International Journal of Applied and Advanced Scientific Research (IJAASR)
Impact Factor: 5.255, ISSN (Online): 2456 - 3080
(www.dvpublication.com) Volume 2, Issue 2, 2017

CHEMICAL REACTION AND DUFOUR EFFECTS ON A STEADY MHD FLOW OVER A VERTICAL POROUS PLATE WITH OHMIC HEATING, VISCOUS DISSIPATION, RADIATION, HALL CURRENT AND HEAT SOURCE

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Cite This Article: Dr. K. Balamurugan & V. Amuthavalli, "Chemical Reaction and Dufour Effects on a Steady MHD Flow Over a Vertical Porous Plate with Ohmic Heating, Viscous Dissipation, Radiation, Hall Current and Heat Source", International Journal of Applied and Advanced Scientific Research, Volume 2, Issue 2, Page Number 173-183, 2017

Abstract:

The present study deals with the analysis of steady MHD flow of an incompressible electrically conducting viscous fluid through a vertical porous plate with ohmic heating, viscous dissipation, radiation, hall current and heat source in presence of chemical reaction and Dufour effect. The governing non-linear partial differential equations are transformed into a set of coupled ordinary differential equations which are then solved analytically by using regular perturbation techniques. The effect of various parameters like Schmidt number (Sc), Prandtl number (Pr), Grashof number (Gr), Modified Grashof number (Gm), Magnetic parameter (M), Radiation parameter (F), Porosity parameter (K), Hall parameter(m), Heat Source parameter (S), Chemical reaction parameter (R) and Dufour number (Du) on velocity, temperature and concentration profiles are discussed with the help of numerical values and the graphs.

Key Words: MHD, Heat and Mass Transfer, Porous Medium, Ohmic Heating, Viscous Dissipation, Radiation, Hall Current, Heat Source & Chemical Reaction and Dufour Effect

Nomenclature:

B_0	Magnetic field component along y' - axis
C	Concentration of the fluid
C'	Concentration of the fluid near the plate
C_p	Specific heat at constant pressure
C_w	Concentration of the fluid at the wall
C_∞	Concentration of the fluid far away from the plate
D_m	Molecular diffusivity
Du	Dufour number
E	Eckert number
F	Radiation parameter
g	Acceleration due to gravity
Gm	Modified Grashof number
Gr	Grashof number
K	The permeability parameter
K'	The permeability of medium
M	Hartmann number
m	Hall current parameter
Nu	Nusselt number
$\Pr$	Prandtl number
R	Chemical reaction parameter
S	Heat source parameter
Sc	Schmidt number
Sh	Sherwood number
T	Non – dimensional temperature
T'	Temperature of the fluid near the plate

T_W	Temperature of the fluid at the wall
T_∞	Temperature of the fluid far away from the plate
u	Dimensionless velocity component in x' - direction
u'	Velocity component in x' direction
v'	Velocity component in y' direction
v_o	Constant suction velocity
x, y	Dimensionless co – ordinates
x', y'	Co – ordinate system

Greek Symbols:

β	Co-efficient of volume expansion for heat transfer
β^*	Co-efficient of volume expansion for mass transfer
μ	Viscosity of the fluid
υ	Kinematic viscosity
ρ	Density of the fluid
σ	Electrical conductivity of the fluid
κ	Thermal conductivity of the fluid
τ	Skin – friction

Introduction:

The influence of magnetic field on viscous incompressible flow of electrically conducting fluid has its important in many applications such as extrusion of plastics in manufacture of rayon and nylon, purification of crude oil, paper industry, textile industry, etc.,. The chemical reaction plays an important role in numerous industrial applications such as polymer production, manufacturing of ceramics and food processing, evaporation at the surface of a water body. However, in the presence of strong electric field, the electrical conductive is affected by magnetic field. Consequently, the conductivity parallel to the electric field is reduced. Hence, the current is reduced to the direction normal to both electric and magnetic fields. This phenomenon is known as hall effect. Bejan and Khair [1] investigated the heat and mass transfer by natural convection in a porous medium while Elbashbeshy [2] examined the heat and mass transfer along a vertical plate with variable surface temperature and concentration in the presence of the magnetic field. Abdus Sattar and Abdul Maleque [3] reported the unsteady MHD natural convection flow along an accelerated porous plate with hall current and mass transfer in a rotating porous medium. The unsteady MHD convective heat transfer past a semi-infinite vertical porous moving plate with variable suction have been studied by Kim [4]. Aboeldahab and Elbarbary [5] studied the hall current effects on Magneto-hydrodynamics free convection flow past a semi-infinite vertical plate with mass transfer while Balamurugan *et. al.*, [6] investigated the thermo diffusion and chemical reaction effects on a three dimensional MHD mixed convective flow along an infinite vertical porous plate with viscous and joules dissipation.

