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ISSN (Online) 2394-2320

International Journal of Engineering Research in Computer Science and Engineering (IJERCSE)
Vol 7, Issue 9, September 2020

Heat and Mass Transfer Analysis on Laminar Mixed Convection Flow with Chemical Reaction and Thermal Radiation

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Abstract: This paper seeks to explore the effect of chemical reaction and thermal radiation on steady MHD mixed convective flow of a viscous, incompressible, electrically conducting fluid which passes through an infinite vertical porous plate. A uniform magnetic field is applied in transversely to the direction of the flow in presence of a heat source. The perturbation technique is used to solve the non-dimensional governing equations. The effects of thermal radiation, thermal-diffusion; heat source and chemical reaction on the characteristics of the flow are studied graphically. It is seen that the effects of thermal-radiation and chemical reaction have a significant role in controlling the flow pattern, the heat and mass transfer characteristics of the flow.

Keywords—MHD, thermal radiation, heat and mass transfer, thermal-diffusion.

I. INTRODUCTION

The study of MHD flow with heat and mass transfer has achieved considerable interest, because of its significant applications in many areas of science and technology. Free convective flow involving heat and mass transfer in non-porous and porous media were studied by a number of researchers like Rapties[11], Bejan and Khair[2] etc. Ghaly[4] developed the radiation effects on a certain MHD free convective flow. Makinde and Ogulu. [8] analyzed the effect of thermal radiation on the heat and mass transfer flow of a variable viscosity fluid past a vertical porous plate permeated by a transverse magnetic field. Ahmed[1] discussed the Soret and radiation effects on transient MHD free convection from an impulsively started infinite vertical plate. Prakash et al.[9] studied the Soret and chemical reaction effects on a three dimensional MHD convective flow of dissipative fluid along an infinite vertical plate. Seth et al.[14] analyzed the heat and mass transfer effects on unsteady MHD natural convection flow of a chemically reactive and radiating fluid through a porous medium past a moving vertical plate with arbitrary ramped temperature. Gurivireddy et al.[5] investigated thermal diffusion effect on MHD heat and mass transfer flow past a semi-infinite moving vertical porous plate with heat generation and chemical reaction. D. Sarma and P.K Mahanta [13] presented Thermo-Diffusion effect on laminar mixed convection flow with Induced Magnetic field. Many papers are found in literature on Soret effect on different convection problems, some of them are Raju et al. [10], Reddy et al. [12] and Ibrahim and Suneetha [6]. In the present work an attempt has been made to study the problem of "Heat and Mass Transfer Analysis on Laminar Mixed Convection Flow with Chemical Reaction and Thermal Radiation".

Mathematical Analysis

We consider a steady two dimensional mixed convective heat and mass transfer flow of a incompressible, viscous, electrically conducting fluid past a continuously moving infinite vertical porous plate under the action of a transverse magnetic field in presence of chemical reaction and Radiation

parameter. We introduce a coordinate system (x′, y′, z′) with x′-axis along the direction of the flow, y′- axis normal to the flow and z′- axis along the width of the plate. As the plate is long enough in x′-direction, therefore all the physical quantities except possibly the pressure are assumed to be independent of x′. Further as the motion is two dimensional with the z′-plane as the plane of the motion, and the physical quantities are also independent of z′.

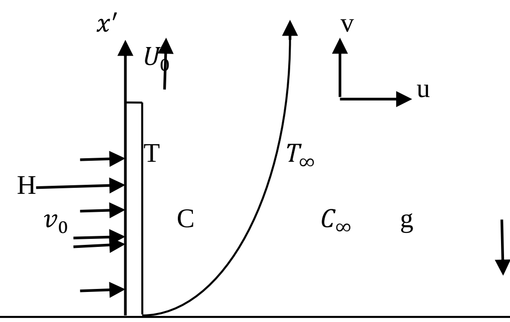

Fig 1: Physical model of the problem

Let $\vec{q} = (u', v', 0)$ be the fluid velocity and $\vec{H} = (H_x, H_y, 0)$ be the magnetic induction vector at the point P (x′,y′,z′) in the fluid. Therefore the equation of continuity is

$$\frac{dv'}{dy'} = 0 \quad (1)$$

which holds for $v' = -v_0$ where v_0 is the constant suction velocity normal to the plate.

