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UNSTEADY NATURAL CONVECTIVE FLOW OF A MICROPOLAR FLUID PAST A VERTICAL MOVING POROUS PLATE IN THE PRESENCE OF POROUS MEDIUM WITH RADIATION AND CHEMICAL REACTION

Loganathan. P *, Sivapoornapriya. C °,*
*Department of Mathematics, Anna University, Chennai 600025, India.
*logu@annauniv.edu, °,*math.priya@gmail.com

ABSTRACT

An analysis is carried out to investigate the effects of radiation and chemical reaction on an unsteady, laminar, natural convective flow of a micropolar fluid past a moving vertical porous plate in the presence of porous medium. A first order chemical reaction and radiation has been considered in the study. The free stream velocity follows an exponentially increasing or decreasing small perturbation law. The method of solution can be applied for small perturbation approximation. The various values of permeability, chemical reaction parameter, radiation, Schmidt number, Prandtl number, viscosity ratio, thermal Grashof number, mass Grashof number on velocity, angular velocity, temperature and concentration are presented graphically. A comparative study between Newtonian fluid and non-Newtonian fluid is also presented. It is observed that an increase in either the radiation or the chemical reaction decreases the velocity. An increase in radiation effect decreases the thermal boundary layer. The concentration boundary layer decreases with an increase in the chemical reaction and Schmidt number.

1. INTRODUCTION

Micro-fluid theory deals with the concept of inertial spin, body moments, micro-stress averages and stress moments which are not present in the classical fluid theories. In these fluids stresses and stress moments are functions of deformation rate tensor, and various micro-deformation rate tensors. Fluids having surface tensions, anisotropic fluids, vortex fluids and fluids in which other gyrational effects are important will fall into the domain of simple micro-fluids [1]. Micropolar fluid being a part of microfluids deals with the motion of fluids whose material point possesses orientation which exhibits micro-rotational effects and micro-rotational inertia. Presence of oriented material points in the fluids is the main difference between the Newtonian fluid and micropolar fluid [2]. Micropolar fluid may represent the behavior of liquid crystals, anisotropic fluids, clouds with dust, magnetic fluids, concrete with sand, discharge of fluids with waste materials and solutions of colloidal suspensions. Micropolar fluids have many interesting real time applications in engineering and industries.

By considering the thermal effects, theory of thermofluids [3] was published as an extension to the theory of microfluids. In this work heat conduction and heat dissipation effects are included. Narasimhan and Eringen [4] presented the thermomicropolar theory of heat conducting nematic liquid crystals where the constitutive equations are formulated by taking into account the thermal gradients on the basis of Eringen's theory of micropolar fluids. Anisotropic fluids are fluids with stable chemical substances or fluids that carry suspensions such as liquid crystals silt carried by rivers, blood flow and emulsions. In chemical industries fluidization, gasification produces fluids that possess viscosities dependent on orientations. Thus giving rise to the theory of anisotropic micropolar fluids by Eringen [5]. Loganathan and Golden Stepha [6] analysed the chemical reaction and radiation effects on a micropolar fluid past a continuously moving porous plate in steady state.

The effect of chemical reaction depends on whether the reaction is heterogeneous or homogeneous. This depends on whether they occur at an interface or as a single phase volume reaction. In recent years micropolar fluids has attracted many researches due to its vast field of applications in industries, engineering and science. Chamka et. al. [7] studies the magnetohydro dynamic oscillatory flow of a micropolar fluid over a vertical porous plate in the presence of porous medium. Bejan and khair [8] studied the heat and mass transfer effects by natural convection in a porous medium. Sharma et. al. [9] analysed the effects of chemical reaction on magneto micropolar fluid flow with radiation and variable permeability. Chaudhary and Abhay [10] illustrated the effects of chemical reactions on magnetohydro dynamic micropolar fluids past a vertical plate in the slip flow regime. Poornima and Bhaskar reddy [11] analysed the effects of thermal radiation and chemical reaction on magneto hydro dynamic natural convective flow past a semi infinite vertical plate in the presence of moving porous plate by the perturbation technique. Ferdows and chen [12] investigated the heat and mass transfer effects for natural convection of an electrically conducting fluid past a vertical plate embedded in a saturated porous medium in the presence of transverse magnetic field.

In this present work, the influence of chemical reaction and radiation effects on free convective flow of micropolar fluids over a vertical moving porous plate in the presence of porous medium is investigated subjected to derivative angular velocity boundary condition, time dependent temperature and concentration. A first order chemical reaction of homogeneous type is assumed to occur between the diffusing species and the fluid. The various parameters like permeability, radiation, chemical reaction, Prandtl number, Schmidt number, thermal Grashof number and mass Grashof number on velocity, micro-rotation, temperature and concentration profiles are illustrated graphically.