Muthukumarasamy [7] examined the effect of heat and mass transfer on flow past an oscillatory vertical plate with variable temperature while the hall effect on MHD flow and heat transfer along a porous flat plate with mass transfer and source/sink have been discussed by Srihari *et. al.*, [8]. Ahmed [9] discussed the MHD convection with Soret and Dufour effect in the three dimensional flow past an infinite vertical porous plate while the Ibrahim and Makinde [10] analyzed the radiation effect on chemically reacting MHD boundary layer flow of heat and mass transfer through porous vertical flat plate. Sri Hari Babu and Ramana Reddy [11] investigated the mass transfer effects on MHD mixed convective flow from a vertical surface with ohmic heating and viscous dissipation while Barik *et. al.*,[12] examined the chemical reaction effect on MHD oscillatory flow through a porous plates with heat source and Soret effect. Rajaiah *et. al.*,[13] discussed the unsteady MHD convective fluid flow past a vertical porous plate with ohmic heating in the presence of suction and injection while Balamurugan *et. al.*,[14] examined the chemical reaction effects on heat and mass transfer of unsteady flow over an infinite vertical porous plate embedded in a porous medium with heat source. Balamurugan and Karthikeyan [15] reported the unsteady MHD free convective heat flow and mass transfer past an infinite vertical porous plate embedded in porous medium in presence of hall current and heat source with chemical reaction. Balamurugan and Karthikeyan [16] investigated the heat and mass transfer of oscillatory free convective MHD rotation flow along a porous medium bounded by two vertical porous plates in the presence of hall current and Soret effect with chemical reaction. The radiation effects of MHD oscillatory rotation flow through a porous medium bounded by two vertical porous plates in the presence of hall current and Dufour effect with chemical reaction have been studied by Balamurugan and Karthikeyan [17].

The objective of the present study is to analyze the chemical reaction, Dufour, hall current, heat source and radiation effects on heat and mass transfer past an infinite vertical porous plate in presence of Ohmic heating and transverse magnetic field.

Mathematical Formulation:

Consider a steady MHD flow of an incompressible and electrically conducting viscous fluid along a hot, non-conducting porous vertical plate. Choose x'- axis along the plate in the upward direction and y'- axis along normal to the plate. A transverse constant magnetic field is applied that is in the direction of y'- axis. Since the motion is two dimensional and length of the plate is large enough therefore all the physical variables are independent of the variable x'. Let u' and v' be the velocity components of fluid flow along x' and y' directions respectively, that is along and perpendicular to the plate. Under the regular Boussinesq's approximation, the governing equations consisting of continuity, momentum, energy and concentration respectively are given by

$$\frac{\partial v'}{\partial y'}=0 \Rightarrow v'=-v_0 \tag{1}$$

$$v'\frac{\partial u'}{\partial y'}=\upsilon\frac{\partial^2 u'}{\partial y'^2}+g\beta\left(T'-T_\infty\right)+g\beta^*\left(C'-C_\infty\right)-\frac{\sigma B_0^{\,2}u'}{\rho\left(1+m^2\right)}-\frac{\upsilon}{K'}u' \tag{2}$$

$$\frac{\partial p'}{\partial y'}=0,\ \ i.e.,\ p'\ is\ independent\ of\ \ y' \tag{3}$$

$$v'\frac{\partial T'}{\partial y'}=\frac{\kappa}{\rho c_p}\frac{\partial^2 T'}{\partial y'^2}+\frac{\upsilon}{c_p}\left(\frac{\partial u'}{\partial y'}\right)^2+\frac{\sigma B_0^{\,2}u'^2}{\rho c_p}-\frac{1}{\rho c_p}\frac{\partial q_r'}{\partial y'}+S'\left(T'-T_\infty\right)+\frac{D_m K_T}{c_s c_p}\frac{\partial^2 C'}{\partial y'^2} \tag{4}$$

$$v'\frac{\partial C'}{\partial y'}=D_m\frac{\partial^2 C'}{\partial y'^2}-R'\left(C'-C_\infty\right) \tag{5}$$

The radiative heat flux is taken in the following form

$$\frac{\partial q_r'}{\partial y'}=4\left(T'-T_\infty'\right)I' \tag{6}$$

where $I'=\int_0^\infty K_{\lambda w}\frac{\partial e_{b\lambda}}{\partial T'}d\lambda$, $K_{\lambda w}$ is the absorption coefficient at wall and $e_{b\lambda}$ is Planck's function.

The boundary conditions are

$$\left.\begin{aligned} &u'=0, T'=T_W, C'=C_W \qquad at\ y'=0\\ &u'\to 0, T'\to T_\infty, C'\to C_\infty \quad as\ y'\to\infty \end{aligned}\right\} \tag{7}$$