The present investigation is restricted to the assumptions:

- Except density other properties of the fluid in the buoyancy force terms are constant.
- The Plate is electrically non- conducting.
- The magnetic Reynolds number is not considerable magnitude so that the induced magnetic field is taken into account.
- The plate is subjected to constant injection/suction.

Using the Boussinesq and usual boundary layer approximations, equations governing the fluid flow reduce to

Momentum Equation

$$-v_0 \frac{du'}{dy'} = g\beta(\bar{T} - \overline{T_\infty}) + g\bar{\beta}(\bar{C} - \overline{C_\infty}) + \vartheta \frac{d^2u'}{dy'^2} + \frac{\mu_e H_0}{\rho} \frac{d\overline{H_x}}{dy'} \quad (2)$$

Magnetic induction equation

$$-v_0 \frac{d\overline{H_x}}{dy'} = H_0 \frac{du'}{dy'} + \frac{1}{\sigma\mu_e} \frac{d^2\overline{H_x}}{dy'^2} \quad (3)$$

Energy equation

$$-v_0 \frac{d\bar{T}}{dy'} = \frac{k}{\rho c_p} \frac{d^2\bar{T}}{dy'^2} + \frac{\mu}{c_p} \left(\frac{d\bar{u}}{dy'}\right)^2 + \frac{1}{\sigma\rho c_p} \left(\frac{d\overline{H_x}}{dy'}\right)^2 - \bar{Q}(\bar{T} - \overline{T_\infty}) - \frac{1}{\rho c_p} \frac{d\overline{q_x}}{dy'} \quad (4)$$

Species continuity equation:

$$-v_0 \frac{d\bar{C}}{dy'} = D_m \frac{d^2\bar{C}}{d\bar{y}^2} + \frac{D_m K_T}{T_m} \frac{d^2\bar{T}}{dy'^2} - \bar{K}(\bar{C} - \overline{C_\infty}) \quad (5)$$

The boundary conditions are

$$u' = \bar{U}_0, \frac{d\bar{T}}{dy'} = -\frac{Q}{k}, \frac{d\bar{C}}{dy'} = \frac{m}{D_m}, \bar{H}_x = \bar{H}_w \, at \; y' = 0 \quad (6)$$

$$u' = 0, \bar{C} = \bar{C}_\infty \;, \; \bar{T} = \bar{T}_\infty \,, \; \bar{H}_x = 0 \quad as \;\; y' \to \infty$$

In order to normalize the mathematical model, we introduce the following non-dimensional quantifies

$$y = \frac{y' v_0}{\vartheta} \;, \;, \; U = \frac{\bar{U}_0}{v_0} \,, \; u = \frac{u'}{v_0} \;, \; \theta = \frac{k v_0(\bar{T} - \bar{T}_\infty)}{\vartheta Q} \,,$$

$$\varphi = \frac{D_m v_0(\bar{C} - \overline{C_\infty})}{\vartheta m} \;, \; Pm = \sigma\vartheta\mu_e$$

$$Pr = \frac{\rho\vartheta c_p}{\boldsymbol{k}}, \quad Sc = \frac{\vartheta}{D_m}, \quad Gr = \frac{\vartheta^2 g\beta Q}{{v_0}^3},$$

$$Gm = \frac{gm\vartheta^2\bar{\beta}}{D_m {v_0}^4} \,, \; \text{H}= \sqrt{\frac{\mu_e}{\rho}} \frac{\bar{H}_x}{v_0}, \alpha = \frac{\vartheta\bar{Q}}{{v_0}^2} \,, \quad (7)$$

$$M = \frac{H_0}{v_0} \sqrt{\frac{\mu_e}{\rho}}, \quad k = \frac{\bar{k}\vartheta}{{v_0}^2}, \quad N = \frac{k k_1}{4\sigma_1 {\bar{T}_\infty}^3},$$

$$Sr = \frac{Q K_T {D_m}^2}{T_m \vartheta k m} \,, E_c = \frac{k {v_0}^3}{\vartheta Q C_p}, \quad \lambda = \frac{3N+4}{3N}$$