2. MATHEMATICAL FORMULATION

Consider an unsteady, laminar, two dimensional, viscous incompressible, natural convective micropolar fluid flow past a moving vertical porous plate in the presence of porous medium with chemical reaction and radiation effects. Let x' axis be taken along the direction of vertical plate and y' axis be taken normal to the plate. It is assumed that the properties of the fluids are constant except the density variation. The Rosseland approximation for radiative heat flux and homogeneous first order chemical reaction is considered along with the Darcy's resistance term. The flow model is given in fig.1.

By usual Boussinesq's approximation the governing non linear coupled, partial differential equations with corresponding initial and boundary conditions are given by

Continuity:

$$\frac{\partial v'}{\partial y'}=0. \tag{1}$$

Linear momentum:

$$\frac{\partial u'}{\partial t'}+v'\frac{\partial u'}{\partial y'}=-\frac{1}{\rho}\frac{\partial p'}{\partial x'}+(\upsilon+\upsilon_r)\frac{\partial^2 u'}{\partial y'^2}+g\beta'(T'-T'_\infty) + g\beta^*(c'-c'_\infty)-\upsilon\frac{u'}{\lambda'}+2\upsilon_r\frac{\partial \omega'}{\partial y'} \tag{2}$$

Angular momentum:

$$\rho j\left(\frac{\partial \omega'}{\partial t'}+v'\frac{\partial \omega'}{\partial y'}\right)=\gamma\frac{\partial^2 \omega'}{\partial y'^2} \tag{3}$$

Energy:

$$\frac{\partial T'}{\partial t'}+v'\frac{\partial T'}{\partial y'}=\frac{k}{\rho c_p}\frac{\partial^2 T'}{\partial y'^2}-\frac{1}{\rho c_p}\frac{\partial q'}{\partial y'} \tag{4}$$

Concentration:

$$\frac{\partial c'}{\partial t'}+v'\frac{\partial c'}{\partial y'}=D\frac{\partial^2 c'}{\partial y'^2}-k_l(c'-c'_\infty) \tag{5}$$

Subjected to the initial and boundary conditions as follows

$$u'=u'_p,\ T'=T'_w+\varepsilon(T'_w-T'_\infty)e^{n't'},\quad c'=c'_w+\varepsilon(c'_w-c'_\infty)e^{n't'},\ \frac{\partial \omega'}{\partial y'}=-\frac{\partial^2 u'}{\partial y'^2}\ \text{at } y'=0 \tag{6}$$

$$u'\to U'_\infty=U_0(1+\varepsilon e^{n't'}),\ T'\to T'_\infty,\ c'\to c'_\infty,\ \omega'\to 0 \ \text{as}\ y'\to\infty$$

The radiative heat flux in the direction normal to the plate according to Rosseland approximation is given by

$$q'=-\frac{4\sigma}{3k'}\frac{\partial T'^4}{\partial y'} \tag{7}$$

where σ and k' are the Stefan-Boltzmann constant and the mean absorption coefficient respectively. The Taylor's series for T'^4 as a linear function by neglecting the higher order terms is given by

$$T'^4 \cong 4T_\infty'^3 T' - 3T_\infty'^4 \tag{8}$$

where n' is a scalar constant, U_0 is a scale of free stream velocity. It is assumed that the porous plate moves with the constant velocity u'_p in the longitudinal direction and u'_∞ is the free stream velocity follows an exponentially increasing or decreasing small perturbation law. From the continuity equation it is clear that the suction velocity normal to the plate is a function of time only and it can be taken in the form:

$$v'=-v_0(1+\varepsilon A e^{n't'}) \tag{9}$$

where A is a real positive constant, ε and εA are much lesser than unity and v_0 is the scale of suction velocity. Outside the boundary layer, Eq. (2) gives

$$\frac{-1}{\rho}\frac{dp'}{dx'}=\frac{dU'_\infty}{dt'}+\frac{\upsilon}{\lambda'}U'_\infty \tag{10}$$

Considering the non dimensional quantities as follows:

$$u=\frac{u'}{U_0},\ t=\frac{t'v_0^2}{\upsilon},\ y=\frac{y'v_0}{\upsilon},\ T=\frac{T'-T'_\infty}{T'_w-T'_\infty},\ \lambda=\frac{\lambda' v_0^2}{\upsilon^2},$$
$$Gr=\frac{\upsilon g\beta'(T'_w-T'_\infty)}{U_0 v_0^2},\ Gc=\frac{\upsilon g\beta^*(c'-c_\infty')}{U_0 v_0^2},\ c=\frac{c'-c_\infty'}{(c'_w-c_\infty')},$$
$$\Pr=\frac{\upsilon\rho c_p}{k},\ Sc=\frac{\upsilon}{D},\ R=\frac{k'k}{4\sigma T_\infty'^3},\ n=\frac{n'\upsilon}{v_0^2},\ \omega=\frac{\upsilon}{U_0 v_0}\omega',$$
$$U_\infty=\frac{U'_\infty}{U_0},\ U_p=\frac{u'_p}{U_0},\ v=\frac{v'}{v_0},\ j=\frac{v_0^2}{\upsilon^2}j',\ k_c=\frac{\upsilon k_l}{v_0^2} \tag{11}$$