Introduce the following dimensionless quantities and variables

$$\begin{gathered} y=\frac{v_0 y'}{\upsilon},\quad u=\frac{u'}{v_0},\quad T=\frac{T'-T_\infty}{T_W-T_\infty},\quad C=\frac{C'-C_\infty}{C_W-C_\infty},\quad \Pr=\frac{\mu c_p}{\kappa},\quad Sc=\frac{\upsilon}{D_m},\\ Gr=\frac{g\beta\upsilon\left(T_W-T_\infty\right)}{v_0^{\,3}},\quad M=\frac{\sigma B_0^{\,2}\upsilon}{\rho v_0^{\,2}},\quad M_1=\frac{M}{1+m^2},\quad Gm=\frac{g\beta^*\upsilon\left(C_W-C_\infty\right)}{v_0^{\,3}},\ K=\frac{K' v_0^{\,2}}{\upsilon^2},\\ E=\frac{v_0^{\,2}}{c_p\left(T_W-T_\infty\right)},\quad R=\frac{R'\upsilon}{v_0^{\,2}},\quad F=\frac{4\upsilon I'}{\rho c_p v_0^{\,2}},\quad Du=\frac{D_m K_T\left(C_w-C_\infty\right)}{\upsilon c_s c_p\left(T_w-T_\infty\right)},\quad S=\frac{4S'\upsilon}{v_0^{\,2}} \end{gathered} \tag{8}$$

The equations (2), (4) and (5) after using (8) become

$$\frac{\partial^2 u}{\partial y^2}+\frac{\partial u}{\partial y}-\left(M_1+\frac{1}{K}\right)u=-\left(GrT+GmC\right) \tag{9}$$

$$\frac{\partial^2 T}{\partial y^2}+\Pr\frac{\partial T}{\partial y}+\Pr\left(S-F\right)T=-\left[\Pr E\left(\frac{\partial u}{\partial y}\right)^2+\Pr EMu^2+\Pr Du\frac{\partial^2 C}{\partial y^2}\right] \tag{10}$$

$$\frac{\partial^2 C}{\partial y^2}+Sc\frac{\partial C}{\partial y}-ScRC=0 \qquad (11)$$

The corresponding non-dimensional boundary conditions are

$$\left.\begin{array}{ll} u=0,\ T=1,\ C=1 & at\ y=0 \\ u\to 0, T\to 0, C\to 0 & as\ y\to\infty \end{array}\right\} \qquad (12)$$

Method of Solution:

The physical variables $u, T\ and\ C$ can be expanded in a series of powers of the Eckert number (E). This can be possible physically as E for the flow of an incompressible fluid is always less than unity.

To solve the system of partial differential equations (9) - (11), we follow the regular perturbation method using E as the perturbation parameter. Therefore the expressions for velocity, temperature and concentration are assumed in the following form.

$$\left.\begin{array}{l} u(y)=u_0(y)+E\,u_1(y)+o(E^2) \\ T(y)=T_0(y)+E\,T_1(y)+o(E^2) \\ C(y)=C_0(y)+E\,C_1(y)+o(E^2) \end{array}\right\} \qquad (13)$$

Substituting the above expressions (13) in the equations (9) - (11) and equating the co-efficient of like powers of E^0 and E^1 (neglecting E^2 terms onwards), we obtain the following set of ordinary differential equations.

$$u_0''+u_0'-(M_1+\frac{1}{K})u_0=-GrT_0-GmC_0 \qquad (14)$$

$$T_0''+\Pr T_0'+\Pr(S-F)T_0=-\Pr DuC_0'' \qquad (15)$$

$$C_0''+ScC_0'-ScRC_0=0 \qquad (16)$$

$$u_1''+u_1'-(M_1+\frac{1}{K})u_1=-GrT_1-GmC_1 \qquad (17)$$

$$T_1''+\Pr T_1'+\Pr(S-F)T_1=-\left[\Pr u_0'^2+\Pr Mu^2{}_0+\Pr DuC_1''\right] \qquad (18)$$

$$C_1''+ScC_1'-ScRC_1=0 \qquad (19)$$

The relevant boundary conditions become

$$\left.\begin{array}{ll} u_0=0,\ u_1=0,\ T_0=1,\ T_1=0,\ C_0=1,\ C_1=0 & at\ \ y=0 \\ u_0\to 0,\ u_1\to 0,\ T_0\to 0,\ T_1\to 0,\ C_0\to 0,\ C_1\to 0 & as\ \ y\to\infty \end{array}\right\} \qquad (20)$$

The equations (14) to (19) are second order linear ordinary differential equations with constant coefficients. The solutions of these equations under the corresponding boundary conditions are

$$C_0(y)=e^{m_1 y} \qquad (21)$$

$$T_0(y)=A_4e^{m_3y}+A_3e^{m_1y} \qquad (22)$$

$$u_0(y)=A_9e^{m_5y}+A_6e^{m_3y}+(A_7+A_8)e^{m_1y} \qquad (23)$$

$$C_1(y)=0 \qquad (24)$$

$$\left.\begin{array}{l} T_1(y)=A_{21}e^{m_3y}+A_{11}e^{2m_5y}+A_{12}e^{2m_3y}+(A_{13}+A_{14}+A_{17})e^{2m_1y}+A_{15}e^{(m_3+m_5)y} \\ \qquad +(A_{16}+A_{20})e^{(m_1+m_3)y}+(A_{18}+A_{19})e^{(m_1+m_5)y} \end{array}\right\} \qquad (25)$$

$$\left.\begin{array}{l} u_1(y)=A_{30}e^{m_5y}+A_{23}e^{m_3y}+A_{24}e^{2m_5y}+A_{25}e^{2m_3y}+A_{26}e^{2m_1y}+A_{27}e^{(m_3+m_5)y} \\ \qquad +A_{28}e^{(m_1+m_3)y}+A_{29}e^{(m_1+m_5)y} \end{array}\right\} \qquad (26)$$

The values for the constants $m's$ and $A's$ are given in the Appendix.

