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MHD free convection flow past a vertical porous plate in a slip flow regime with radiation chemical reaction and temperature gradient dependent heat source in presence of Dufour effect

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Abstract
This paper deals with the MHD free convection flow past a vertical porous plate in a slip flow regime taking into account radiation ,chemical reaction and temperature gradient dependent heat source in presence of Dufour effect. The magnetic effect is applied normal to the flow. The permeability of the porous medium and the suction velocity at the plate decrease exponentially with time about a constant mean. The expression for velocity, temperature and concentration are obtained using the regular perturbation method. The skin-friction, rate of heat and mass transfer are also derived. A number of graphs are drawn for various flow quantities based on governing parameters and deduce important results.

Keywords
MHD, Free convection, heat and mass transfer, radiation, chemical reaction, and Dufour effect.

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Contents

1. Introduction

Free convection arises in fluids when temperature changes results in density variation leading to buoyancy forces acting on the fluid elements. This type of flow has applications in many branches of science and engineering. The study of such flow under the influence of magnetic field has attracted the interest of many investigators in view of its application in MHD generators, plasma studies, nuclear reactors etc.

The fluid under consideration there does occur some chemical reaction e.g. air and benzene react chemically, so also water and sulfuric acid. During such chemical reactions, there is always generation of heat. Combining heat and mass transfer problems with a chemical reaction have importance in many processes and have therefore received a considerable amount of attention in recent years. One of the simplest chemical reactions is the first-order reaction in which the rate of the reaction is directly proportional to the species concentration. The chemical reactions can be codified as either heterogeneous or homogenous processes. In most cases of chemical reactions the reaction rate depends on the concentration of the species itself. If the rate of reaction is directly proportional to the concentration then the reaction is said to be a homogeneous reaction or first order reaction.

Radiation effects of MHD oscillatory flow along a porous medium bounded by two vertical porous plates in presence of hall current and Dufour effect with chemical reaction was analyzed by Balamurugan K et al.[5].

In many practical applications, the particles adjacent to a solid surface no longer takes the velocity of the surface. The particle at the surface has a finite tangential velocity; it "slips" along the surface. The flow regime is called the slip -flow regime and this effect cannot be neglected. Using these assumptions, Sharma and Chaudhary [6], discussed the free convection flow past a vertical plate in slip-flow regime and also discussed the free convection flow past a vertical plate in slip-flow regime and also discussed its various applications for engineering purpose. Also, Coupled non-linear partial differential equations governing free convection flow, heat and mass transfer has been obtained analytically using the perturbation technique. The fluids considered in this investigation are air (Pr = 0.71) and water (Pr = 7) in the presence of Hydrogen (Sc = 0.22).Magneto hydrodynamic convective heat and mass transfer in a boundary layer slip flow past a vertical permeable plate with thermal radiation and chemical reaction were investigated by Pal and Talukda [13]. Gupta. M and Sharma.S [7] have studied MHD flow through porous medium bounded by oscillating porous plates in slip regime. Recently, Jaiswal.B.S and Soundalgekar.V.M [9] have discussed the flow past an infinite vertical plate oscillating in its plane in the presence of a temperature gradient dependent heat source. while Taneja.R and Jain. N.C [18] have presented a theoretical analysis for unsteady free convection flow with radiation in slip flow regime. Madhusdhana Rao etc et.al [17] studied MHD transient free convection and chemically reactive flow past a porous vertical plate with radiation and temperature gradient dependent heat source in slip flow regime.

When heat and mass transfer occur simultaneously in a moving fluid, the relations them between the fluxes and the driven potential are important. It has been found that the energy flux can be generated not only by temperature gradient but also by the composition gradient. The energy caused by a composition gradient is called the Dufour or the diffusion thermo effect. The Dufour effect is the energy flux due to a mass concentration gradient occurring as a coupled effect of irreversible processes. It is the reciprocal phenomenon to the soret effect. The concentration gradient results in a temperature change. Rushi Kumar B and Sivaraj R[15] Radiation and Dufour effects on chemically reacting MHD mixed convective a slip-flow in irregular channel.

The present paper is to study the unsteady MHD free convection flow of a viscous fluid past a vertical porous plate in a slip flow regime taking into account the radiation chemical reaction and temperature gradient dependent heat source with dufour effect. The Permeability of the porous medium and the suction velocity are considered to be as exponentially decreasing function of time. It is an extension work of Madhusudhan rao et.al[17].by including the dufour effect.

2. Formulation of the problem

We consider a two-dimensional unsteady free convection flow of an incompressible viscous fluid past an infinite vertical porous plate. The Cartesian coordinate system we is adopted by taking x'-axis along the plate in the direction of the flow and the y'-axis normal to it. Further the flow is considered in presence of temperature gradient dependent heat source radiation, chemical reaction and dufour effect.