The governing equations (1)-(6) can be written as

$$\frac{\partial u}{\partial t}+v\frac{\partial u}{\partial y}=\frac{dU_\infty}{dt}+(1+\beta)\frac{\partial^2 u}{\partial y^2}+GrT+Gcc+N(U_\infty-u) +2\beta\frac{\partial \omega}{\partial y} \tag{12}$$

$$\frac{\partial \omega}{\partial t}+v\frac{\partial \omega}{\partial y}=\frac{1}{\eta}\frac{\partial^2 \omega}{\partial y^2} \tag{13}$$

$$\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial y}=\frac{1}{\Pr}\left[1+\frac{4}{3R}\right]\frac{\partial^2 T}{\partial y^2} \tag{14}$$

$$\frac{\partial c}{\partial t}+v\frac{\partial c}{\partial y}=\frac{1}{Sc}\frac{\partial^2 c}{\partial y^2}-k_c c \tag{15}$$

$$\text{Where } N=\frac{1}{\lambda},\ \eta=\frac{\mu j'}{\gamma}=\frac{2}{2+\beta} \tag{16}$$

subject to the boundary conditions as follows:

$$u=U_p,\ T=(1+\varepsilon e^{nt}),\ c=(1+\varepsilon e^{nt}),\ \frac{\partial \omega}{\partial y}=-\frac{\partial^2 u}{\partial y^2}\ \text{at } y=0 \tag{17}$$
$$u\to U_\infty,\ T\to 0,\ c\to 0,\ \omega\to 0\ \text{as}\ y\to\infty$$

In few cases the effects of microstructures are negligible where the flow behaves like a Newtonian fluid flow. Gorla [13]. Furthermore, for a non- Newtonian fluid, the spin-gradient viscosity γ which gives some relationship between the coefficients of viscosity and micro-inertia is defined by

$$\gamma=\left(\mu+\frac{\Lambda}{2}\right)j'=\mu j'\left(\frac{2+\beta}{2}\right) \tag{18}$$

where $\beta=\frac{\Lambda}{\mu}$ denotes the dimensionless viscosity ratio is the material parameter and Λ is the coefficient of vortex viscosity. The derivation for γ for micropolar fluids is given by Ahmadi [14].

Here u and v are the dimensionless velocity components, t is the dimensionless time, y is the dimensionless Cartesian coordinate, n is the dimensionless scalar constant, λ is the dimensionless permeability parameter, T is the dimensionless temperature of the plate and c is the dimensionless concentration of the plate, k_c is the dimensionless chemical reaction parameter.

3. METHOD OF SOLUTION

The partial differential Eq.(12) to (15) are unsteady, coupled, non-linear, partial differential equations. These equations are reduced to ordinary differential equations by the method of perturbation technique. Considering the velocity, microrotation, temperature and concentration in terms of power series and neglecting the higher order terms we get,

$$u = u_0(y) + \varepsilon e^{nt} u_1(y) + o(\varepsilon^2) + \dots\dots\dots\dots \tag{19}$$

$$\omega = \omega_0(y) + \varepsilon e^{nt} \omega_1(y) + o(\varepsilon^2) + \dots\dots\dots\dots \tag{20}$$

$$T = T_0(y) + \varepsilon e^{nt} T_1(y) + o(\varepsilon^2) + \dots\dots\dots\dots \tag{21}$$

$$c = c_0(y) + \varepsilon e^{nt} c_1(y) + o(\varepsilon^2) + \dots\dots\dots\dots \tag{22}$$

Using the above Eqns. (19)-(22) in Eqns. (12)-(15) and in Eq. (17) the coupled non linear partial differential equations can be reduced to ordinary differential equation by equating the harmonic and non harmonic terms and by neglecting the higher order terms of $o(\varepsilon^2)$. The resulting ordinary differential equations are given as follows

$$(1+\beta)u_0'' + u_0' - N u_0 = -Gr T_0 - Gc c_0 - N - 2\beta \omega_0' \tag{23}$$

$$(1+\beta)u_1'' + u_1' - (N+n)u_1 = -(N+n) - A u_0' - Gr T_1 - Gc c_1 - 2\beta \omega_1' \tag{24}$$

$$\omega_1'' + \eta \omega_1' - n\eta \omega_1 = -A\eta \omega_0' \tag{25}$$

$$\omega_0'' + \eta \omega_0' = 0 \tag{26}$$

$$R_1 T_0'' + \Pr T_0' = 0 \tag{27}$$

$$R_1 T_1'' + \Pr T_1' - n \Pr T_1 = -A \Pr T_0' \tag{28}$$

$$c_0'' + Sc\, c_0' - Sc k_c c_0 = 0 \tag{29}$$

$$c_1'' + Sc\, c_1' - Sc(\mathrm{k}_c + \mathrm{n}) c_1 = -A Sc\, c_0' \tag{30}$$