The non-dimensional form of the equations (2)-(5) are as follows:

$$\frac{d^2u}{dy^2} + M\frac{dH}{dy} + \frac{du}{dy} = -Gr\theta - Gm\emptyset \quad (8)$$

$$\frac{1}{Pm}\frac{d^2H}{dy^2} + M\frac{du}{dy} + \frac{du}{dy} = 0 \quad (9)$$

$$\frac{d^2\theta}{dy^2} + \frac{1}{\lambda}Pr\frac{d\theta}{dy} - \frac{1}{\lambda}Pr\alpha\theta = -\frac{1}{\lambda}PrE_c\left[\frac{\mu}{\vartheta}\left(\frac{du}{dy}\right)^2 + \left(\frac{dH}{dy}\right)^2\right]$$
(10)

$$\frac{d^2\emptyset}{dy^2} + S_c\frac{d\emptyset}{dy} + S_cS_r\frac{d^2\theta}{dy^2} = KS_c\emptyset \quad (11)$$

$$u = U, \frac{d\theta}{dy} = -1, \frac{d\varphi}{dy} = -1, H = h(say), at \; y = 0 \quad (12)$$

$$U = 0\,, \theta = 0\,, \varphi = 0\,, H = 0 \quad as \;\; Y \to \infty$$

where $h = \frac{\overline{\bar{M}H_w}}{H_0}$

Method of solution

Using perturbation technique, the complete solutions of equation from(8) to (12) with the boundary conditions (12) are found as below :

$$u = \text{A}_{10}e^{-A_1y} + \text{A}_{11}e^{-A_2y} + \text{A}_{12}e^{-A_9y} + E_c(\text{z}_1e^{-L_1y} + \text{z}_2e^{-L_2y} + \text{z}_3e^{-L_3y} + \text{z}_4e^{-L_4y} + \text{z}_5e^{-L_5y} + \text{z}_6e^{-L_6y} + \text{z}_7e^{-L_7y} + \text{z}_8e^{-L_8y} + \text{z}_9e^{-L_9y} + \text{z}_{10}\,e^{-L_{10}y} + \text{z}_{11}e^{-L_{11}y} + \text{z}_{12}e^{-A_1y} + \text{z}_{13}e^{-A_9y})$$

$$H = \text{A}_{17}e^{-A_1y} + \text{A}_{18}e^{-A_2y} + \text{A}_{16}e^{-A_9y} + \text{A}_{19}e^{-P_my} + E_c(\text{I}_1e^{-L_1y} + \text{I}_2e^{-L_2y} + \text{I}_3e^{-L_3y} + \text{I}_4e^{-L_4y} + \text{I}_5e^{-L_5y} + \text{I}_6e^{-L_6y} + \text{I}_7e^{-L_7y} + \text{I}_8e^{-L_8y} + \text{I}_9e^{-L_9y} + \text{I}_{10}\,e^{-L_{10}y} + \text{I}_{11}e^{-L_{11}y} + \text{I}_{12}e^{-A_1y} + \text{I}_{13}e^{-A_9y} + \text{I}_{14}e^{-P_my})$$

$$\varphi = \text{A}_3e^{-A_1y} + \text{A}_4e^{-A_2y} + E_c(\text{y}_1e^{-L_1y} + \text{y}_2e^{-L_2y} +$$

