last few decades due to its application in various disciplines, such as geophysical, solar power collectors, cooling of electronic systems, chemical catalytic reactors, thermal insulating engineering, high-performance building insulating modeling of packed sphere beds etc. Singh et al (2003) have analyzed the effect of heat and mass transfer in MHD flow of a viscous fluid past a vertical plate under oscillatory suction velocity. The unsteady free convective MHD flow with heat transfer past a semi-infinite vertical porous moving plate with variable suction has been studied by Kim (2008).

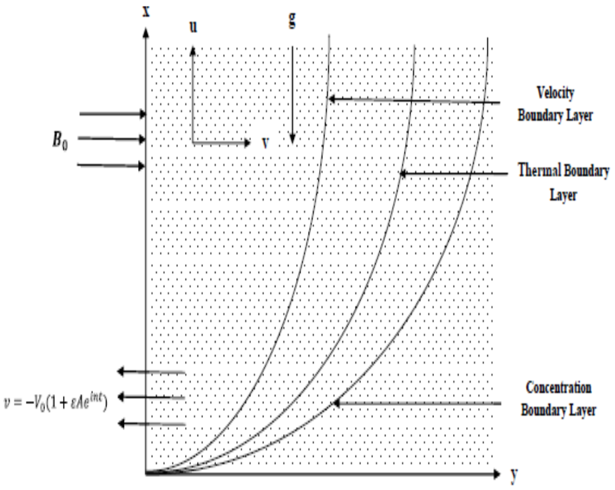
It is known that the effects of radiation on MHD flow and heat transfer problem have become more important industrially. The application of radiation heat transfer becomes very important in the design of pertinent equipment. Other possible applications of this type of flow can be found in nuclear power plants, gas turbines, missiles, satellites, space vehicles and in the various devices for aircraft. Soundalgekar and Takhar(1993) have considered radiation effects on free convection flow past a semi-infinite vertical plate. Chamkha(2003) studied the analytical solutions for MHD flow of a uniformly stretched vertical permeable surface with effect of heat generation/absorption and chemical reaction. Ibrahim *et al*. (2008), in their work, presented the effect of chemical reaction and radiation absorption on laminar flow of a Newtonian, viscous, electrically conducting, MHD flow on a continuously, moving permeable surface with heat source and time dependent suction.

The energy flux caused by a composition gradient is called the Dufour or diffusion-thermo effect. Dursunkaya and Worek91992) studied diffusion-thermo and thermal-diffusion effects in transient and steady natural convection from a vertical surface. Alam*et al*. (2006) studied numerically the Dufour and Soret effects on combined free–forced convection and mass transfer flow past a semi-infinite vertical plate under the influence of transversely applied magnetic field. The heat and mass transfer characteristics of the natural convection about a vertical surface embedded in a saturated porous medium subjected to a chemical reaction taking into account the Soret and Dufour effect was analyzed by

Postelnicu(2007). Osalusi*et al*. (2008) investigated thermo diffusion and diffusion thermo effects on combined heat and mass transfer of a steady hydromagnetic convective and slip flow due to a rotating disk in the presence of viscous dissipation and ohmic heating.

The aim of the present chapter is to study the free convection heat and mass transfer flow of a Newtonian, viscous electrically conducting and heat generation/absorption fluid over a continuously vertical permeable surface in the presence of radiation, a first order homogeneous chemical reaction and Dufour effect. The governing equations of motion have been solved by Perturbation technique. Graphical results for velocity, temperature and concentration profiles of both phases based on the analytical solutions are presented and discussed.

FORMULATION OF THE PROBLEM



Physical Model
An unsteady two-dimensional flow of a laminar, viscous, electrically conducting and heat absorbing fluid past a semi-infinite vertical permeable moving plate embedded in a porous medium and under the influence of uniform transverse magnetic field in the presence of Diffusion Thermo, thermal and concentration buoyancy effects are considered. It is assumed that there is no applied voltage which implies the absence of an electrical field. The fluid properties are assumed to be constant except that the influence of density variation with temperature has been considered only in the body force term. The concentration of diffusing species is very small in comparison to other chemical species, the concentration of species far from the wall, $C_\infty{}^*$, is infinitesimally small. The chemical reactions are taking place in the flow and all thermo physical properties are assumed to be constant of the linear momentum equation which is approximated variables are functions of y^* and time t^* only. Under these assumptions, the governing equations of flow are

$$\frac{\partial v^*}{\partial y^*} = 0 \qquad (1)$$

$$\frac{\partial u^*}{\partial t^*} + v^*\frac{\partial u^*}{\partial y^*} = -\frac{1}{\rho}\frac{\partial p^*}{\partial x^*} + g\beta(T^* - T_\infty{}^*) + g\beta^*(C^* - C_\infty{}^*) + \vartheta\frac{\partial^2 u^*}{\partial y^{*2}} - \frac{\sigma B_0{}^2}{\rho}u^* - \frac{\vartheta}{K^*}u^* \qquad (2)$$