The boundary conditions are

$$\begin{aligned} &u_0 = U_p,\ u_1 = 0,\ T_0 = 1,\ T_1 = 1,\ \omega_0' = -u_0'', \quad \text{at } y = 0 \\ &\omega_1' = -u_1'',\ c_0 = 1,\ c_1 = 1 \\ &u_0 \to 1,\ u_1 \to 1,\ T_0 \to 0,\ T_1 \to 0,\ \omega_0 \to 0, \quad \text{as } y \to \infty \\ &\omega_1 \to 0,\ c_0 \to 0,\ c_1 \to 0 \end{aligned} \tag{31}$$

The solutions of Eqns. (23)-(30) subject to the conditions in Eq. (31) are

$$c_0 = e^{-h_2 y} \tag{32}$$

$$c_1 = (1 - \mathrm{h}_3) e^{-L_2 y} + h_3 e^{-h_2 y} \tag{33}$$

$$T_0 = e^{-L_3 y} \tag{34}$$

$$T_1 = e^{-L_5 y} + (\frac{A}{n} L_3)\left[e^{-L_5 y} - e^{-L_3 y}\right] \tag{35}$$

$$\omega_0 = b_3 e^{-\eta y} \tag{36}$$

$$\omega_1 = \left(\frac{X - b_8 \eta}{L_7}\right) e^{-L_7 y} + b_8 e^{-\eta y} \tag{37}$$

$$u_0 = b_7 e^{-L_9 y} + 1 + b_4 e^{-L_3 y} + b_5 e^{-h_2 y} + b_3 b_6 e^{-\eta y} \tag{38}$$

$$\begin{aligned} u_1 = {} & b_{21} e^{-L_{11} y} + 1 + b_9 e^{-L_9 y} + (b_{10} + b_{15}) e^{-L_3 y} + b_{11} e^{-h_2 y} \\ & + b_{18} \mathrm{x}\, e^{-L_7 y} + (b_{12} + b_{20}) e^{-\eta y} + (b_{13} + b_{14}) e^{-L_5 y} \\ & + b_{10} e^{-L_3 y} + b_{17} e^{-h_2 y} + b_{19} e^{-L_7 y} \end{aligned} \tag{39}$$

The constants are given in the appendix.

4. RESULTS AND DISCUSSION

Radiation and chemical reaction effects on unsteady, laminar, two dimensional natural convective flow of micropolar fluid over a vertical moving porous plate in the presence of porous medium is investigated subject to a change in angular velocity, time dependent temperature and concentration. The numerical values are computed for a suitable value of $y_{\max}$. In order to get a physical insight of the problem, the velocity, angular velocity, temperature and concentration are computed for various values of permeability, radiation parameter, chemical reaction parameter, viscosity ratio, Prandtl number, Schmidt number, thermal Grashof number and mass Grashof number.

Fig.2 (a) shows the typical velocity profiles in the boundary layer for different viscosity ratio. It is clearly observed that the velocity profile is lower for Newtonian fluid ($\beta = 0$) with fixed flow through a porous plate and material parameters as compared with the micropolar fluid for the viscosity ratio lesser than 0.7. When viscosity ratio takes values greater than 0.7 the velocity distribution shows a decelerating nature near the porous plate. Fig. 2 (b) shows the angular velocity for different values of viscosity ratio. When viscosity ratio is higher than 0.7 the angular velocity decreases and a reverse pattern is seen for viscosity ratio less than 0.7 near the porous plate and gradually reaches the free stream boundary condition. When ($\beta < 0.7$) the angular velocity profile for Newtonian fluid seems to be greater when compared to non Newtonian fluid.

Fig.3 (a) shows the velocity profiles for different plate moving velocity. The numerical results shows that for increasing values of plate moving velocity the velocity profile increases, and then approaches a constant value which is relevant to the free stream velocity at the edge of the boundary layer. In Fig. 3 (b), angular velocity for different plate moving velocity is shown. When compared to the velocity profile in Fig. 3(a), similar type of behavior is visualized for angular velocity.

For different values of radiation parameter, velocity profile is shown in Fig. 4(a). It is observed that the thickness of the velocity boundary layer reduces with increased radiation effects. When the radiation effect is higher, the velocity profile does not show much variation. Similar type of behavior is seen for angular velocity for different values of radiation parameter and it is shown in Fig. 4(b). In Fig. 5 (a), velocity profile for different chemical reaction parameter is shown. The thickness of the velocity boundary layer increases with decreasing values of chemical reaction parameter. In Fig. 5 (b), angular velocity for different chemical reaction parameter is presented. It is viewed that angular velocity increases with increasing values of chemical reaction parameter. There is no difference in the profile for very small changes in the chemical reaction parameter.