The flow is entirely due to buoyancy force caused by temperature difference between the porous plate and the fluid. Under the above assumptions, the governing equations are respectively given below

$$\frac{\partial v'}{\partial y'} = 0 \tag{2.1}$$

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = \nu\frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_0^2}{\rho}u' + g\beta\left(T' - T'_\infty\right) + g\beta_c\left(C' - C'_\infty\right) - \frac{\nu}{K'(t)}u' \tag{2.2}$$

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{K_T}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2} - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y'} + \frac{Q'}{\rho C_p}\frac{\partial T'}{\partial y'} + \frac{Dmk_T}{C_s C_p}\frac{\partial^2 C'}{\partial y'^2} \tag{2.3}$$

$$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2} - K'_c\left(C' - C'_\infty\right) \tag{2.4}$$

The relevant boundary conditions are

$$u' = L_1\left(\frac{\partial u'}{\partial y'}\right), T = T'_w, C = C'_w \text{ at } y' = 0$$
$$u' \to 0,\ T' \to T'_\infty, C' \to C'_\infty \text{ at } y' \to \infty \tag{2.5}$$

Where u' and v' are the components of velocity along x' and y'directions, t is the time, g is the acceleration due to gravity, β and β_ε are the coefficients of volume expansion, ν the kinematic viscosity of fluid, $k'(t)$ is the permeability of the porous medium, ρ is the density of the fluid, σ is the electrical conductivity of the fluid, B_0 the uniform magnetic field, T' is the temperature, K_r is the thermal conductivity, C_r is the specific heat at constant pressure, q, the radioactive heat flux, Q' the heat source, T'_W is the temperature of the wall as well as the temperature of the fluid at the plate, T' is the temperature of the fluid far away from the plate, $L = \left(\frac{2-m_1}{m_1}\right)$ is the mean free path where m_1 is the Maxwell's reflection coefficient, C' is the concentration, D the diffusion coefficient, D_m the thermal diffusion coefficient, K'_* is chemical reaction parameter and C'_∞ is the concentration of the wall as well as the concentration of the fluid at the plate. The equation of continuity (1) relevants that v' is either a constant or some function of time, hence assume that

$$v' = -v'_0\left(1 + \varepsilon e^{-n''}\right), \tag{2.6}$$

where $v'_0 > 0$ is the suction velocity at the plate and n' is a positive constant. The negative sign indicates that the suction velocity acts towards the plate.

Consider the fluid which is optically thin with a relatively low density and there by the radioactive heat flux is given by

Ede [7] in the following form

$$\frac{\partial q_r}{\partial y'} = 4\left(T' - T'_\infty\right) I \tag{2.7}$$

Where I is the absorption coefficient at the plate. The Permeability $k'(t)$ of the porous medium is considered in the following form

$$k'(t) = k'_0\left(1 + \varepsilon e^{-n't'}\right) \tag{2.8}$$

Introduce the following dimensionless quantities and variable

$$\begin{aligned} &y = \frac{y'v'_0}{v}, t = \frac{t'v_0'^2}{4v}, u = \frac{u'}{v'_0}, n = \frac{4vn'}{v_0'^2},\\ &M = \frac{\sigma B_0^2 v}{v_0'^2}, K_c = \frac{k'c'}{v_0'^2}, T = \frac{T' - T'_\infty}{T'_w - T'}, C = \frac{C' - C'_\infty}{C'_w - C'_\infty}\\ &\Pr = \frac{\rho v C_p}{K_T}, Gr = \frac{vg\beta\left(T'_w - T'_\infty\right)}{v_0^3}, Gm = \frac{vg\beta_c\left(C'_w - C'_\infty\right)}{v_0^3}, \end{aligned} \tag{2.9}$$

$$\begin{aligned} &Du = \frac{D_m K_T\left(C'_w - C'_\infty\right)}{vC_sC_p\left(T'_w - T'_\infty\right)}, K_0 = \frac{k'_0 v_0^2}{v^2}\\ &R = \frac{4vI}{\rho C_\rho v_0'^2}, s_c = \frac{v}{D}, H = \frac{Q'v}{\rho C_p v_0'^2\left(T'_w - T'_\infty\right)}. \end{aligned}$$

The set of equations (2.2)-(2.4) after introducing (2.9), we obtain the non-dimensional form of the governing equations as follows:

$$\begin{aligned} &\frac{1}{4}\frac{au}{\partial t} - \left(1 + \varepsilon e^{-nt}\right)\frac{Ou}{\partial y}\\ &= \frac{\partial^2 u}{\partial y^2} - \left[M + \frac{1}{k_0\left(1 + \varepsilon e^{-mt}\right)}\right]u + GrT + GmC \end{aligned} \tag{2.10}$$

$$\frac{1}{4}\frac{\partial T}{\partial t} - \left(1 + \varepsilon e^{-nt}\right)\frac{\partial T}{\partial y} = \frac{1}{\Pr}\frac{\partial^2 T}{\partial y^2} - RT + H\frac{\partial T}{\partial y} + Du\frac{\partial^2 C}{\partial y^2} \tag{2.11}$$

$$\frac{1}{4}\frac{\partial c}{\partial t} - \left(1 + \varepsilon e^{-nt}\right)\frac{\partial c}{\partial y} = \frac{1}{\mathrm{Sc}}\frac{\partial^2 c}{\partial y^2} - K_c C \tag{2.12}$$

and the boundary conditions (2.5) reduce to

$$\begin{aligned} &u = h\left(\frac{\partial u}{\partial y}\right), T = 1, C = 1,\ \text{at } y = 0\\ &u \to 0,\ T \to 0, C \to 0 \text{ at } y \to \infty \end{aligned} \tag{2.13}$$

where, $h = \frac{L_1 v_0'^2}{v}$.