$$\left[\frac{\partial T^*}{\partial t^*} + v^*\frac{\partial T^*}{\partial y^*}\right] = \frac{1}{\rho C_p}\left[k\frac{\partial^2 T^*}{\partial y^{*2}} - Q_0(T^* - T_\infty{}^*)\right] + Q_1{}^*(C^* - C_\infty{}^*) - \frac{1}{\rho C_p}\frac{\partial q_r{}^*}{\partial y^*} + \frac{D_m K_T}{C_s C_p}\frac{\partial^2 C^*}{\partial y^{*2}} \qquad (3)$$

$$\frac{\partial C^*}{\partial t^*} + v^*\frac{\partial C^*}{\partial y^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} - K_r{}^*(C^* - C_\infty{}^*) \qquad (4)$$

The boundary conditions for the velocity, temperature and concentration fields are given as follows.

$u^* = u_p{}^*, T^* = T_w{}^* + \varepsilon(T_w{}^* - T_\infty{}^*)e^{n^*t^*}, C^* = C_w{}^* + \varepsilon(C_w{}^* - C_\infty{}^*)e^{n^*t^*}$

at $y^*=0$

$$u^* \to U_\infty{}^* = U_0(1 + \varepsilon e^{n^*t^*}), T^* \to T^*_\infty, C^* \to C_\infty{}^* \; as \; y^* \to \infty \qquad (5)$$

It is clear from equation (1) that the suction velocity at the plate surface is a function of time only. Hence the suction velocity normal to the plate is assumed in the form

$$v^* = -V_0(1 + \varepsilon A e^{n^*t^*}) \qquad (6)$$

Where A is a real positive constant, $\varepsilon, \varepsilon A$ is small values less than unity, and V_0 is a scale of suction velocity which is non zero positive constant. The negative sign indicates that the suction is towards the plate. Outside the boundary layer, Equation (2) gives

$$-\frac{1}{\rho}\frac{\partial p^*}{\partial x^*} = \frac{dU_\infty{}^*}{dt^*} + \frac{\vartheta}{K^*}U_\infty{}^* + \frac{\sigma\beta_0{}^2}{\rho}U_\infty{}^* \qquad (7)$$

Eliminating $\frac{\partial p^*}{\partial x^*}$ between (2) and (7), we obtain

$$\frac{\partial u^*}{\partial t^*} + v^*\frac{\partial u^*}{\partial y^*} = \frac{dU_\infty{}^*}{dt^*} + g\beta(T^* - T_\infty{}^*) + g\beta^*(C^* - C_\infty{}^*) + \vartheta\frac{\partial^2 u^*}{\partial y^{*2}} + \frac{\sigma\beta_0{}^2}{\rho}(U_\infty{}^* - u^*) + \frac{\vartheta}{K^*}(U_\infty{}^* - u^*) \qquad (8)$$

By using Rosseland diffusion approximation, the radiative heat flux is given by

$$q_r{}^* = -\frac{4\sigma^*}{3K_1{}^*}\frac{\partial T^{*4}}{\partial y^*} \qquad (9)$$

Where $\sigma^* and K_1{}^*$ are the Stefan-Boltzmann constant and the Roseland mean absorption coefficient, respectively. We assume that the temperature differences within the flow are sufficiently small such that T^{*4} may be expressed as a linear function of the temperature. This is accomplished by expanding in a Taylor series about T^{*4} and neglecting higher order terms, thus

$$T^{*4} \cong 4T_\infty{}^{*3}T^* - 3T_\infty{}^{*4} \qquad (10)$$

Using (9) and (10) in Equation (3) we obtain

$$\left[\frac{\partial T^*}{\partial t^*}+v^*\frac{\partial T^*}{\partial y^*}\right]=\frac{1}{\rho C_p}\left[k\frac{\partial^2 T^*}{\partial y^{*2}}-Q_0(T^*-T_\infty^*)\right]+Q_1^*(C^*-C_\infty^*)+\frac{16\sigma^* T_\infty^{*3}}{3K_1^*\rho C_p}\frac{\partial^2 T^*}{\partial y^{*2}}+\frac{D_m K_T}{C_s C_p}\frac{\partial^2 C^*}{\partial y^{*2}} \qquad (11)$$

On introducing the dimensionless variables as follows

$$y=\frac{y^* V_0}{\vartheta},\ t=\frac{t^* V_0^2}{\vartheta},\ u=\frac{u^*}{U_0},\quad U_\infty=\frac{U_\infty^*}{U_0}, U_p=\frac{U_p^*}{U_0} v=\frac{v^*}{V_0}$$

$$\theta=\frac{T^*-T_\infty^*}{T_W^*-T_\infty^*},\ C=\frac{C^*-C_\infty^*}{C_W^*-C_\infty^*},$$

$$Gr=\frac{g\beta\vartheta(T_W^*-T_\infty^*)}{V_0^2 U_0},\ Gm=\frac{g\beta\vartheta(C_W^*-C_\infty^*)}{V_0^2 U_0},$$