ISSN (Online) 2394-6849
International Journal of Engineering Research in Computer Science and Engineering (IJERCSE)
Vol 7, Issue 9, September 2020

$$y_3 e^{-L_3 y} + y_4 e^{-L_4 y} + y_5 e^{-L_5 y} + y_6 e^{-L_6 y} + y_7 e^{-L_7 y} + y_8 e^{-L_8 y} + y_9 e^{-9y} + y_{10}\, e^{-L_{10} y} + y_{11} e^{-A_1 y} + y_{12} e^{-L_{11} y}\ )$$

$$\theta = \frac{1}{A_1} e^{-A_1 y} + E_c(x_{11} e^{-L_1 y} + x_{12} e^{-L_2 y} + x_{13} e^{-L_3 y} + x_{14} e^{-L_4 y} + x_{15} e^{-L_5 y} + x_{16} e^{-L_6 y} + x_{17} e^{-L_7 y} + x_{18} e^{-L_8 y} + x_{19} e^{-9y} + x_{20}\, e^{-L_{10} y} + x_{21} e^{-A_1 y})$$

Skin friction

The non-dimensional form of skin friction coefficient at plate is given by

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

$$= \tau_0 + E_c \tau_1$$

The rate of heat transfer per unit area at the plate is given by

$$Q = (\frac{\partial \bar{T}}{\partial \bar{y}})_{\bar{y}=0}$$

The dimensionless rate of heat transfer in terms of Nusselt number at the plate quantified by

$$Nu = \frac{Q\vartheta}{kv_0(\bar{T} - \bar{T_\infty})} = (\frac{1}{\theta})_{y=0}$$

The rate of mass transfer of the plate is given by

$$m = -\rho D_m (\frac{\partial \bar{C}}{\partial \bar{y}})_{\bar{y}=0}$$

Sherwood number

Hence the dimensionless form of the rate of mass transfer in terms of Sherwood number at the plate y=0 is given by

$$Sh = \frac{\vartheta}{kv_0(\bar{C} - \bar{C_\infty})} = (\frac{1}{\varphi})_{y=0}$$

Results and discussion

In this problem, we investigate the effects of Schmidt number, heat source parameter, thermal Grashof number, radiation parameter, Hartmann number, Soret number and Prandtl number and chemical reaction on a steady MHD mixed convective fluid flow past a continuously moving infinite vertical porous plate under the influence of a transversely applied magnetic field in presents of heat source. The non-dimensional governing equations are solved with the help of perturbation technique and results are reported in terms of graphs.