Fig.6, illustrates the behavior of the velocity profiles for different thermal Grashof number and mass Grashof number. The velocity profile increases with increasing values of Grashof number. Grashof number being the dimensionless number gives the relation between buoyancy force due to the density variation and the restraining force due to viscosity. Hence it is conclude that the thickness of the velocity boundary layer increase with increasing values of Grashof number. This is because of the less resistance leading to an increase in Grashof number thereby increasing the velocity profile.

In Fig. 7, velocity profiles for different permeability parameter are presented. It is visualized that an increase in the permeability parameter increases the velocity boundary layer. An increase in the permeability always increases the velocity because of Darcy's law, which relates the flow rate and the fluid properties to the pressure gradient applied to the porous medium. Velocity profiles for different Prandtl number are illustrated in Fig. 8. It is observed that the velocity profile decreases with increasing values of Prandtl number. The Prandtl number being the ratio of momentum diffusivity to thermal diffusivity will affect the fluid flow as long as the temperature and velocity field are coupled. Hence there is a increase in the velocity boundary layer for decreasing values of Prandtl number due to less viscous nature of the fluid.

Velocity profile for simultaneous variation in permeability parameter and Prandtl number is shown in Fig. 9. Under the presence of radiation and chemical reaction, it is observed that, for water (Pr = 7), the velocity profile increases with increasing values of permeability parameter and for air (Pr = 0.71), the velocity profile increases with increasing values of permeability parameter. This is because of less viscosity and Darcy's law.

Temperature profile for different Prandtl number is shown in Fig.(10). It is visualized that the thermal boundary layer decreases with increasing values of Prandtl number in the presence of radiation and chemical reaction effects. The reduction in the thermal boundary layer is due to the slow movement of heat as a result of low thermal diffusivity. In Fig. 11, temperature profile for different values of radiation parameter is shown. For increasing values of radiation parameter, the thickness of the thermal boundary layer decreases. It is observed that, there is no effect in thermal boundary layer for large values of radiation parameter.

The influence of chemical reaction parameter is analyzed for k_c = 0, 0.2, 0.4, 0.6, 0.8 and 0.9. In the present study a homogeneous first order chemical reaction is considered. A first order reaction is a reaction that proceeds at a rate that depends linearly on only one reactant concentration. In a homogeneous reaction the diffusion species can either be created or destroyed depending on the values of chemical reaction parameter. In the concentration profiles shown in Fig. 12, a destructive reaction is considered. Hence it is observed that the concentration boundary layer decreases with increasing values of chemical reaction parameter.

In Fig. 13, concentration profile for different values of Schmidt number is presented. Ratio between the momentum diffusivity and mass diffusivity is defined as the Schmidt number. The mass diffusivity is based on the diffusivity of the substances. It physically relates the relative thickness of the hydrodynamic layer and mass-transfer boundary layer. The concentration profile decreases with increasing values of Schmidt number. This is because of slow mass diffusivity resulting in a reduced concentration boundary layer thickness.

5. CONCLUSION

The present paper is focused on unsteady natural convective flow over a moving vertical porous plate in the presence of porous medium with chemical reaction and radiation. . The method of solution can be applied for small perturbation approximation. The results for velocity, temperature and concentration profile for various flow parameters such as chemical reaction, radiation, viscosity ratio, permeability, plate velocity, Prandtl number, Schmidt number, thermal Grashof number, mass Grashof number are illustrated graphically. It is concluded that

1) The velocity boundary layer increases with increasing values of thermal and mass Grashof number.
2) The velocity decreases with increasing values of chemical reaction parameter, Prandtl number and radiation.
3) The velocity increases with increasing values of permeability and plate velocity.
4) The angular velocity increases with increasing values of chemical reaction parameter, permeability and plate velocity.
5) The angular velocity decreases for increasing value of radiation and Prandtl number.
6) The thermal boundary layer decreases for increasing values of Prandtl number.
7) The thermal boundary layer is reduced for increasing values of radiation parameter.
8) The concentration boundary layer decreases for increasing values of chemical reaction parameter and also for increasing values of Schmidt number.