Substituting $u_0(y)$ and $u_1(y)$ in (13), the velocity field $u(y)$ is

$$\left.\begin{aligned} u(y) = & \left[A_9 e^{m_5 y} + A_6 e^{m_3 y} + (A_7 + A_8) e^{m_1 y}\right] + E\left[A_{30} e^{m_5 y} + A_{23} e^{m_3 y} + A_{24} e^{2m_5 y}\right. \\ & \left. + A_{25} e^{2m_3 y} + A_{26} e^{2m_1 y} + A_{27} e^{(m_3+m_5)y} + A_{28} e^{(m_1+m_3)y} + A_{29} e^{(m_1+m_5)y}\right] \end{aligned}\right\} \tag{27}$$

Substituting $T_0(y)$ and $T_1(y)$ in (13), the temperature field $T(y)$ is

$$\left.\begin{aligned} T(y) = & \left[A_4 e^{m_3 y} + A_3 e^{m_1 y}\right] + E\left[A_{21} e^{m_3 y} + A_{11} e^{2m_5 y} + A_{12} e^{2m_3 y} + (A_{13} + A_{14} + A_{17}) e^{2m_1 y}\right. \\ & \left. + A_{15} e^{(m_3+m_5)y} + (A_{16} + A_{20}) e^{(m_1+m_3)y} + (A_{18} + A_{19}) e^{(m_1+m_5)y}\right] \end{aligned}\right\} \tag{28}$$

Substituting $C_0(y)$ and $C_1(y)$ in (13), the concentration field $C(y)$ is

$$C(y) = e^{m_1 y} \tag{29}$$

Skin Friction:

The expression for the skin friction τ at the plate is given by

$$\tau = \left(\frac{\partial u}{\partial y}\right)_{y=0}$$

$$\tau = \left(\frac{\partial u_0}{\partial y}\right)_{y=0} + E\left(\frac{\partial u_1}{\partial y}\right)_{y=0}$$

$$\left.\begin{aligned} \tau = & \left[A_9 m_5 + A_6 m_3 + (A_7 + A_8) m_1\right] + E\left[A_{30} m_5 + A_{23} m_3 + 2A_{24} m_5 + 2A_{25} m_3 + 2A_{26} m_1\right. \\ & \left. + A_{27}(m_3 + m_5) + A_{28}(m_1 + m_3) + A_{29}(m_1 + m_5)\right] \end{aligned}\right\} \tag{30}$$

Rate of Heat Transfer:

The expression for the rate of heat transfer in terms of Nusselt number Nu is given by

$$Nu = -\left(\frac{\partial T}{\partial y}\right)_{y=0}$$

$$Nu = -\left\{\left(\frac{\partial T_0}{\partial y}\right)_{y=0} + E\left(\frac{\partial T_1}{\partial y}\right)_{y=0}\right\}$$

$$\left.\begin{aligned} Nu = & -\left\{\left[A_4 m_3 + A_3 m_1\right] + E\left[A_{21} m_3 + 2A_{11} m_5 + 2A_{12} m_3 + 2(A_{13} + A_{14} + A_{17}) m_1\right.\right. \\ & \left.\left. + A_{15}(m_3 + m_5) + (A_{16} + A_{20})(m_1 + m_3) + (A_{18} + A_{19})(m_1 + m_5)\right]\right\} \end{aligned}\right\} \tag{31}$$

Rate of Mass Transfer:

The expression for the rate of mass transfer in terms of Sherwood number Sh is given by

$$Sh = -\left(\frac{\partial C}{\partial y}\right)_{y=0}$$

$$Sh = -\left\{\left(\frac{\partial C_0}{\partial y}\right)_{y=0} + E\left(\frac{\partial C_1}{\partial y}\right)_{y=0}\right\}$$

$$Sh = -m_1 \tag{32}$$

Results and Discussion:

The flow parameters play an important role in determining the magnitude of velocity of the flow field. The flow parameters affecting the velocity flow field are Grashof number, Modified Grashof number, Hall parameter, Magnetic parameter, Porosity parameter and Heat source parameter. Figures 1-6 depict the effects of these parameters on the velocity of the flow field.