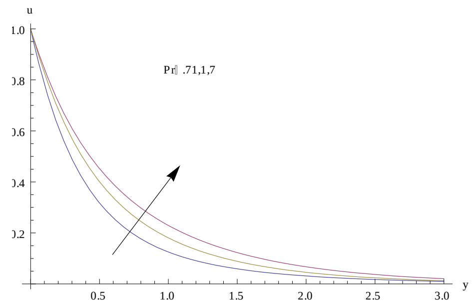

Fig2:Pm=1,α=1,Gr=10,Gm=10,Sr=1, Sc=0.3,M=2, ε=0.001,K=4,N=4,ρ=1,h=1

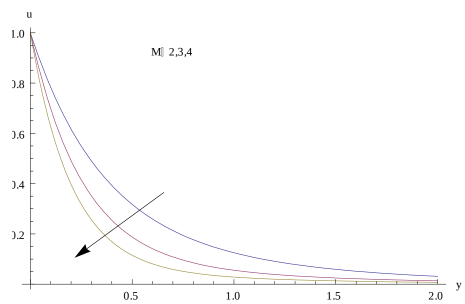

Fig3:Pr=.71,Pm=1,α=1,Gr=10,Gm=10,Sr=1, Sc=0.3, ε=0.001,K=4,N=4,ρ=1,h=1

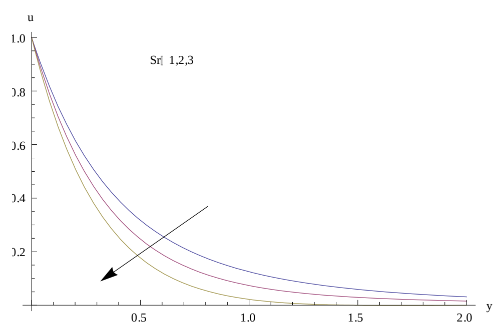

Fig4:Pr=.71,Pm=1,α=1,Gr=10,Gm=10,Sr=1, M=2, ε=0.001,K=4,N=4,ρ=1,h=1

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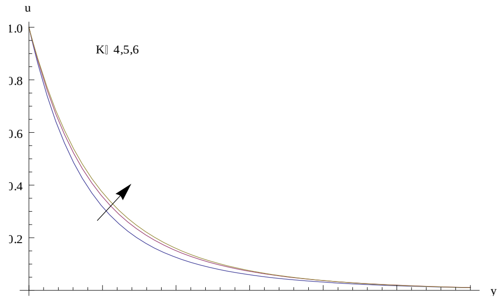

Fig5:Pr=.71,Pm=1,α=1,Gr=10,Gm=10,Sr=1, Sc=0.3,M=2, ε=0.001,N=4,ρ=1,h=1

Figures 2 to9 present the behaviour of the velocity distribution versus normal coordinate y under the influence of Prandtl Number, Hartmann number, thermal-diffusion , chemical reaction, heat source parameter , radiation parameter, thermal Grashof number and, mass Grashof number respectively.

It is seen from the figures 3 and 4 that the fluid motion is reduced for increasing Hartmann number and thermal diffusion. It indicates that the fluid velocity is retarded due to application of transverse magnetic field and under the effect of thermal diffusion.