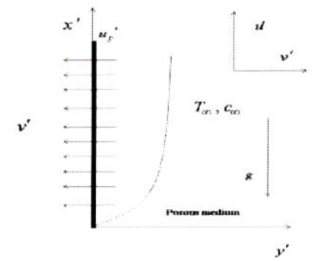

Fig. 1 The physical model and coordinate system

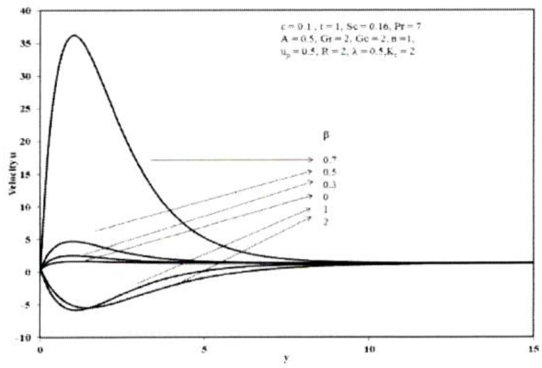

Fig. 2(a) Velocity for different viscosity ratio

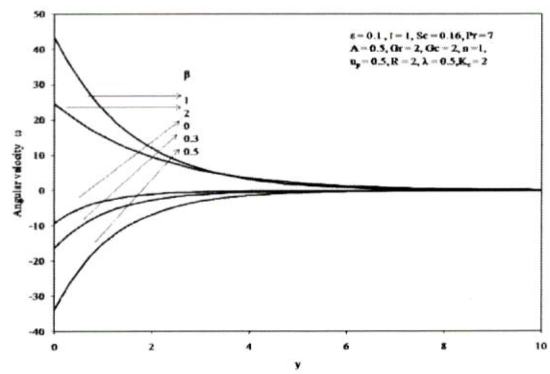

Fig. 2(b) Angular velocity for different viscosity ratio

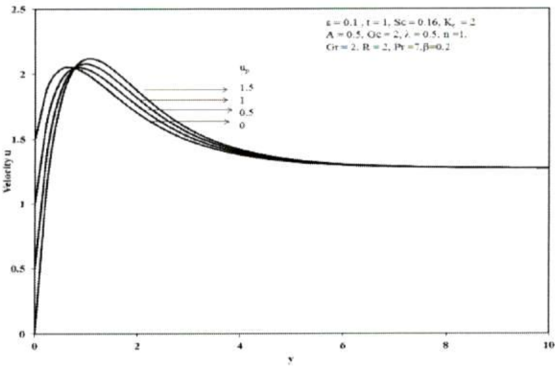

Fig. 3(a) Velocity for different u_p

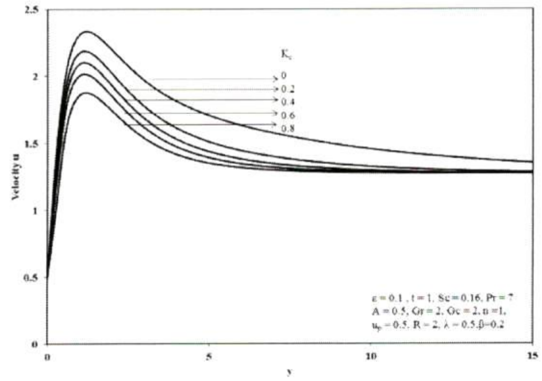

Fig. 5(a) Velocity for different chemical reaction

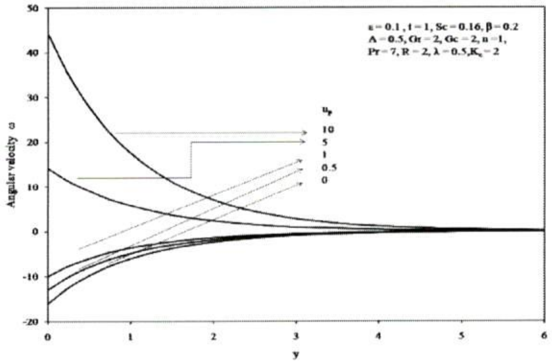

Fig. 3(b) Angular velocity for different u_p

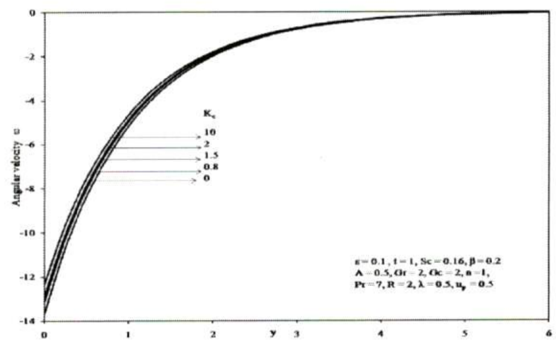

Fig. 5(b) Angular velocity for different chemical reaction

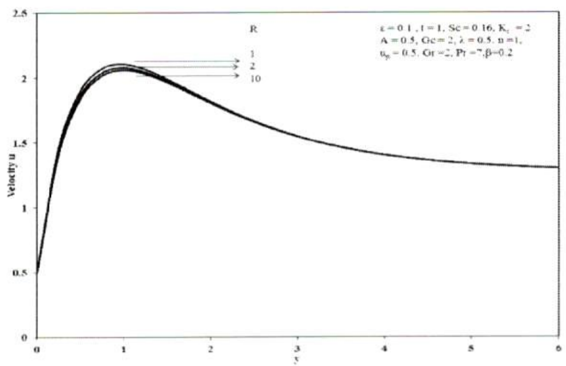

Fig. 4(a) Velocity for different radiation

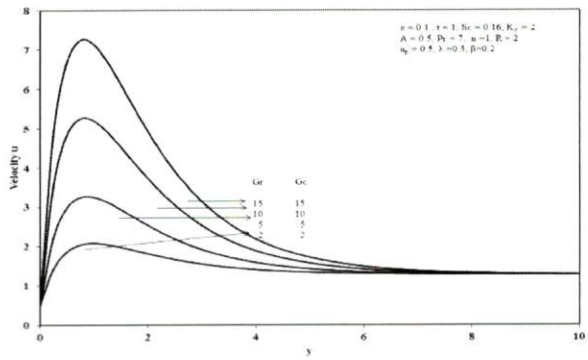

Fig. 6 Velocity for different Gr and Gc

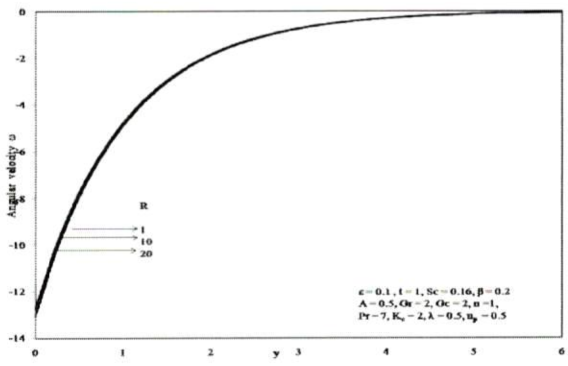

Fig. 4(b) Angular velocity for different radiation

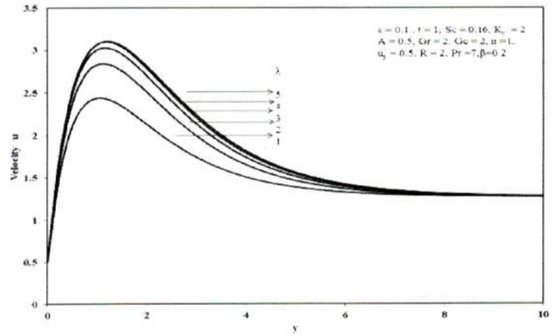

Fig. 7 Velocity for different permeability

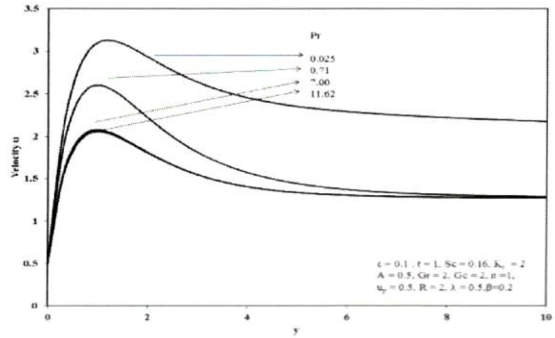

Fig. 8 Velocity for different Prandtl number

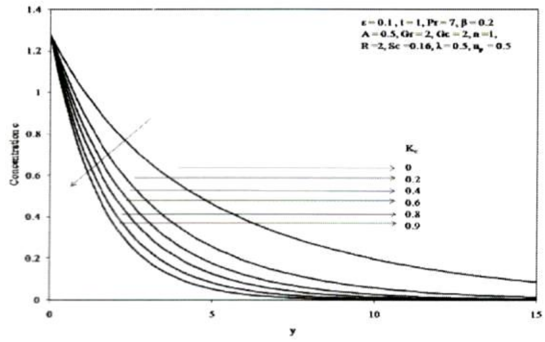

Fig. 12 Concentration for different chemical reaction

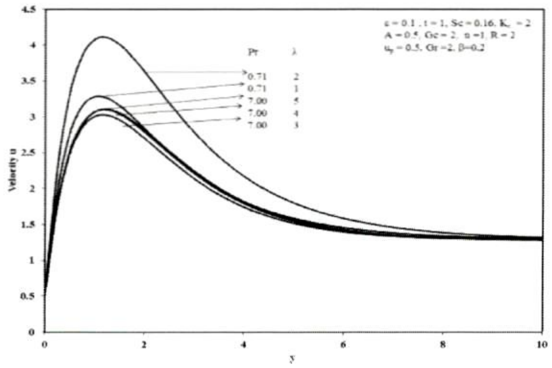