$$Pr=\frac{\mu C_p}{k}=\frac{\vartheta\rho C_p}{k},\ Sc=\frac{\vartheta}{D},$$

$$S=\frac{Q_0\vartheta}{\rho C_p V_0^2},\ \gamma=\frac{K_r^*\vartheta}{V_0^2},\ Du=\frac{D_m K_T(C_W^*-C_\infty^*)}{\vartheta C_s C_p(T_W^*-T_\infty^*)},$$

$$K=\frac{K^* V_0^2}{\vartheta^2},\ M=\frac{\sigma\beta_0^2\vartheta}{\rho V_0^2},\ N=\frac{4\sigma^* T_\infty^{*3}}{K_1^* K}$$

$$n=\frac{n^*\vartheta}{V_0^2},\ Q_1=\frac{\vartheta Q_1^*(T_W^*-T_\infty^*)}{V_0^2(C_W^*-C_\infty^*)} \qquad (12)$$

Using equation (12), the governing equations (4), (8) and (11) reduce to the following dimensionless form

$$\frac{\partial u}{\partial t}-(1+\varepsilon A e^{nt})\frac{\partial u}{\partial y}=\frac{dU_\infty}{dt}+Gr\theta+GmC+\frac{\partial^2 u}{\partial y^2}+M_1(U_\infty-u) \qquad (13)$$

$$\frac{\partial\theta}{\partial t}-(1+\varepsilon A e^{i\omega t})\frac{\partial\theta}{\partial y}=\frac{1}{Pr}\left(1+\frac{4N}{3}\right)\frac{\partial^2\theta}{\partial y^2}-S\theta+Q_1 C+Du\,\frac{\partial^2 c}{\partial y^2} \qquad (14)$$

$$\frac{\partial C}{\partial t}-(1+\varepsilon A e^{i\omega t})\frac{\partial C}{\partial y}=\frac{1}{Sc}\frac{\partial^2 C}{\partial y^2}-\gamma C \qquad (15)$$

Where $M_1 = M+\frac{1}{K}$

The boundary conditions to the problem in the dimensionless form are

$u = U_p,\ \theta = 1+\varepsilon e^{nt},\ C = 1+\varepsilon e^{i\omega t}$ at y=0

$$u\to U_\infty = 1+\varepsilon e^{nt},\ \theta\to 0,\ C\to 0\quad as\ y\to\infty \qquad (16)$$

SOLUTION OF THE PROBLEM

In order to reduce the above system of partial differential equations to a system of ordinary differential equations in dimensionless form, we may represent the velocity, temperature and concentration as follows

$$u(y,t) = u_0(y)+\varepsilon u_1(y)e^{nt}+o(\varepsilon^2) \qquad (17)$$

$$\theta(y,t) = \theta_0(y)+\varepsilon\theta_1(y)e^{nt}+o(\varepsilon^2) \qquad (18)$$

$$C(y,t) = C_0(y)+\varepsilon C_1(y)e^{nt}+o(\varepsilon^2) \qquad (19)$$

Substituting (17) – (19) in equations (13) – (15), equating the coefficients of harmonic and non harmonic terms and neglecting the coefficients of $o(\epsilon^2)$ we get the following equations

$$u_0''+u_0'-M_1 u_0=-M_1-Gr\theta_0-GmC_0 \qquad (20)$$

$$u_1''+u_1'-(M_1+n)u_1=-(M_1+n)-Gr\theta_1-GmC_1-Au_0' \qquad (21)$$

$$(1+\tfrac{4N}{3})\theta_0''+\Pr\theta_0'-SPr\theta_0=-\Pr Q_1 C_0-DuPr\,C_0'' \qquad (22)$$

$$(1+\tfrac{4N}{3})\theta_1''+\Pr\theta_1'-\Pr(n+S)\theta_1=-APr\theta_0'-\Pr Q_1 C_1-DuPr\,C_1'' \qquad (23)$$

$$C_0''+ScC_0'-\gamma ScC_0=0 \qquad (24)$$

$$C_1''+Sc\,C_1'-SC(n+\gamma)=-AScC_0' \qquad (25)$$

The corresponding boundary conditions reduce to

$u_0=U_p, u_1=0, \theta_0=1, \theta_1=1,\ C_0=1, C_1=1$ at y=0

$u_0=0, u_1=0, \theta_0=0, \theta_1=0,\ C_0=0, C_1=0$ as $y\to\infty$ (26)

Where primes denote differentiation with respect to 'y'.