Figure 1 shows the effect of Grashof number on the velocity field. It is seen that as the Grashof number increases the velocity increases. Figure 2 illustrates the effect of Modified Grashof number on the velocity field. It is observed that as the Modified Grashof number increases the velocity increases. Figure 3 displays the effect of Hall parameter on the velocity field. It is seen that as the Hall parameter increases the velocity increases. Figure 4 depicts the effect of Magnetic parameter on the velocity field. It is noticed that as the Magnetic parameter increases the velocity decreases. Physically, it is true due to the fact that the application of a transverse magnetic field to an electrically conducting fluid gives rise to a body force known as Lorentz force which tends to resist the fluid flow and slow down its motion in the boundary layer region. Figure 5 presents the effect of Porosity parameter on the velocity field. It is observed that as the Porosity parameter increases the velocity increases. Figure 6 discusses the effect of Heat source parameter on the velocity field. It is seen that as the Heat source parameter increases the velocity increases.

Figures 7-10 elucidate the temperature profiles of the flow field with the variation of the flow parameters such as Prandtl number, Radiation parameter, Heat source parameter and Dufour number. Figure 7 shows the effect of Prandtl number on the temperature field. It is noticed that as the Prandtl number increases the temperature decreases. Figure 8 presents the effect of Radiation parameter on the temperature field. It is observed that as the Radiation parameter increases the temperature decreases. It is due to the fact that increase in radiation parameter results in the temperature within the boundary layer, as well as decreased thickness of the temperature boundary layers. Figure 9 illustrates the effect of Heat source parameter on the temperature field. It is seen that as the Heat source parameter increases the temperature increases. Figure 10 discusses the effect of Dufour number on the temperature field. It is observed that as the Dufour number increases the temperature increases.

The Chemical reaction parameter and Schmidt number play a dominant role in determining the concentration field shown in the Figures 11 and 12. Figure 11 illustrates the effect of Chemical reaction parameter on the concentration field. It is noticed that as the Chemical reaction parameter increases the concentration decreases. Physically, it is true due to the fact that the destructive chemical reduces the solutal boundary layer thickness and increases the mass transfer there is a decrease in the concentration of species in the boundary layer. Figure 12 discusses the effect of Schmidt number on the concentration field. It is seen that as the Schmidt number increases the concentration decreases. This is due to the fact that the concentration of the species is higher for small values of Schmidt number, as the increase of Schmidt number means decrease of molecular diffusion. Hence there is a decrease in concentration with the increase of Schmidt number.

Figure 13 shows the effect of Grashof number on the skin friction. It is noticed that as the Grashof number increases the skin friction increases. Figure 14 represents the effect of Schmidt number on the Nusselt number. It is seen that as the Schmidt number increases the Nusselt number decreases.

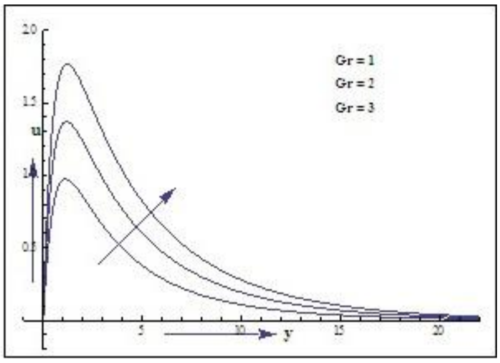

Figure 1: Velocity profile for various values of Gr
E=0.001,Pr=0.025,M=2,Gm=2,K=1,F=3,Sc=0.22
R=1.30,Du=1.25, m=1.5,S=1.7

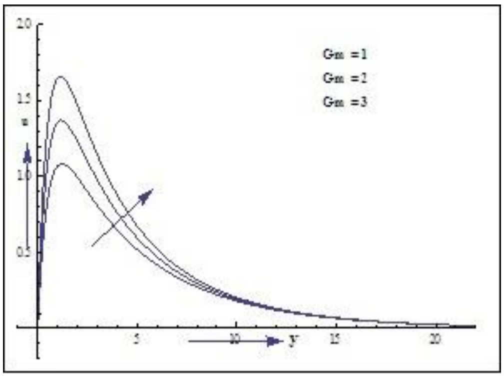

Figure 2: Velocity profile for various values of Gm
E=0.001,Pr=0.025,M=2,Gr=2,K=1,F=3,Sc=0.22,
R=1.30,Du=1.25, m=1.5,S=1.7

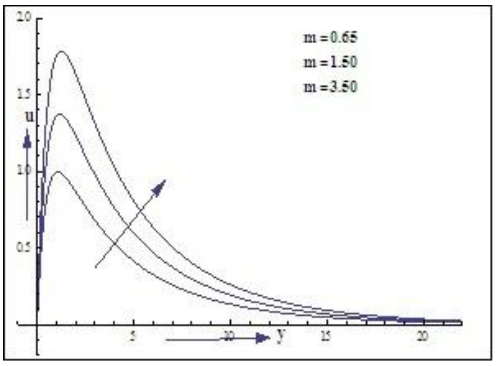

Figure 3: Velocity profile for various values of m
E=0.001,Pr=0.025,M=2,Gr=2,Gm=2,K=1,F=3,
Sc=0.22,R=1.30,Du=1.25,S=1.7