Fig. 9 Velocity for different permeability and Pr

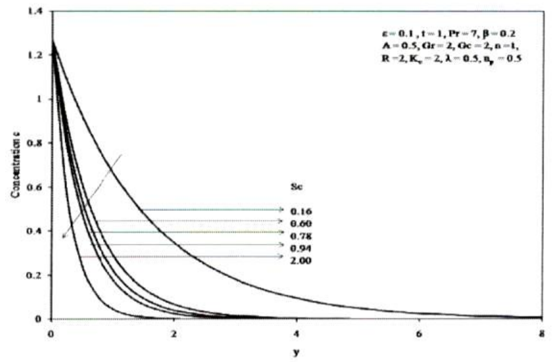

Fig. 13 Concentration for different Schmidt number

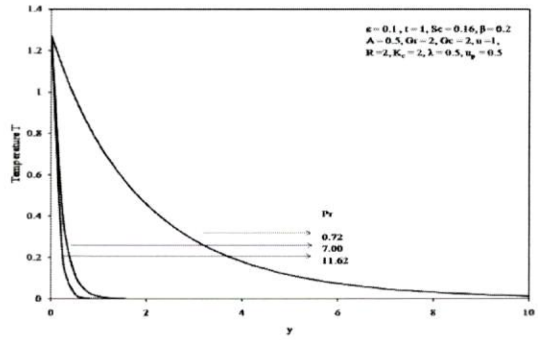

Fig. 10 Temperature for different Pr

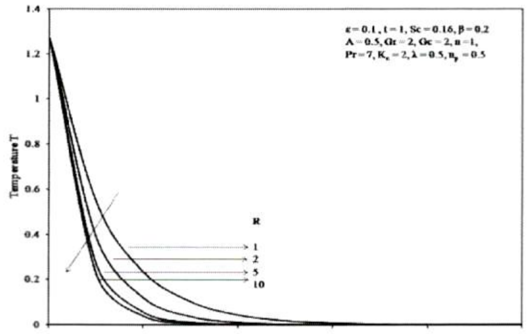

Fig. 11 Temperature for different radiation

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7. APPENDIX

$$L_2 = \frac{Sc + \sqrt{Sc^2 + 4h}}{2},$$

$$L_3 = \frac{\Pr}{R_1},$$

$$L_5 = \frac{L_3 + \sqrt{L_3^2 + 4nL_3}}{2},$$

$$L_7 = \frac{\eta + \sqrt{\eta^2 + 4n\eta}}{2},$$

$$h_2 = \frac{Sc + \sqrt{Sc^2 + 4Sck_c}}{2},$$

$$h_3 = \frac{ASch_2}{h_2^2 + Sch_2 - h},$$

$$b2 = \frac{A}{n} L_3,$$

$$R_1 = 1 + \frac{4}{3R},$$

$$b_3 = \frac{L_9^2(U_p - 1 - b_4 - b_5) + b_4 L_3^2 + b_5 h_2^2}{\eta - b_6(\eta - L_9^2)}$$

$$L_9 = \frac{1 + \sqrt{1 + 4N(1+\beta)}}{2(1+\beta)},$$

$$L_{11} = \frac{1 + \sqrt{1 + 4(N+n)(1+\beta)}}{2(1+\beta)},$$

$$b_4 = \frac{-Gr}{(1+\beta)L_3^2 - L_3 - N},$$

$$b_5 = \frac{-Gc}{(1+\beta)h_2^2 - h_2 - N},$$

$$b_6 = \frac{2\beta\eta}{(1+\beta)\eta^2 - \eta - N},$$

$$b_7 = U_p - 1 - b_4 - b_5 - b_3 b_6,$$

$$b_8 = -\frac{A}{n}\eta b_3,$$

$$X = a_1''(0).$$

$$b_9 = \frac{AL_9 b_7}{(1+\beta)L_9^2 - L_9 - (N+n)},$$