Solving the Eqns. (20) to (25) under the boundary conditions (26) we get

$$c_0(y)=e^{-m_1 y} \qquad (27)$$

$$c_1(y)=(1-A_5)e^{-m_4 y}+A_5 e^{-m_1 y} \qquad (28)$$

$$\theta_0(y)=e^{-m_2 y}+A_1(e^{-m_2 y}-e^{-m_1 y}) \qquad (29)$$

$$\theta_1(y)=A_9 e^{-m_5 y}+A_6 e^{-m_1 y}+A_7 e^{-m_2 y}+A_8 e^{-m_4 y} \qquad (30)$$

$$u_0(y)=1+A_4 e^{-m_3 y}+A_2 e^{-m_1 y}+A_3 e^{-m_2 y} \qquad (31)$$

$$u_1(y)=1+A_{15}e^{-m_6 y}+A_{10}e^{-m_1 y}+A_{11}e^{-m_2 y}+A_{12}e^{-m_3 y}+A_{13}e^{-m_4 y}+A_{14}e^{-m_5 y} \qquad (32)$$

Using the above expressions (27) to (32) in equations (17) - (19) we obtain the velocity, temperature and concentration fields as

$$u(y,t)=1+A_4 e^{-m_3 y}+A_2 e^{-m_1 y}+A_3 e^{-m_2 y}+\varepsilon e^{nt}[1+A_{15}e^{-m_6 y}+A_{10}e^{-m_1 y}+A_{11}e^{-m_2 y}+A_{12}e^{-m_3 y}+A_{13}e^{-m_4 y}+A_{14}e^{-m_5 y}] \qquad (33)$$

$$\theta(y,t)=e^{-m_2 y}+A_1(e^{-m_2 y}-e^{-m_1 y})+\varepsilon e^{nt}[A_9 e^{-m_5 y}+A_6 e^{-m_1 y}+A_7 e^{-m_2 y}+A_8 e^{-m_4 y}] \qquad (34)$$

$$C(y,t)=e^{-m_1 y}+\varepsilon e^{nt}(1-A_5)e^{-m_4 y}+A_5 e^{-m_1 y} \qquad (35)$$

Skin friction

Knowing the velocity field, the Skin friction at the plate can be obtained, which is non- dimensional form is given by

$$\tau=\frac{\tau_w^*}{\rho U_0 v_0}=\left(\frac{\partial u}{\partial y}\right)_{y=0}=\left(\frac{\partial u_0}{\partial y}+\varepsilon e^{nt}\frac{\partial u_1}{\partial y}\right)_{y=0}$$

$$\tau = -\begin{bmatrix} -m_3A_4 - m_1A_2 - m_2A_3 + \varepsilon e^{nt}(-m_6A_{15} - m_1A_{10} - m_2A_{11} \\ -m_3A_{12} - m_4A_{13} - m_5A_{14}) \end{bmatrix} \quad (36)$$

Nusselt number

Knowing the temperature field, the rate of heat transfer coefficient can be obtained, which is non-dimensional form is given, in terms of the Nusselt number is given by

$$Nu = -x\frac{\left(\frac{\partial T^*}{\partial y^*}\right)_{y^*=0}}{(T_w^* - T_\infty^*)}, NuRe_x^{-1} = \left(\frac{\partial \theta}{\partial y}\right)_{y=0} = \left(\frac{\partial \theta_0}{\partial y} + \varepsilon e^{nt}\frac{\partial \theta_1}{\partial y}\right)_{y=0}$$

$$NuRe_x^{-1} = -[-m_2 - m_2A_1 + m_1A_1 + \varepsilon e^{nt}(-m_1A_6 - m_2A_7 - m_4A_8 - m_5A_9] \quad (37)$$

Sherwood number

Knowing the concentration field, the rate of mass transfer coefficient can be obtained, which is non-dimensional form is given, in terms of the Sherwood number is given by

$$Sh = -x\frac{\left(\frac{\partial C^*}{\partial y^*}\right)_{y^*=0}}{(C_w^* - C_\infty^*)}, ShRe_x^{-1} = \left(\frac{\partial C}{\partial y}\right)_{y=0} = \left(\frac{\partial C_0}{\partial y} + \varepsilon e^{nt}\frac{\partial C_1}{\partial y}\right)_{y=0}$$

$$ShRe_x^{-1} = -[-m_1 + \varepsilon e^{nt}(-(1 - A_5)m_4 - m_1A_5] \quad (38)$$

RESULTS AND DISCUSSION

In order to get physical insight in to the problem the effects of various governing parameters on the physical quantities are computed and presented in Figures 1-10 and discussed in detail.

Figure.1 illustrates the effect of Schmidt number Sc on concentration profiles. It is seen that the concentration decreases with increasing Schmidt number Sc.For different values of the Dufour number Du, the temperature and velocity profiles are plotted in figures.2and 5. It is obvious that as Dufour number Du increases temperature and velocity profiles increase. Fig.3. illustrates the effect of Grashof number Gr on velocity profiles. It is observed that as the Grashof number Gr increases, the velocity also increases. The velocity profile for different values of modified Grashof number Gm are shown in figure.4. This shows that the velocity increases with increasing values of modified Grashof number Gm. For different values of the Chemical reaction parameter γ, velocity profiles are plotted in figure.6. It is obvious that as Chemical reaction parameter γ increases, velocity decreases within the boundary layer. Figure.7 shows the effect of Heat source parameter S onvelocity profiles. It is seen that the velocity increases with increasing values of Heat source parameter S.