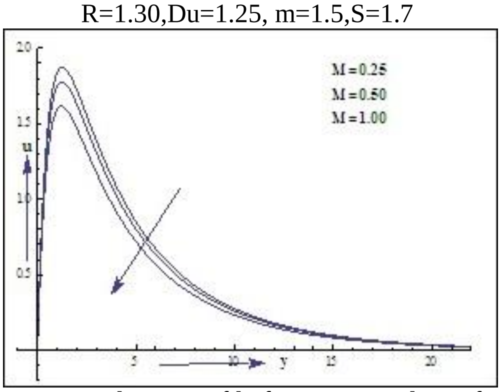

Figure 4: Velocity profile for various values of M
E=0.001,Pr=0.025,Gr=2,Gm=2,K=1,F=3,Sc=0.22,
R=1.30,Du=1.25,m=1.5,S=1.7

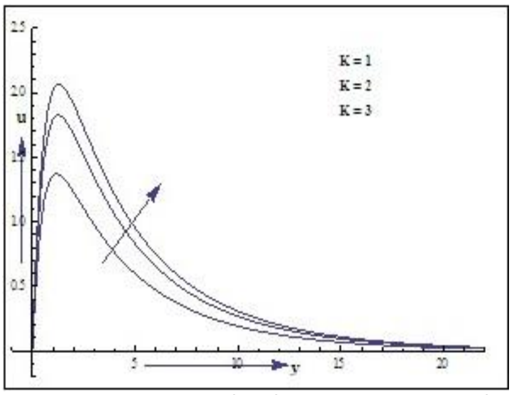

Figure 5: Velocity profile for various values of K E=0.001,Pr=0.025,M=2,Gr=2,Gm=2,F=3, Sc=0.22,R=1.30,Du=1.25,m=1.5,S=1.7

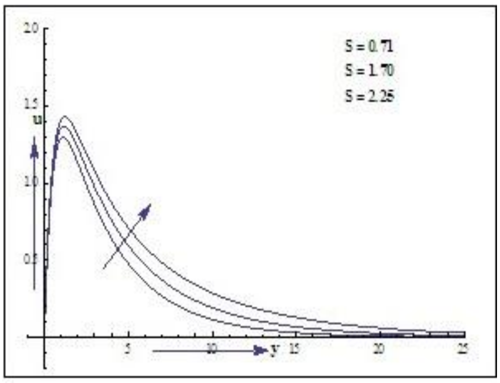

Figure 6: Velocity profile for various values of S E=0.001,Pr=0.025,M=2,Gr=2,Gm=2,K=1,F=3, Sc=0.22,R=1.30,Du=1.25,m=1.5

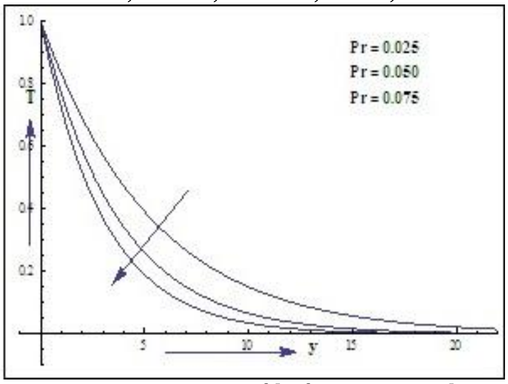

Figure 7: Temperature profile for various values of Pr E=0.001,M=0.5,Gr=2,Gm=2,K=1,F=3,Sc=0.22, R=1.30,Du=1.25, m=1.5,S=1.7

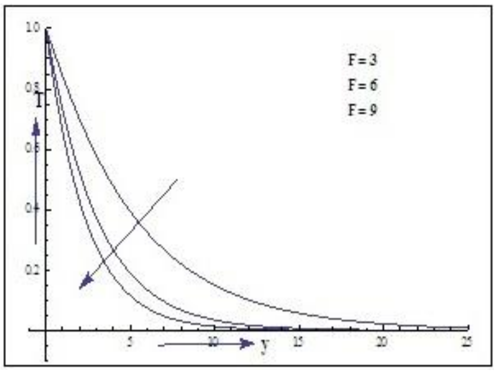

Figure 8: Temperature profile for various values of F E=0.001,Pr=0.025,M=0.5,Gr=2,Gm=2,K=1,Sc=0.60, R=1.30,Du=1.25,m=1.5,S=1.7

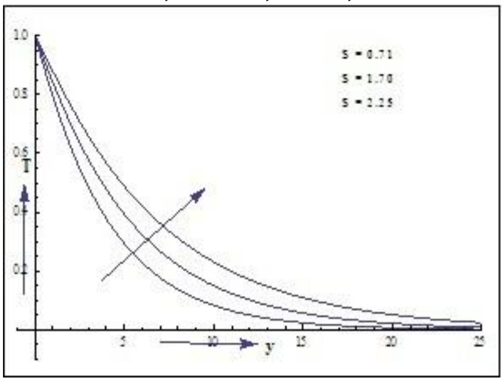

Figure 9: Temperature profile for various values of S E=0.001,Pr=0.025,M=0.5,Gr=2,Gm=2,K=1, F=3, Sc=0.60,R=1.30,Du=1.25,m=1.5