3. Method of solution

The present flow is governed by the system of partial differential equations (2.10), (2.11) and (2.12), with the boundary conditions (2.13). Assuming ε to be so small so that one can express velocity, temperature and concentration as a regular perturbation serieses interms of $\mathscr{E}$ in the neighborhood of the plate as,

$$u(y,t) = u_0(y) + \varepsilon u_1(y)e^{-nt} \tag{3.1}$$

$$T(y,t) = T_0(y) + \varepsilon T_1(y)e^{-nt} \tag{3.2}$$

$$C(y,t) = C_0(y) + \varepsilon C_1(y)e^{-m} \tag{3.3}$$

Substituting the above expressions (3.1), (3.2), (3.3) in equations (2.10),(2.11),(2.12) and equating the coefficients of $\varepsilon^0, \varepsilon^1$ (neglecting ε^2 terms etc.,), we obtain the following set of ordinary differential equations.

$$u''(y) + u'(y) - M_1 u_0(y) = -GrT_0(y) - GmC_0 \tag{3.4}$$

$$\begin{aligned} &u_1''(y) + u_1'(y) - M_2\ F_1(y)\\ &= \frac{1}{k_0}u_0(y) - u'(y) - GrT_1(y) - GmC_1(y) \end{aligned} \tag{3.5}$$

$$T_0''(y) + (1+H)\Pr T_0'(y) - R\Pr T_0(y) = -\Pr DuC_0''(y) \tag{3.6}$$

$$T_1''(y) + (1+H)\Pr T_1'(y) - \left(R - \frac{n}{4}\right)\Pr T_1(y) = -prT_0'(y) \tag{3.7}$$

$$C_0''(y) + ScC_0'(y) - ScKcC_0(y) = 0 \tag{3.8}$$

$$C_1''(y) + ScC_1'(y) - \left(k_0 - \frac{n}{4}\right)ScC_0(y) = -ScC_0'(y) \tag{3.9}$$

Where $M_1 = M + \frac{1}{k_0}$ and $M_2 = M + \frac{1}{k_0} - \frac{n}{4}$.

The boundary conditions (2.13) reduce to,

$$\begin{aligned} &u_0 = hu_0', u_1 = hu_1', T_0 = 0, C_0 = 1, C_1 = 0 \text{ at } y = 0\\ &u_0 \to 0, u_1 \to 0,\ T_1 \to 0, C_0 \to 0, C_1 \to 0 \text{ at } y \to \infty \end{aligned} \tag{3.10}$$

The equations from (3.4) to (3.9) are second order ordinary linear differential equations with constant coefficients. The solutions of these paired equations under the corresponding boundary conditions (3.10) are,

$$C_0(y) = e^{-m_1 y} \tag{3.11}$$

$$C_1(y) = A_1\left(e^{-m_1 y} - e^{-m_2 y}\right) \tag{3.12}$$

$$T_0(y) = \left(1 - A_2\right)e^{-m_3 y} + A_2 e^{-m_1 x} \tag{3.13}$$

$$\begin{aligned} T_1(y) = &-\left(A_3 + A_2 + A_5\right)e^{-m_4 y} + A_3 e^{-m_3 y}\\ &+ A_4 e^{-m_3 y} + A_5 e^{-m_1 y} \end{aligned} \tag{3.14}$$

$$\begin{aligned} u_0(y) = &A_{10}e^{-m_3 y} + A_6 e^{-m_3 y} + A_7 e^{-m_3 y} + A_8 e^{-m_1 y}\\ &+ A_9 e^{-m_1 y} \end{aligned} \tag{3.15}$$

$$\begin{aligned} u_1(y) = &A_{27}e^{-m_6 y} + A_{11}e^{-m_5 y} + A_{12}e^{-m_3 y} + A_{13}e^{-m_3 y}\\ &+ A_{14}e^{-m_1 y} + A_{15}e^{-m_1 y} + A_{16}e^{-m_5 y} + A_{17}e^{-m_3 x}\\ &+ A_{18}e^{-m_3 y} + A_{19}e^{-m_1 y} + A_{20}e^{-m_1 y} + A_{21}e^{-m_4 y}\\ &+ A_{22}e^{-m_3 y} + A_{23}e^{-m_3 y} + A_{24}e^{-m_1 y} + A_{25}e^{-m_1 y}\\ &+ A_{26}e^{-m_2 y} \end{aligned} \tag{3.16}$$