Figures.8 illustrates the effect of absorption Radiation parameter Q_1 on the velocity field. It is observed that as the absorption Radiation parameter Q_1increases, velocity field also increases. For different values of the thermal Radiation parameter N, velocity profiles are plotted in figure.9. It is seen that as thermal Radiation parameter N increases, the velocity profiles decreases. Figure.10.shows the velocity profiles for different values of Magnetic field parameter M. It is obvious that as the Magnetic field parameter M increases, the velocity decreases.

Table shows numerical values of the Skin friction coefficient τ, Nusselt number Nu and Sherwood number Sh for various values of Schmidt number *Sc*, Dufour number Du, Chemical reaction parameter γ, Radiation parameter N, Heat source parameter S and absorption Radiation parameter Q_1. From table.2.1, it is observed that as Chemical reaction parameter and Schmidt number increases, the Skin friction decreases and Nusselt number, Sherwood number increases. It is also observed that as Absorption radiation parameter, Dufour number and Heat source parameter increases, Skin friction increases and Nusselt number decreases. It is seen that as Radiation parameter increases, Skin friction decreases and Nusselt number increases.

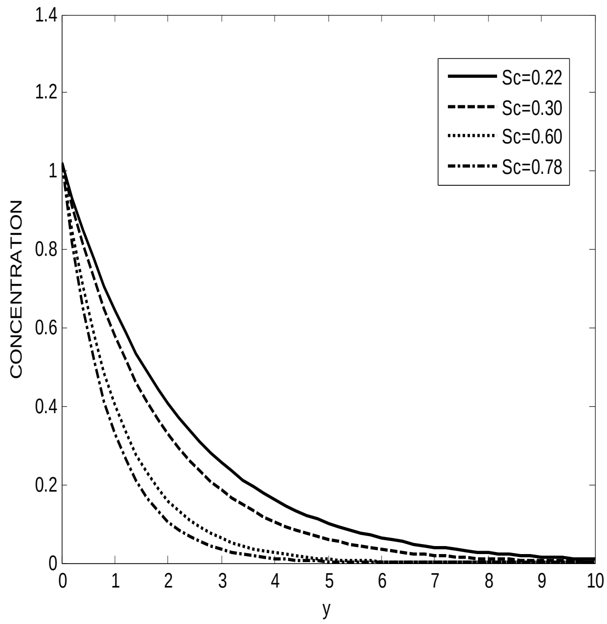


Fig.1. Effect of Schmidt number Sc on concentration profiles with $\gamma = 0.5$, n = 0.1, A = 0.5,t = 1, $\varepsilon = 0.02$

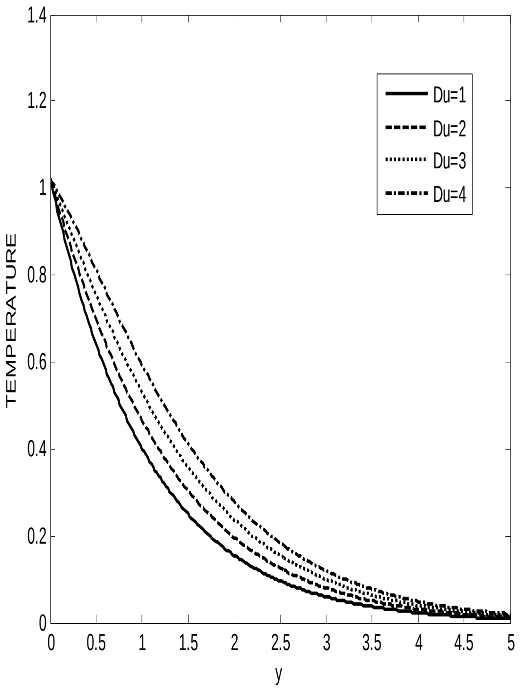


Fig. 2. Effect of Dufour number Du on temperature profiles with Pr = 0.71, R = 1, Sc = 0.65, A = 0.5, n = 0.1, t=1, Q_1= 1, $S = 0.5, \varepsilon = 0.02, \ \gamma = 0.5$

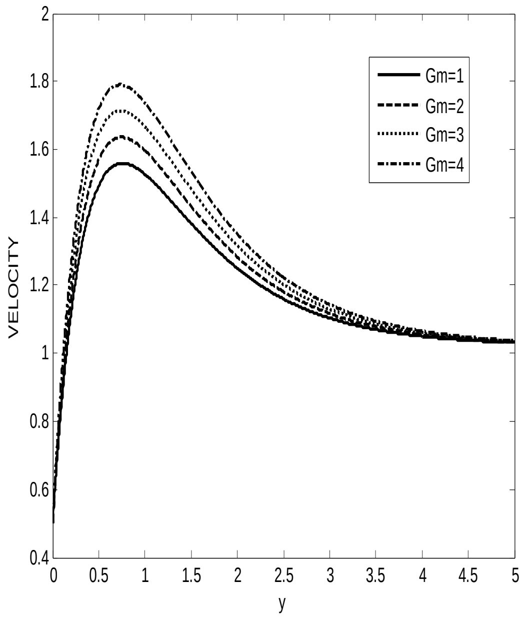


Fig.4. Effect of modified Grashof number Gm on velocity profiles with $S = 0.5$,

K = 0.5,Sc = 0.65, K = 0.5, $\gamma = 0.5, \varepsilon = 0.02$, Up = 0.5, Pr=0.71, Gr = 2, n = 0.1, t = 1,Du = 1, A = 0.5, Q_1=1, R = 1