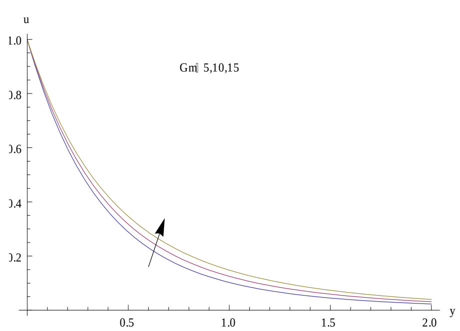

Fig6:Pr=.71,Pm=1,α=1,Gr=10,Sr=1, Sc=0.3,M=2, ε=0.001,K=4,N=4,ρ=1,h=1

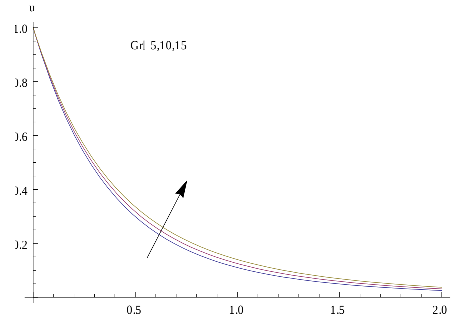

Fig7:Pr=.71,Pm=1,α=1,Gm=10,Sr=1, Sc=0.3,M=2, ε=0.001,K=4,N=4,ρ=1,h=1

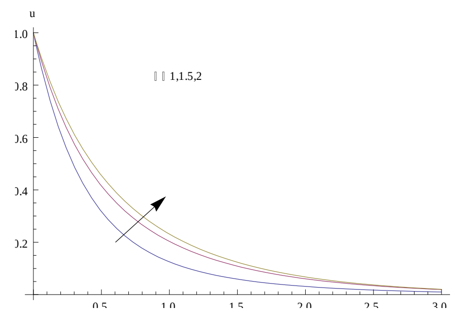

Fig8:Pr=.71,Pm=1, Gr=10,Gm=10,Sr=1, Sc=0.3,M=2, ε=0.001,K=4,N=4,ρ=1,h=1

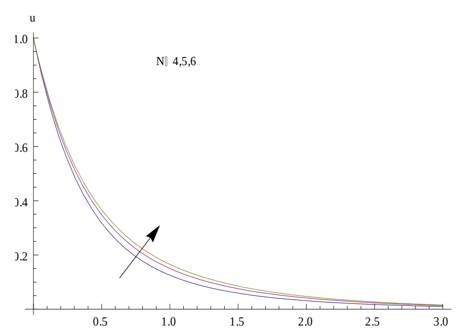

Fig9:Pr=.71,Pm=1,Gr=10,Gm=10,Sr=1, Sc=0.3,M=2, ε=0.001,K=4,ρ=1,h=1

It is observed in figure 2,5,6,7,8 and 9 that there is a comprehensive growth in fluid velocity under the effect of Prandti number, chemical reaction, mass Grashof number, Grashof number, heat source parameter and thermal radiation parameter, respectively. It is seen in all these figures the maximum velocity attains in the vicinity of the plate and then decreases asymptotically as y increases. This observation show that the buoyancy force is more effective near the plate and its effect is nullified as moved far away from the plate.

It is seen from the figures 3 and 4 that the fluid motion is reduced for increasing Hartmann number and thermal diffusion. It indicates that the fluid velocity is retarded due to application of transverse magnetic field and under the effect of thermal diffusion. It is seen in all these figures the maximum velocity attains in the vicinity of the plate and then decreases asymptotically as y increases. This observation show that the buoyancy force is more effective near the plate and its effect is nullified as moved far away from the plate.

The variation of temperature against y is displayed in figures 10, 11 and 12. These figures show that temperature falls under the effect of, Prandtl number, radiation parameter and heat source parameter.

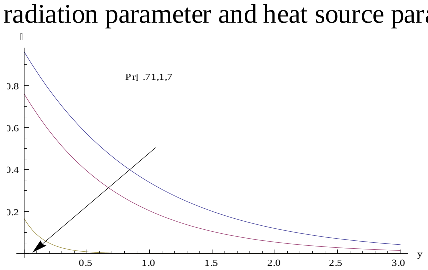

Fig10:Pm=1,α=1,Gr=10,Gm=10,
Sr=1,Sc=0.3,M=2, ε=0.001,K=4,N=4,ρ=1,h1

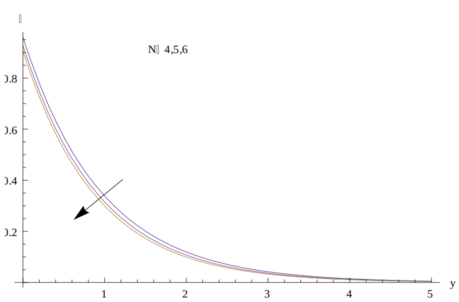

Fig11:Pr=.71,Pm=1,α=1,Gr=10,Gm=10,
Sr=1, Sc=0.3,M=2, ε=0.001,K=4,ρ=1,h=1

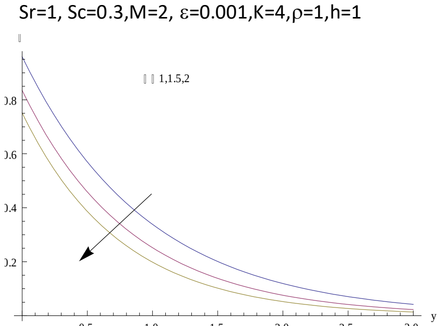

Fig12:Pr=.71,Pm=1,Gr=10,Gm=10,
Sr=1,Sc=0.3,M=2, ε=0.001,K=4,N=4,ρ=1,h=1

The temperature decreases due to increase in Prandtl number which shows that viscous boundary layer thickness than the thermal boundary layer. Further the figures indicate that the temperature falls asymptotically from its maximum value θ = 1 to its minimum value θ = 0. \

Figures 13 to 15 demonstrate the change of behaviour of concentration profile versus y under the influence of chemical reaction, and Schmidt number and thermal-diffusion.