The values of the constants A_1, A_2 etc. are given in the Appendix. The profiles of velocity, temperature and the concentration are,

$$
\begin{aligned}
u(y,t) =& A_{10}e^{-m_5y}+A_6e^{-m_3y}+A_7e^{-m_3y}+A_8e^{-m_Ly} \\
&+A_9e^{-m_1y}+\varepsilon\left(A_{27}e^{-m_6y}+A_{11}e^{-m_3y}\right. \\
&+A_{12}e^{-m_3y}+A_{13}e^{-m_3y}+A_{14}e^{-m_1y}+A_{15}e^{-m_1y} \\
&+A_{16}e^{-m_5y}+A_{17}e^{-m_3y}+A_{18}e^{-m_3y}+A_{19}e^{-m_1y} \\
&+A_{20}e^{-m_1y}+A_{21}e^{-m_4y}+A_{22}e^{-m_3y}+A_{23}e^{-m_3y}
\end{aligned}
$$

$$
\left.+A_{24}e^{-m_0y}+A_{25}e^{-m_1y}+A_{26}e^{-m_2y}\right)e^{-nt} \qquad (3.17)
$$

$$
\begin{aligned}
T(y,t) =& (1-A_2)e^{-m_3y}+A_2e^{-m_0y} \\
&+\varepsilon\left(-(A_3+A_4+A_5)e^{-m_4y}\right. \\
&\left.+A_3e^{-m_3y}+A_4e^{-m_3y}+A_5e^{-m_4y}\right)e^{-nt}
\end{aligned} \qquad (3.18)
$$

$$
C(y,t) = e^{-m_1y}+\varepsilon A_1\left(e^{-m_1y}-e^{-m_2y}\right)e^{-nt} \qquad (3.19)
$$

3.1 Skin friction

The expression for the skin-friction (τ) at the plate is,

$$
\tau = \left(\frac{du}{dy}\right)_{y-0} = \left(\frac{du_0}{dy}\right)_{y-0} + \varepsilon\left(\frac{du_1}{dy}\right)_{y-0} e^{-nt}
$$

$$
\tau = \left(\frac{du}{dy}\right)_{y-0} = A_{28}+\varepsilon A_{29}e^{-nt} \qquad (3.20)
$$

3.2 Rate of heat transfer

The expression for the rate of heat transfer at the plate in terms of Nusselt number (Nu) is

$$
N_v = \left(\frac{dT}{dy}\right)_{y-0} = \left(\frac{dT_0}{dy}\right)_{y-0} + \varepsilon\left(\frac{dT_l}{dy}\right)_{y-0} e^{-nt}
$$

$$
N_v = \left(\frac{dT}{dy}\right)_{y-0} = A_{31}+\varepsilon A_{32}e^{-nt} \qquad (3.21)
$$

3.3 Rate of mass transfer

The expression for the rate of heat transfer at the plate in terms of Sherwood number (Sh) is

$$
S_h = \left(\frac{dC}{dy}\right)_{y-0} = \left(\frac{dC_0}{dy}\right)_{y-0} + \varepsilon\left(\frac{dC_1}{dy}\right)_{y-0} e^{-nt}
$$

$$
S_h = \left(\frac{dC}{dy}\right)_{y-0} = -m_1+\varepsilon A_{30}e^{-nt} \qquad (3.22)
$$

4. Results And Discussions

To assess the physical depth of the problem, the effects of various parameters like Heat source parameter H, Dufour number Du, Radiation parameter R, Permeability of porous medium K0, Grashof number Gr, Modified Grashof number Gm, Prandtl number Pr , Schimidt number Sc on Velocity distribution, Temperature and Concentration distribution are studied in figures 1-12, while keeping the other parameters as constants. The variation in Skin friction, Heat flux and Mass flux have been analysed numerically and discussed with the help of graphical representation.

Figure 1 display the behavior of the velocity distribution by varying the Heat source parameters H, this shows that the velocity decreases with an increase in H. In figure 2 the effect of Dufour number Du on velocity is shown. From this figure it is noticed velocity increases as an increase in Du. In figure 3 the velocity decreases as Radiation parameter R increases. From figure 4 it is observed that the velocity increases as Permeability of porous medium Ko increases. In figure 5 the velocity increases as Grashof number Gr increases. In figure 6 the velocity decreases as Modified Grashof number Gm increases.

In figure 7 the temperature distribution increases as Dufour number Du increases. From figure 8 it is observed that the temperature distribution decreases as Heat source parameters H increases. In figures 9,10 the temperature distribution decreases as the Prandtl number Pr and Radiation parameter R increase respectively.

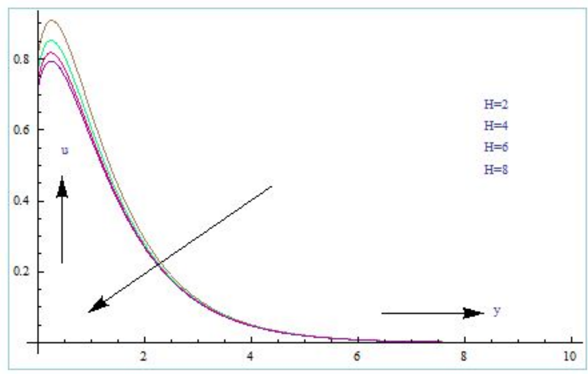

Figure 1. Velocity Profile For Various Value of H ($Pr=0.71, R=2, n=1.0, t=1.0, \varepsilon=0.01, Sc=0.25, Kc=2.25, K0=2, Du=1.0, M=2.0, Gr=2, Gm=4, h=1.0$)