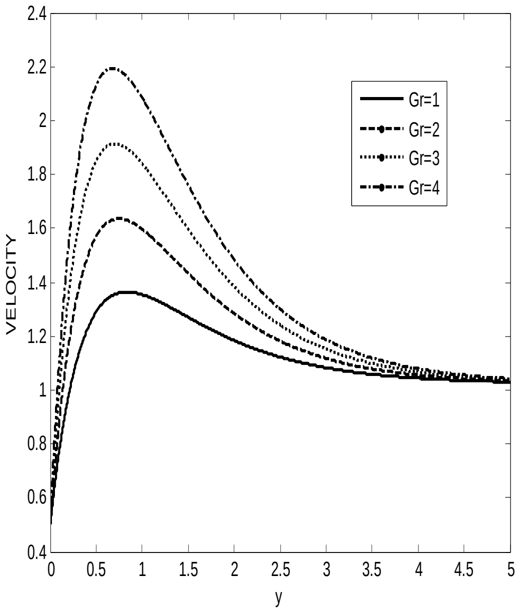


Fig. 3. Effect of Grashof number Gr on velocity profiles with $= 0.5$, K = 0.5,

Sc = 0.65,K = 0.5, $\gamma = 0.5, \varepsilon = \ 0.02$, Up = 0.5, Pr=0.71, Gm = 2, n = 0.1, t = 1,
Du = 1, A = 0.5, Q_1=1, R = 1

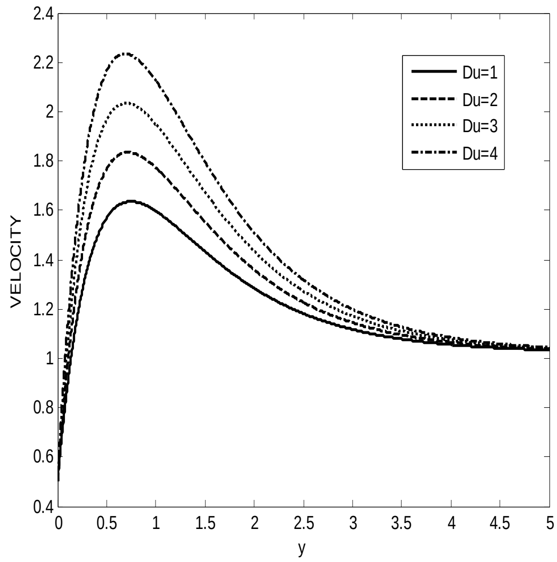


Fig.5.Effect of Dufour number Du on velocity profiles with $S = 0.5$, Sc = 0.65,

$\gamma = 0.5, \varepsilon = 0.02$, Up = 0.5, Pr=0.71, Gr = 2,
Gm = 2, n = 0.1, t = 1, Q_1 = 1,
A = 0.5, R=1, K = 0.5

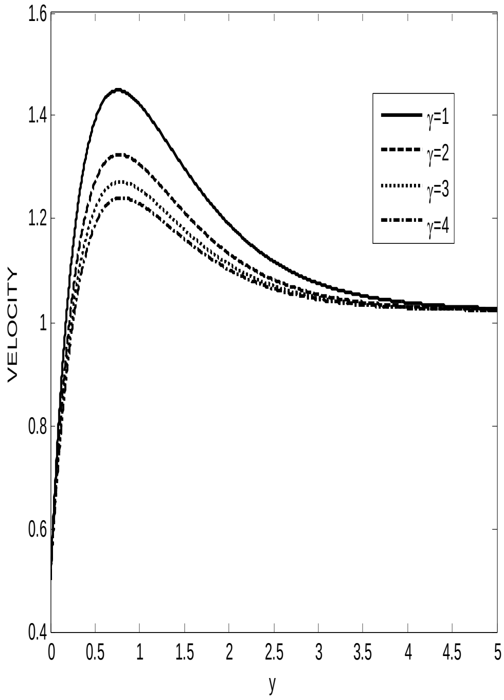


Fig.6. Effect of Chemical reaction parameter γ on velocity profiles with
Pr = 0.71, K = 0.5,Sc = 0.65, K = 0.5,
$S = 0.5, \varepsilon = 0.02$, Up = 0.5,
Gr = 2, Gm = 2, n = 0.1, t = 1,Du = 1, A = 0.5, Q_1=1, R = 1