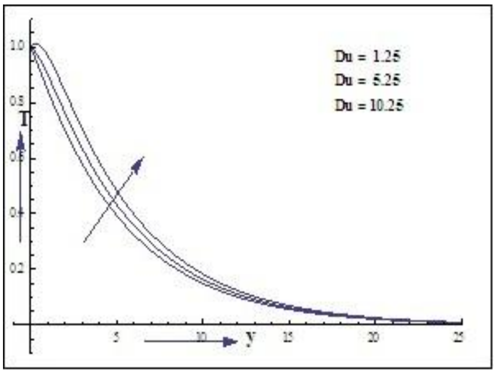

Figure 10: Temperature profile for various values of Du E=0.001,Pr=0.025,M=0.5,Gr=2,Gm=2,K=1, F=3,Sc=0.60,R=1.30,m=1.5,S=1.7

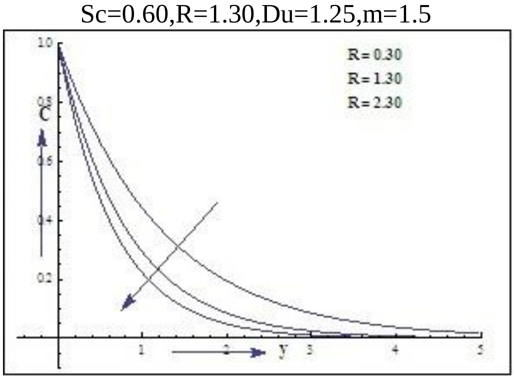

Figure 11: Concentration profile for various values of R E=0.001,Pr=0.025,M=0.5,Gr=2,Gm=2,K=1, F=3,Sc=0.60,Du=1.25,m=1.5,S=1.7

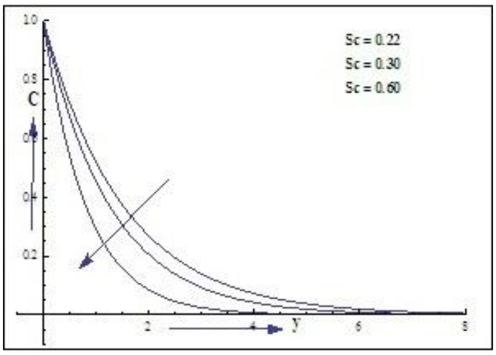

Figure 12: Concentration profile for various values of Sc E=0.001,Pr=0.025,M=0.5,Gr=2,Gm=2,K=1, F=3,R=1.30,Du=1.25,m=1.5,S=1.7

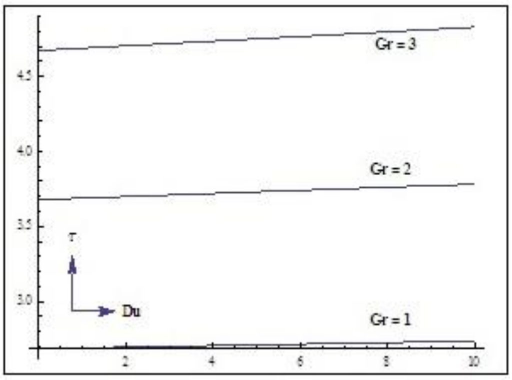

Figure 13: Skin friction for various values of Gr
E=0.001,Pr=0.025,M=2,Gm=2,K=1,F=3, Sc=0.22, R=0.30, m=1.5, S=1.7

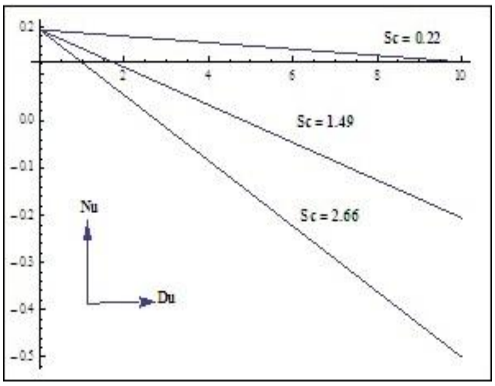

Figure 14: Heat flux for various values of Sc
E=0.001,Pr=0.025,M=2,Gr=2,Gm=2,K=1,F=3, R=0.30,m=1.5,S=1.7

Conclusion:

The above analysis brings out the following results of physical interest on velocity temperature and concentration distribution of the flow field.

- ✓ The Grashof number (Gr) and Modified Grashof number (Gm) accelerate the velocity of the flow field.
- ✓ The Hall parameter (m) accelerates the velocity of the flow field but growing of Magnetic parameter (M) retards the velocity.
- ✓ The Porosity parameter (K) and Heat source parameter (S) increase the velocity of the flow field.
- ✓ The Heat source parameter (S) accelerates the temperature of the flow field but growing of Prandtl number (Pr) retards the temperature.
- ✓ The Dufour number (Du) increases the temperature of the flow field but growing of Radiation parameter (F) reduces the temperature.
- ✓ Growing of chemical reaction parameter (R) and Schmidt number (Sc) decrease the concentration distribution of the flow field.
- ✓ The Grashof number (Gr) accelerates the skin friction.
- ✓ Nusselt number (Nu) decreases with increase in Schmidt number (Sc).