$$b_{10} = \frac{AL_3 b_4}{(1+\beta)L_3^2 - L_3 - (N+n)},$$

$$b_{11} = \frac{Ah_2 b_5}{(1+\beta)h_2^2 - h_2 - (N+n)},$$

$$b_{16} = \frac{-Gc(1-h_3)}{(1+\beta)L_2^2 - L_2 - (N+n)},$$

$$b_{17} = \frac{-Gch_3}{(1+\beta)h_2^2 - h_2 - (N+n)},$$

$$b_{18} = \frac{2\beta}{(1+\beta)L_7^2 - L_7 - (N+n)},$$

$$b_{19} = \frac{2\beta b_8 \eta}{(1+\beta)L_7^2 - L_7 - (N+n)},$$

$$b_{20} = \frac{2\beta b_8 \eta}{(1+\beta)\eta^2 - \eta - (N+n)},$$

$$b_{21} = -(1 + b_9 + b_{10} + b_{11} + b_{12} + b_{13} + b_{14} + b_{15} + b_{16} + b_{17} + b_{18}X + b_{19} + b_{20})$$

8. NOMENCLATURE

u'	velocity in the x'-direction
v'	velocity in the y'-direction
t'	time
n'	scalar constant
T'	temperature of the plate
T_∞'	free stream temperature
c'	concentration near the plate
c_∞'	free stream concentration
ω'	microrotation vector
g	acceleration due to gravity
k	thermal conductivity
λ'	permeability parameter
c_p	specific heat at constant pressure
D	mass diffusivity
A	real positive constant
R	Radiation parameter
j	microinertia density
v_0	scale of suction velocity
k_1	chemical reaction parameter

Greek symbols

η	scalar constant
υ	kinematic viscosity
α	thermal diffusivity
β	Viscosity ratio
γ	Spin-gradient viscosity
Λ	vortex viscosity
ε	scalar constant (<< 1)
ω	microrotation