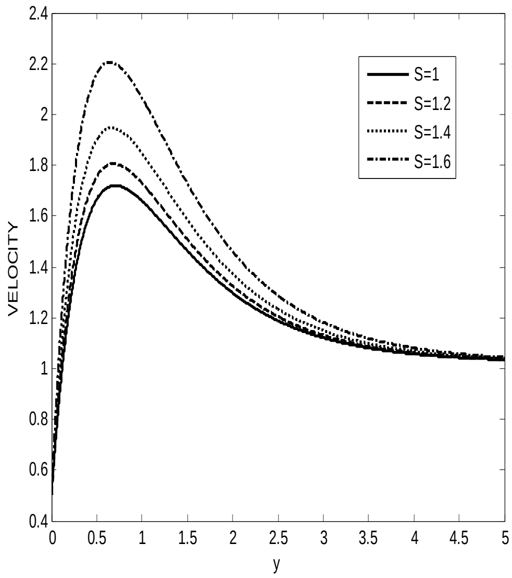


Fig.7. Effect of Heat source parameter S on velocity profiles with Pr = 0.71,
K = 0.5,Sc = 0.65, K = 0.5, $\gamma = 0.5, \varepsilon = 0.02$, Up = 0.5, Gr = 2, Gm = 2, n = 0.1,
t = 1,Du = 1, A = 0.5, Q_1=1, R = 1

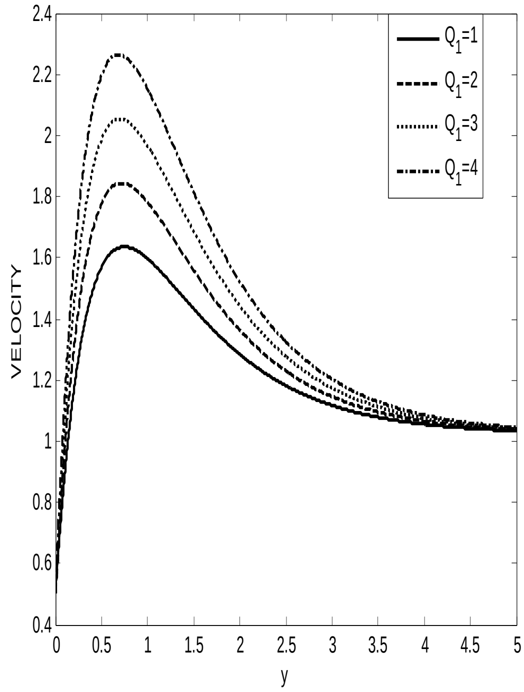


Fig. 8. Effect of absorption Radiation parameter Q_1 on velocity profiles with
S $= 0.5$,Sc = 0.65, $\gamma = 0.5, \varepsilon = 0.02$, Up = 0.5, Pr=0.71, Gr = 2, Gm = 2, n = 0.1, t = 1,Du = 1, A = 0.5, R=1, K = 0.5

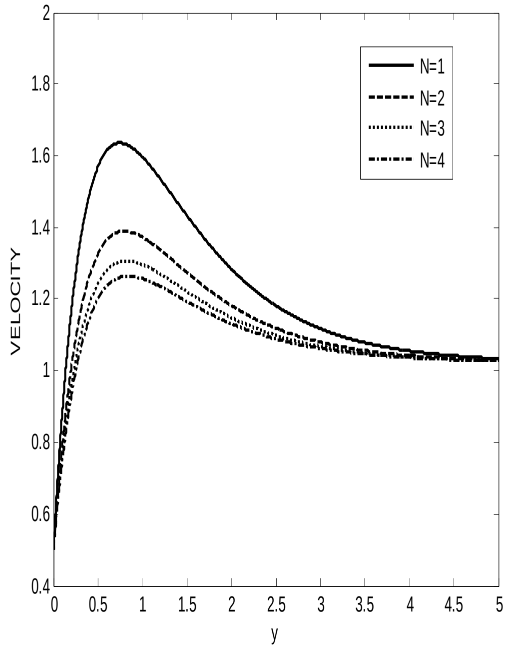


Fig.9. Effect of Thermal Radiation parameter N on velocity profiles with $S = 0.5$,Sc = 0.65,
$\gamma = 0.5, \varepsilon = 0.02$, Up = 0.5, Pr=0.71, Gr = 2,
Gm = 2, n = 0.1, t = 1,
Du = 1, A = 0.5, Q_1=1, K = 0.5