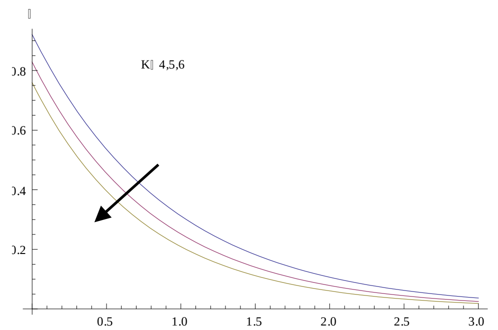

Fig13:Pr=.71,Pm=1,Gr=10,Gm=10,Sr=1,
Sc=0.3,M=2, ε=0.001, α=1,N=4,ρ=1,h=1

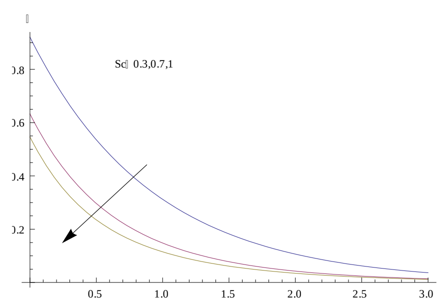

Fig14:Pr=.71,Pm=1,α=1,Gr=10,Gm=10,Sr=1,
M=2 , ε=0.001,K=4,N=4,ρ=1,h=1

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International Journal of Engineering Research in Computer Science and Engineering (IJERCSE)
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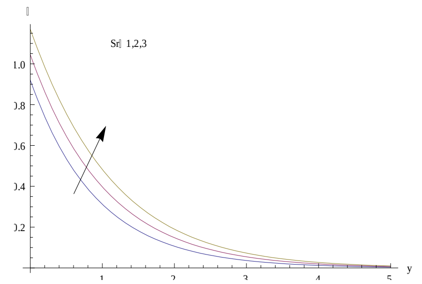

Fig15: Pr=.71,Pm=1,α=1,Gr=10,Gm=10,Sr=1, Sc=0.3, M=2, ε=0.001,K=4,N=4,ρ=1,h=1

These figures show that the concentration profile of the fluid first increases in a thin layer adjacent to the plate and after it falls asymptotically away from the plate. It is inferred from figure 14 that there is a steady growth in the concentration level of the fluid under effect of thermal-diffusion, heat source parameter and radiation parameter whereas a substantial fall in the fluid under the effect of chemical reaction and Schmidt number which is marked in figure 13 and 15.

The figures 16,17,18and 19 show that magnitude if induced magnetic field decreases due to the increase of chemical reaction, radiation parameter and thermal Grashof number respectively where as it increases with the increasing value of thermal diffusion effect.