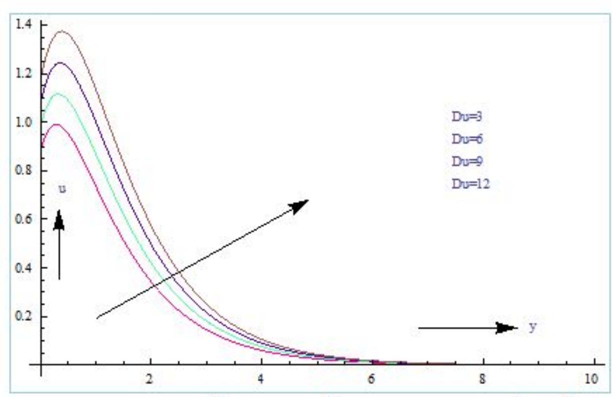

Figure 2. Velocity Profile For Various Value of Du ($Pr=0.71, H=2, R=2, n=1.0, t=1.0, \varepsilon=0.01, Sc=0.25, Kc=2.25, K0=2, M=2.0, Gr=2, Gm=4, h=1.0,$)

In figures 11,12 the concentration decreases as Radiation parameter R and Schimidt number Sc increase respectively.

In figure 13 the skin friction increases as Grashof number Gr increases. Figure 14 the Nusselt number Nu increases as Schmidt number Sc increases. In figure 15 the Sherwood number Sh decreases Radiation parameter R increases.

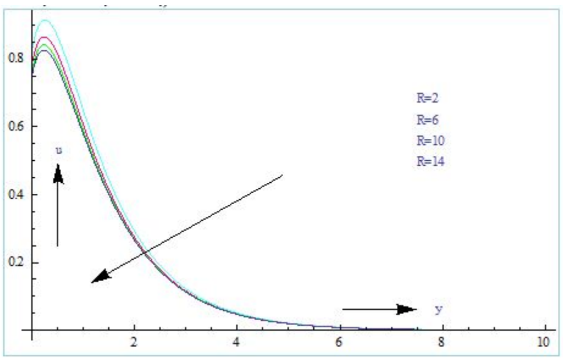

Figure 3. Velocity Profile For Various Value of R ($Pr = 0.71, H = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, Kc = 2.25, K0 = 2, Du = 1.0, M = 2.0, Gr = 2, Gm = 4, h = 1.0$)

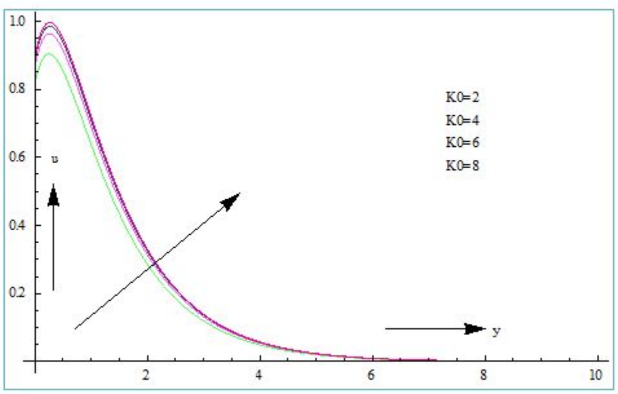

Figure 4. Velocity Profile For Various Value of K0 ($Pr = 0.71, R = 2, H = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, Kc = 2.25, Du = 1.0, M = 2.0, Gr = 2, Gm = 4, h = 1.0$)

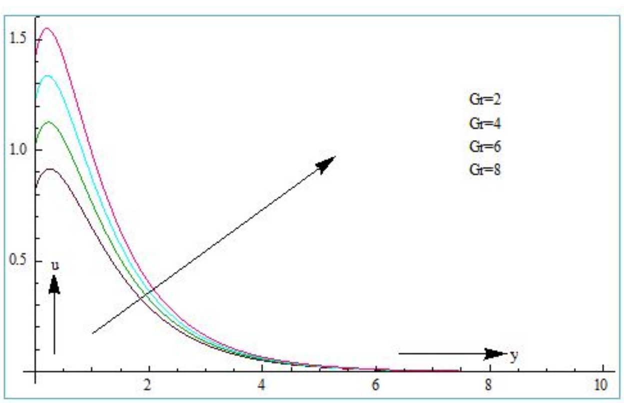

Figure 5. Velocity Profile for various value of Gr ($Pr = 0.71, H = 2, R = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, Kc = 2.25, K0 = 2, Du = 1.0, M = 2.0, Gm = 4, h = 1.0$)

