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Heat Source and Soret Effects on Megneto-Micropolar Fluid Flow with Variable Permeability and Chemical Reaction

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Abstract

Present paper deals with the effects of heat source on the hydromagnetic mixed convection flow of an electrically conducting micropolar fluid past a vertical plate through porous medium with Soret effect, taking into account the homogeneous chemical reaction of first order. A uniform magnetic field has also been considered in the study which absorbs the micropolar fluid with a varying suction velocity and acts perpendicular to the porous surface of the above plate. The governing non-linear partial differential equations have been transformed in to linear partial differential equations, which are solved numerically by applying explicit finite difference method. The numerical results are presented graphically in the form of velocity, micro- rotation, concentration and temperature profiles for different material parameters.

Keywords: Micropolar fluid, magneto- hydrodynamics, heat and mass transfer, Soret effect, heat source.

INTRODUCTION

In order to study the theory of micropolar fluids, Eringen [1] developed a simple theory which includes the effect of local rotary inertia, the couple stress and the inertial spin. This theory is expected to be useful in analyzing the behavior of non-Newtonian fluids. Eringen [2] has also developed the theory of micropolar fluids for the cases where only microrotational effects and microrotational inertia exist. He [3] extended the theory of thermo-micropolar fluids and derived the constitutive law for fluids with microstructure. This general theory of micropolar fluids deviates from that of Newtonian fluid by adding two new variables to the velocity. These variables are micro-rotation that is spin and microinertia tensor describing the distributions of atoms and molecules inside the microscopic fluid particles. However, the theory may be applied to explain the phenomenon of the flow of colloidal fluids, liquid crystals, polymeric suspensions, animal blood etc. In view of ´Lukaszewicz [4], micropolar fluids represent those fluids which consist of randomly oriented particles suspended in a viscous medium. Several authors have studied the characteristics of the boundary layer flow of micropolar fluid under different boundary conditions. An excellent review of micropolar fluids and their applications was given by Ariman et. al. [5]. Gorla [6] has also discussed the steady state heat transfer in a micropolar fluid flow over a semi-infinite plate. Rees and Pop [7] studied free convection boundary layer flow of a micropolar fluid from a vertical flat plate. Micropolar fluid flow over a horizontal plate with surface mass transfer was presented by Yucel [8]. Gorla et al. [9-10] investigated further the concept of natural convection from a heated vertical plate in micropolar fluid.

Flows of fluids through porous media are of principal interest because these are quite prevalent in nature. Such flows have attracted the attention of a number of scholars due to their applications in many branches of science and technology, viz. in the fields of agriculture engineering to study the underground water resources, seepage of water in river beds, in petroleum technology to study the movement of natural gas, oil, and water through the oil reservoirs, in chemical engineering for filtration and purification processes. Also, the porous media heat transfer problems have several practical engineering applications such as crude oil extraction, ground water pollution and biomechanical problems e.g. blood flow in the pulmonary alveolar sheet and in filtration transpiration cooling. Hiremath and Patil [11] studied the effect on free convection currents on the oscillatory flow of polar fluid through a porous medium, which is bounded by vertical plane surface of constant temperature. The problem of flow and heat transfer for a micropolar fluid past a porous plate embedded in a porous medium has been of great use in engineering studies such as oil exploration, thermal insulation, etc. Raptis and Takhar [12] have considered the micropolar fluid through a porous medium. Fluctuating heat and mass transfer on three-dimensional flow through a porous medium with variable permeability has been discussed by Sharma et al. [13].

Hydromagnetic convection with heat and mass transfer in porous medium has been studied due to its importance in the design of Magnetohydrodynamics (MHD) generators and accelerators in geophysics, design of ground water system, energy storage system, soil-sciences, astrophysics, nuclear power reactors and so on. Magnetohydrodynamics is currently undergoing a period of great enlargement and differentiation of subject matter. The interest in these new problems generates from their importance in liquid metals, electrolytes and ionized gases. Unsteady hydromagnetic free convection flow of Newtonian and polar fluid has been investigated by Helmy [14]. Chaudhary and Sharma [15] considered combined heat and mass transfer by laminar mixed convection flow from a vertical surface with induced magnetic field. El-Hakien et.al. [16] studied the effects of viscous and Joule heating on MHD-free convection flow with variable plate temperature in a micropolar fluid. El-Amin [17] considered the MHD free-convection and mass transfer flow in a micropolar fluid over a stationary vertical plate with constant suction.