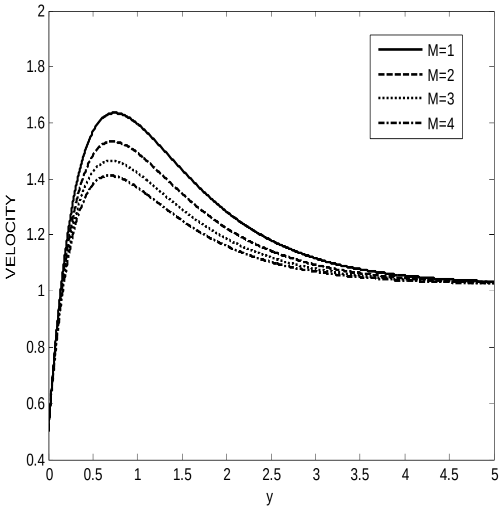


Fig.10. Effect of Magnetic field parameter M on velocity profiles with Pr = 0.71,
K = 0.5, Sc = 0.65,
$\gamma = 0.5, S = 0.5, \varepsilon = 0.02$,Up = 0.5, Gr = 2, Gm = 2,
n = 0.1, t = 1,Du = 1, A = 0.5, Q_1=1, R = 1

TABLE
Values for Skinfriction, Nusselt number and Sherwood number with Gr=2, Gm=2, Pr=0.71,A=0.5, t=1, $\varepsilon = 0.02$

γ	S	Q_1	N	Du	Sc	τ	Nu	Sh
1	0.5	0.5	1	1	0.65	3.7837	1.2776	1.2263
2	0.5	0.5	1	1	0.65	3.2829	1.4501	1.5491
3	0.5	0.5	1	1	0.65	3.0626	1.5519	1.8025
1	0.5	0.5	1	1	0.65	4.5303	1.0547	1.2263
1	0.5	0.5	1	1	1	3.4717	1.3770	1.6626
1	0.5	0.5	1	1	1.5	2.9771	1.5984	2.2480
1	0.5	1	1	1	0.65	5.1223	0.9484	-
1	0.5	2	1	1	0.65	6.4462	0.7360	-
1	0.5	3	1	1	0.65	7.7701	0.5235	-
1	0.1	0.5	1	1	0.65	4.4486	0.9741	-
1	0.5	0.5	1	1	0.65	4.5303	1.0547	-
1	1	0.5	1	1	0.65	5.1223	0.8387	-
1	0.5	0.5	1	1	0.65	5.1223	1.0547	-
1	0.5	0.5	2	1	0.65	3.4393	1.3488	-
1	0.5	0.5	3	1	0.65	3.0105	1.5687	-
1	0.5	0.5	1	1	0.65	4.5303	1.0547	-
1	0.5	0.5	1	2	0.65	5.4575	0.8527	-
1	0.5	0.5	1	3	0.65	7.3120	0.6508	-

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APPENDIX

$$m_1 = \frac{Sc+\sqrt{Sc^2+4\gamma Sc}}{2},$$

$$m_2 = \frac{3Pr+\sqrt{9Pr^2+12PrS(3+4N)}}{2},$$

$$M_1 = M + \frac{1}{K},$$

$$m_3 = \frac{1+\sqrt{1+4N}}{2}, m_4 = \frac{Sc+\sqrt{Sc^2+4Sc(\gamma+n)}}{2},$$

$$m_5 = \frac{3Pr+\sqrt{9Pr^2+12Pr(n+S)(3+4N)}}{2}$$

$$m_6 = \frac{1+\sqrt{1+4(n+M_1)}}{2} A_1 = -\frac{3PrQ_1+3DuPrm_1^2}{(3+4N)m_1^2-3Pr\,m_1-3PrS}$$

$$, A_2 = \frac{-(GrA_1+Gm)}{m_1^2-m_1-M_1},$$

$A_3 = -\frac{Gr(1+A_1)}{m_2{}^2 - m_2 - M_1} A_4 = U_p - (1 + A_2 + A_3)$

, $A_5 = \frac{AScm_1}{m_1{}^2 - Scm_1 - Sc(\gamma + n)}$,

$A_6 = -\frac{3\Pr\,(AA_1 m_1 + Q_1 A_4 + DuA_5 m_1{}^2}{(3+4R)m_1{}^2 - 3Pr\,m_1 - 3\Pr\,(n+S)}$, $A_7 = \frac{3APrm_2(1+A_1)}{(3+4R)m_2{}^2 - 3Prm_2 - 3\Pr\,(n+S)}$

,

$A_8 = -\frac{3Pr(1-A_5)(Q_1 + Dum_4{}^2)}{(3+4R)m_4{}^2 - 3Pr\,m_4 - 3\Pr\,(n+S)}$

,$A_9 = 1 - (A_6 + A_7 + A_8)$

$A_{10} = \frac{AA_2 m_2 - GrA_6 - GmA_5}{m_1{}^2 - m_1 - (n+M_1)}$,

$A_{11} = \frac{AA_3 m_2 - GrA_7}{m_2{}^2 - m_2 - (n+M_1)}$, ,

$A_{12} = \frac{m_1 AA_4}{m_3{}^2 - m_3 - (M_1 + n)}$

$A_{13} = -\frac{Gr\,A_8 + Gm\,(1-A_5)}{m_4{}^2 - m_4 - (n+M_1)}$,

$A_{14} = \frac{Gr\,A_9}{m_5{}^2 - m_5 - (n+M_1)}$,

$A_{15} = -(1 + A_{10} + A_{11} + A_{12} + A_{13} + A_{14})$