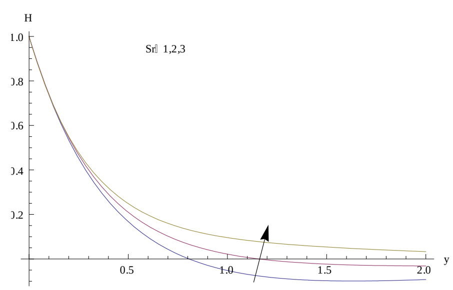

Fig16:Pr=.71,Pm=1,α=1,Gr=10,Gm=10,Sr=1, M=2, ε=0.001,K=4,N=4,ρ=1,h=1

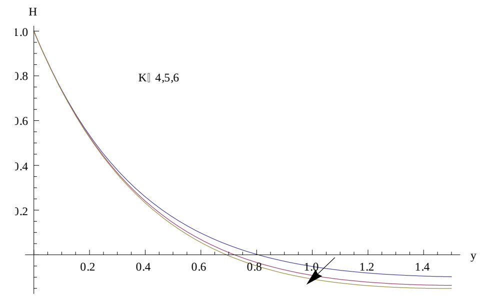

Fig17:Pr=.71,Pm=1,α=1,Gr=10,Gm=10,Sr=1, Sc=0.3,M=2, ε=0.001,N=4,ρ=1,h=1

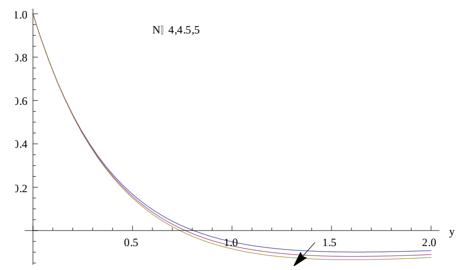

Fig18:Pr=.71,Pm=1,α=1,Gr=10,Gm=10,Sr=1, Sc=0.3,M=2, ε=0.001,K=4,ρ=1,h=1

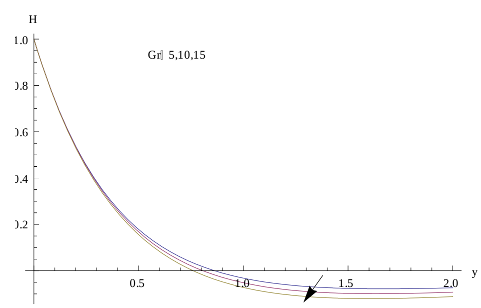

Fig19: Pr=.71,Pm=1,α=1,Gr=10,Gm=10,Sr=1, Sc=0.3, M=2, ε=0.001,K=4,N=4,ρ=1,h=1

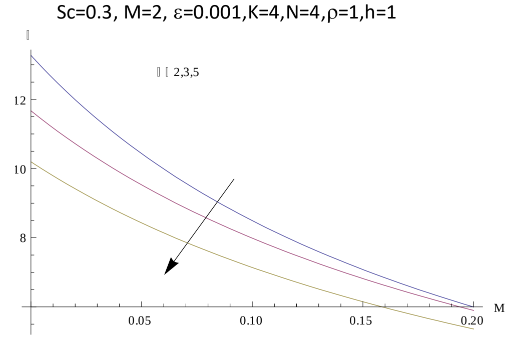

Fig20: Pr=.71,Pm=1,Gr=10,Gm=10,Sr=1, Sc=0.3,M=2, ε=0.001,K=4,N=4,ρ=1,h=1

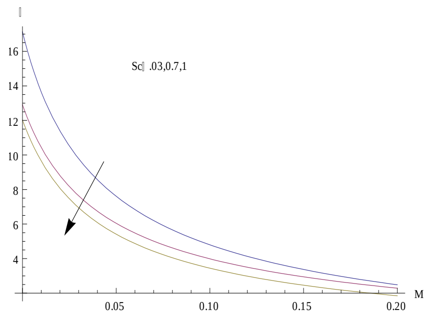

Fig21: Pr=.71,Pm=1,α=1,Gr=10,Gm=10,Sr=1, M=2, ε=0.001,K=4,N=4,ρ=1,h=1

Variation of skin friction against M for different values of heat source parameter and Schmidt number are shown in the figure 20 and 21.It is evident from this figure that a rise in heat source parameter and Schmidt number contributes to decrease the viscous drag at the plate considerably. Further, it is seen from the figure that increase in Hartmann number M causes the skin friction to fall. In other words the application of the transverse magnetic field minimizes the frictional resistance at the plate to a good extent. Thus the application of the magnetic field is a regular mechanism in controlling the viscous drag at the plate.

Conclusion:

Our investigation in the present paper leads to the following conclusions:

- Arise in chemical reaction increases the velocity profile and decreases concentration distribution and magnitude of induced magnetic field.
- The velocity profile increases with the increase of thermal radiation, chemical reaction, heat source parameter, Prandtl number and thermal Grashof number and decreases due to the increase of Hartmann number.
- The fluid temperature decreases due to thermal diffusion, chemical reaction and heat source parameter.
- The concentration of the fluid rises under the effect of Soret effect but it falls due to the effect of chemical reaction and Schmidt number.
- The magnitude of induced magnetic field decreases with increasing thermal radiation, chemical reaction and thermal Grashof number where as it increases due to the effect for thermal diffusion.
- The coefficient of skin friction decreases due to the application of generating heat source and Soret number.

There is a scope to investigate both the Soret and Dufour effect in this phenomenon.MATH

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