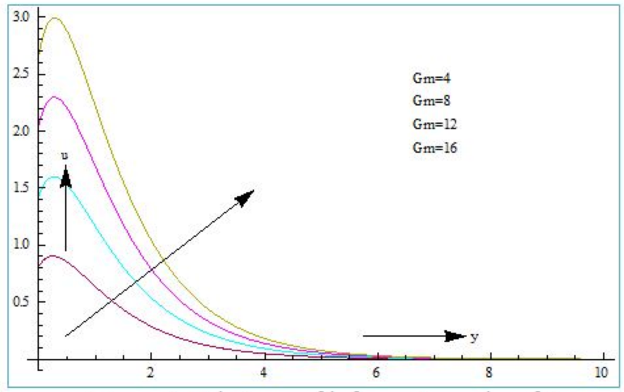

Figure 6. Velocity profile for various value of Gm ($Pr = 0.71, H = 2, R = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, K0 = 2, Kc = 2.25, Du = 1.0, M = 2.0, Gr = 2, h = 1.0,$)

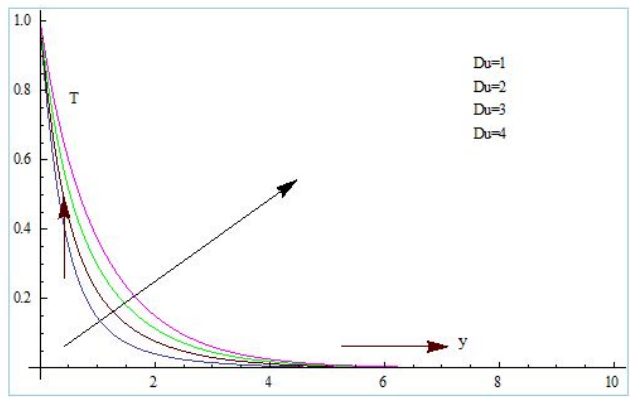

Figure 7. Temperature profile for various value of Du ($Pr = 0.71, R = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, Kc = 2.25, Gr = 2, Gm = 4, h = 1.0,$)

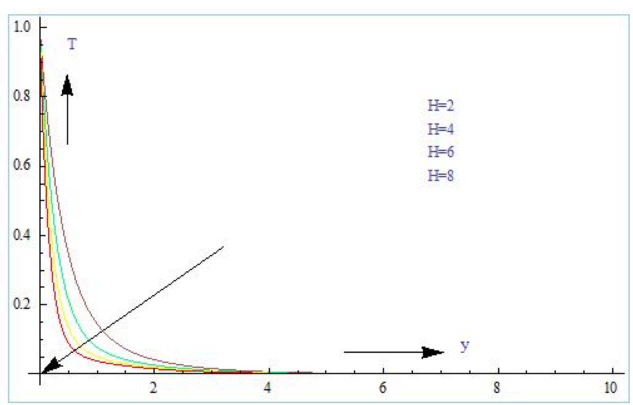

Figure 8. Temperature profile for various value of H ($Pr = 0.71, R = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, Du = 1.0, Kc = 2.25, Gr = 2, Gm = 4, h = 1.0,$)

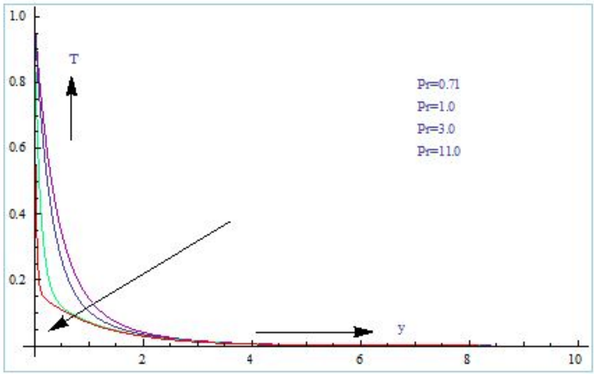

Figure 9. Temperature profile for various value of Pr ($R = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, Du = 1.0, Kc = 2.25, Gr = 2, Gm = 4, h = 1.0$)

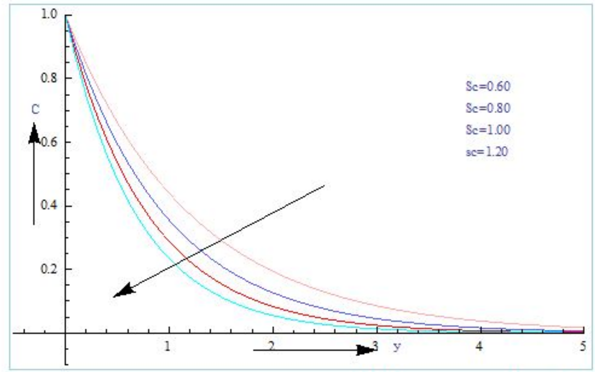

Figure 12. Concentration profile for various value of Sc ($R = 0.30, n = 1.0, t = 1.0, \varepsilon = 0.01, Kc = 2$)

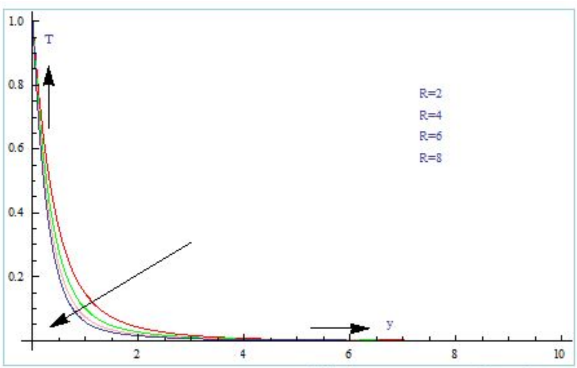

Figure 10. Temperature profile for various value of R ($Pr = 0.71, n = 1.0, t = 1.0, \varepsilon = 0.01, Du = 1.0, Sc = 0.25, Kc = 2.25, Gr = 2, Gm = 4, h = 1.0$)