Appendix:

$$m_1 = -\frac{\left[Sc + \sqrt{Sc^2 + 4ScR}\right]}{2}$$

$$m_3 = -\frac{\left[\Pr + \sqrt{\Pr^2 - 4\Pr(S-F)}\right]}{2}$$

$$m_5 = -\frac{\left[1 + \sqrt{1 + 4\left(M_1 + \frac{1}{K}\right)}\right]}{2}$$

$$A_3 = -\frac{\Pr Du\, m_1^2}{m_1^2 + \Pr m_1 + \Pr(S-F)}$$

$$A_4 = 1 - A_3$$

$$A_6 = -\frac{GrA_4}{m_3^2 + m_3 - \left(M_1 + \frac{1}{K}\right)}$$

$$A_7 = -\frac{GrA_3}{m_1^2 + m_1 - \left(M_1 + \frac{1}{K}\right)}$$

$$A_8 = -\frac{Gm}{m_1^2 + m_1 - \left(M_1 + \frac{1}{K}\right)}$$

$$A_9 = -\left(A_6 + A_7 + A_8\right)$$

$$A_{11} = -\frac{\Pr\left(M + m_5^2\right)A_9^2}{4m_5^2 + 2\Pr m_5 + \Pr\left(S - F\right)}$$

$$A_{12} = -\frac{\Pr\left(M + m_3^2\right)A_6^2}{4m_3^2 + 2\Pr m_3 + \Pr\left(S - F\right)}$$

$$A_{13} = -\frac{\Pr\left(M + m_1^2\right)A_7^2}{4m_1^2 + 2\Pr m_1 + \Pr\left(S - F\right)}$$

$$A_{14} = -\frac{\Pr\left(M + m_1^2\right)A_8^2}{4m_1^2 + 2\Pr m_1 + \Pr\left(S - F\right)}$$

$$A_{15} = -\frac{2\Pr A_6 A_9\left(M + m_3 m_5\right)}{\left(m_3 + m_5\right)^2 + \Pr\left(m_3 + m_5\right) + \Pr\left(S - F\right)}$$

$$A_{16} = -\frac{2\Pr A_6\, A_7\left(M + m_1 m_3\right)}{\left(m_1 + m_3\right)^2 + \Pr\left(m_1 + m_3\right) + \Pr\left(S - F\right)}$$

$$A_{17} = -\frac{2\Pr\left(M + m_1^2\right)A_7 A_8}{4m_1^2 + 2\Pr m_1 + \Pr\left(S - F\right)}$$

$$A_{18} = -\frac{2\Pr A_8 A_9\left(M + m_1 m_5\right)}{\left(m_1 + m_5\right)^2 + \Pr\left(m_1 + m_5\right) + \Pr\left(S - F\right)}$$

$$A_{19} = -\frac{2\Pr A_7 A_9\left(M + m_1 m_5\right)}{\left(m_1 + m_5\right)^2 + \Pr\left(m_1 + m_5\right) + \Pr\left(S - F\right)}$$

$$A_{20} = -\frac{2\Pr A_6\, A_8\left(M + m_1 m_3\right)}{\left(m_1 + m_3\right)^2 + \Pr\left(m_1 + m_3\right) + \Pr\left(S - F\right)}$$

$$A_{21} = -\left(A_{11} + A_{12} + A_{13} + A_{14} + A_{15} + A_{16} + A_{17} + A_{18} + A_{19} + A_{20}\right)$$

$$A_{23} = -\frac{GrA_{21}}{m_3^2 + m_3 - \left(M_1 + \frac{1}{K}\right)}$$

$$A_{24} = -\frac{GrA_{11}}{4m_5^2 + 2m_5 - \left(M_1 + \frac{1}{K}\right)}$$

$$A_{25} = -\frac{GrA_{12}}{4m_3^2 + 2m_3 - \left(M_1 + \frac{1}{K}\right)}$$

$$A_{26} = -\frac{Gr\left(A_{13} + A_{14} + A_{17}\right)}{4m_1^2 + 2m_1 - \left(M_1 + \frac{1}{K}\right)}$$

$$A_{27} = -\frac{Gr A_{15}}{(m_3+m_5)^2+(m_3+m_5)-\left(M_1+\frac{1}{K}\right)}$$

$$A_{28} = -\frac{Gr(A_{16}+A_{20})}{(m_1+m_3)^2+(m_1+m_3)-\left(M_1+\frac{1}{K}\right)}$$

$$A_{29} = -\frac{Gr(A_{18}+A_{19})}{(m_1+m_5)^2+(m_1+m_5)-\left(M_1+\frac{1}{K}\right)}$$

$$A_{30} = -(A_{23}+A_{24}+A_{25}+A_{26}+A_{27}+A_{28}+A_{29})$$

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