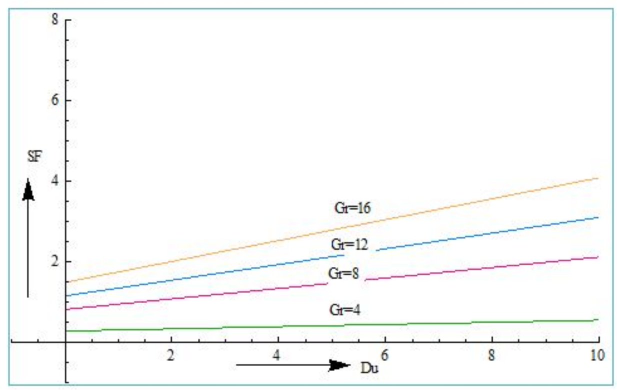

Figure 13. Skin friction for various value of Grashof number ($Pr = 0.71, H = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Sc = 0.25, Kc = 2.25, K0 = 2, M = 2.0, Gm = 4, h = 1.0,$)

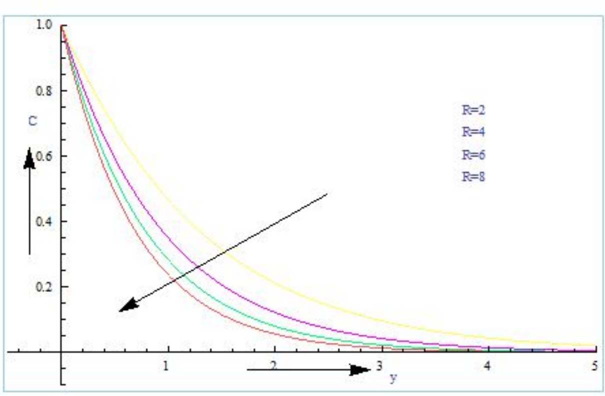

Figure 11. Concentration profile for various value of R ($R = 0.30, n = 1.0, t = 1.0, \varepsilon = 0.1, Sc = 0.22, Kc = 2$)

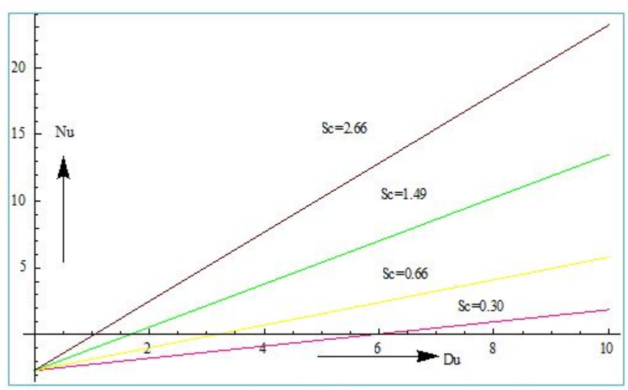

Figure 14. Nusselt number for various values of Schmidt number ($Pr = 0.71, R = 2, H = 2, n = 1.0, t = 1.0, \varepsilon = 0.01, Kc = 2.25, h = 1.0$)

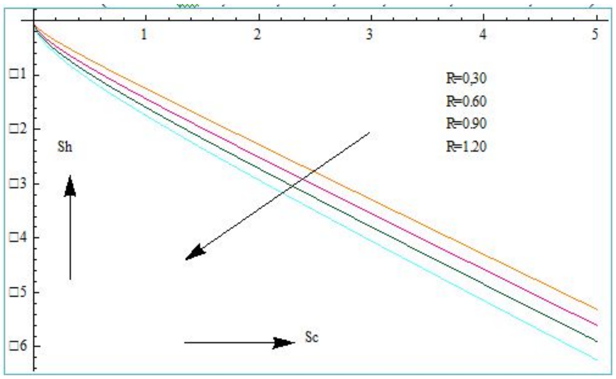

Figure 15. Mass flux for various values of R
$(n = 1.0, t = 1.0, \varepsilon = 0.1, Kc = 2)$

5. Conclusion

1. The velocity increases with an increase in Heat source parameter H, Dufour number Du, permeability of porous medium Ko, Grashof number Gr,

2. The temperature decreases with an increase in Heat source parameter H, Prandtl number Pr, Radiation parameter R. Also temperature increases when increase in the Dufour number Du.

3. The concentration decrease with an increase in Radiation parameter R, Schimidt number Sc,

4. The Skin friction increases while increase in the Grashof number. The Nusselt number increases with increase in the Schmidt number. Increase in the radiation parameter decreases the Sherwood number.

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$$m_1 = \frac{S_c + \sqrt{S_c^2 + 4K_cS_c}}{2}, m_2 = \frac{S_c + \sqrt{S_c^2 + 4\left(K_c - \frac{n}{4}\right)S_c}}{2},$$

$$m_3 = \frac{(1+H)P_r + \sqrt{(1+H)^2P_r^2 + 4P_rR}}{2}$$

$$m_4 = \frac{(1+H)P_r + \sqrt{(1+H)^2P_r^2 + 4P_r\left(R - \frac{n}{4}\right)}}{2},$$

$$m_5 = \frac{1 + \sqrt{1+4M_1}}{2}, m_6 = \frac{1 + \sqrt{1+4M_2}}{2}$$

$$A_1 = \frac{S_cm_1}{m_1^2 - S_cm_1 - \left(K_c - \frac{n}{4}\right)S_c}, A_2 = \frac{P_rm_1^2Du}{m_1^2 - (1+H)P_ym_1 - P_rR},$$

$$A_3 = \frac{P_rm_3}{m_3^2 - (1+H)P_7m_3 - P_r\left(R - \frac{n}{4}\right)},$$

$$A_4 = \frac{-P_rm_3A_2}{m_3^2 - (1+H)P_rm_3 - P_r\left(R - \frac{n}{4}\right)},$$

$$A_5 = \frac{-Gr}{m_3^2 - (1+H)P_7m_3 - P_r\left(R - \frac{n}{4}\right)}, A_6 = \frac{-Gr}{m_3^2 - m_3 - M_1}$$

$$A_7 = \frac{GrA_2}{m_3^2 - m_3 - M_1}, A_8 = \frac{-GrA_2}{m_1^2 - m_1 - M_1}, A_9 = \frac{-Gm}{m_1^2 - m_1 - M_1}$$

$$A_{10} = \frac{-1}{(1+h)}\left[A_6(1+hn_3) + A_3(1+mn_3) + A_3(1+hm_1)\right.$$
$$\left. + A_3(1+hn_1)\right]$$

$$A_{11} = \frac{\frac{1}{K_0}A_{10}}{m_3^2 - m_3 - M_2}, A_{12} = \frac{\frac{1}{K_0}A_6}{m_3^2 - m_3 - M_2}, A_{13} = \frac{\frac{1}{K_0}A_7}{m_3^2 - m_3 - M_2},$$

$$A_{14} = \frac{\frac{1}{K_0}A_3}{m_3^2 - m_3 - M_2}, A_{15} = \frac{\frac{1}{K_0}A_9}{m_1^2 - m_1 - M_2}, A_{16} = \frac{m_3A_{10}}{m_3^2 - m_3 - M_2},$$

$$A_{17} = \frac{m_3A_6}{m_3^2 - m_3 - M_2}, A_{18} = \frac{m_3A_2}{m_3^2 - m_3 - M_2}, A_{19} = \frac{m_1A_3}{m_1^2 - m_1 - M_2},$$

$$A_{20} = \frac{m_1A_3}{m_1^2 - m_1 - M_2}, A_{21} = \frac{Gr(A_3 + A_4 + A_5)}{m_4^2 - m_4 - M_2}, A_{22} = \frac{-GrA_3}{m_3^2 - m_3 - M_2},$$

$$A_{23} = \frac{-GrA_4}{m_3^2 - m_3 - M_2}, A_{24} = \frac{-GrA_3}{m_1^2 - m_1 - M_2}, A_{25} = \frac{-GmA_1}{m_1^2 - m_1 - M_2}$$

$$A_{26} = \frac{GmA_1}{m_2^2 - m_2 - M_2}$$

$$A_{27} = \frac{-1}{(1+hm_6)}$$

$$\begin{bmatrix} A_{11}(1+hm_5) + A_{12}(1+hm_3) + A_{13}(1+hm_3) + A_{14}(1+hm_1) \\ +A_{15}(1+hm_1) + A_{16}(1+hm_5) + A_{17}(1+hm_3) + A_{18}(1+hm_3) \\ +A_{19}(1+hm_1) + A_{20}(1+hm_1) + A_{21}(1+hm_4) + A_{22}(1+hm_3) \\ +A_{23}(1+hm_3) + A_{24}(1+hm_1) + A_{25}(1+hm_1) + A_{26}(1+hm_2) \end{bmatrix}$$

$$A_{28} = -(m_5A_{10} + m_3A_6 + m_3A_7 + m_1A_8 + m_1A_9)$$

$$A_{29} = -(m_6A_{27} + m_5A_{11} + m_3A_{12} + m_3A_{13} + m_1A_{14} + m_1A_{15}$$
$$+ m_5A_{16} + m_3A_{17} + m_3A_{18} + m_1A_{19} + m_1A_{20} + m_4A_{21}$$
$$+ m_3A_{22} + m_3A_{23} + m_1A_{24} + m_1A_{25} + m_2A_{26})$$

$$A_{30} = -A_1m_1 + A_1m_2$$

$$A_{31} = -m_3 + A_2m_3 - A_2m_1$$

$$A_{32} = m_4A_3 + m_4A_4 + m_4A_5 - m_3A_3 - m_3A_4 - m_1A_5$$

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