Combined heat and mass transfer problems with chemical reaction are of importance in many processes and have, therefore, received a considerable amount of attention in recent years. In processes such as drying, evaporation at the surface of water body, energy transfer in wet cooling tower and the flow in a desert cooler, heat and mass transfer occur simultaneously. Chemical reaction can be codified as either homogeneous or heterogeneous processes. A homogeneous reaction is one that occurs uniformly through a given phase. In contrast, a heterogeneous reaction takes place in a restricted region or within the boundary of a phase. A reaction is said to be first order, if the rate of reaction is directly proportional to the concentration itself which has many applications in different chemical engineering processes and other industrial applications such as polymer production, manufacturing of ceramics or glassware and food processing [18]. Das et al. [19] considered the effects of first order chemical reaction on the flow past an impulsively started infinite vertical plate with constant heat flux and mass transfer. Muthucumarswamy and Ganesan [20] and Muthucumarswamy [21] studied first order homogeneous chemical reaction on flow past infinite vertical plate. In the above mentioned studies the effects of heat sources/sinks and radiation have not been considered. Many processes in new engineering areas occur at high temperature and knowledge of heat transfer becomes imperative for the design of the pertinent equipment. Nuclear power plants, gas turbines and various propulsion devices for aircraft, missiles, satellites, and space vehicles are examples of such engineering areas. Sharma et al. [22-23] reported on the radiation effect with simultaneous thermal and mass diffusion in the MHD mixed convection flow from a vertical surface. Kandasamy et al. [24] discussed the heat and mass transfer effect along a wedge with heat source and concentration in the presence of suction/injection taking into account the chemical reaction of first order.. Recently, Sharma et al.[25] have investigated the Effects of chemical reaction on magneto-micropolar fluid flow from a radiative surface with variable permeability.

Hence based on the above discussion, the objective of the present paper is to study the effect of radiation on mixed convection flow of a magneto-micropolar fluid past a vertical porous plate through porous medium with variable permeability in slip-flow regime.

MATHEMATICAL FORMULATION

Consider the two dimensional, mixed convective flow of a micropolar fluid past a semi-infinite vertical plate embedded in a porous medium and subjected to a transverse magnetic field with variable permeability by taking into account the homogeneous chemical reaction of first order. The x*-axis is taken along the porous plate in the upward direction and y*-axis normal to it. Due to the semi-infinite plane surface assumption, the flow variables are functions of y* and t* only. Under these conditions, the governing equations are given by:

Continuity equation

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

Linear momentum equation

$$\frac{\partial u^*}{\partial t^*} + v*\frac{\partial u^*}{\partial y^*} = (\nu + \nu_r)\frac{\partial^2 u^*}{\partial y^{*2}} + g\beta(T^* - T^*_\infty) + g\beta_c(C^* - C^*_0)$$

$$-\frac{\nu u^*}{K^*} - \frac{\sigma}{\rho}B_0^2 u^* + 2\nu_r\frac{\partial \omega^*}{\partial y^*} \qquad \ldots(2)$$

Permeability of the medium is assumed to be of the form

$K*(t*) = K*_0((1 + \in A\, e^{n*t*})$

Angular momentum

$$\rho J^*\left(\frac{\partial \omega^*}{\partial t^*} + v^*\frac{\partial \omega^*}{\partial y^*}\right) = \gamma\frac{\partial^2 \omega^*}{\partial y^{*2}} \qquad \ldots(3)$$

Energy equation

$$\frac{\partial T^*}{\partial t^*} + v^*\frac{\partial T^*}{\partial y^*} = \frac{\kappa}{\rho Cp}\frac{\partial^2 T^*}{\partial y^{*2}} + S*T* \qquad \ldots(4)$$

Mass transfer equation

$$\frac{\partial C^*}{\partial t^*} + v^* \frac{\partial C^*}{\partial y^*} = D^* \frac{\partial^2 C^*}{\partial y^{*2}} - K_1^* C^* + D_T^* \frac{\partial^2 T^*}{\partial y^{*2}} \qquad \ldots(5)$$

The boundary conditions suggested by the physics of the problem are:

$$\left\{\begin{array}{ll} u^* = U_0 + L_1^*\left(\frac{\partial u^*}{\partial y^*}\right), \quad \omega^* = -m\frac{\partial u^*}{\partial y^*}, T^* = T_w^* + \varepsilon(T^*_w - T^*_\infty)e^{n^*t^*}, & \\ C^* = C_w^* + \varepsilon(C^*_w - C^*_\infty)e^{n^*t^*} & \text{at } y^* = 0 \end{array}\right\} \qquad \ldots(6)$$

$$u^* \to 0, \omega^* \to 0, T^* \to T_\infty^*,, C^* \to C_\infty^* \text{ as } y^* \to \infty \qquad \ldots(7)$$

The boundary conditions for microrotation variables ω^* describes its relationship with surface stress. In this equation, the parameter m is a number between 0 and 1 that relates the microgyration vector to the shear stress. The value m = 0 corresponds to the case where the particle density is sufficiently large so that microelements close to the wall are unable to rotate. The value m = 0.5 is indicative of weak concentration and when m = 1 flows are believed to represent turbulent boundary layers.

From the continuity equation (1), the suction normal to the plate can be written as

$$v^* = -V_0(1 + \in B e^{n^* t^*}) \qquad \ldots(8)$$

where B is a real positive constant with a magnitude less than unity and V_0 is scale of suction velocity which has non-zero positive constant.

Now introduce the following non-dimensional quantities:

$$u = \frac{u^*}{U_0}, \; v = \frac{v^*}{V_0}, \; y = \frac{V_0 y^*}{\nu}, \; \omega = \frac{\nu}{U_0 V_0}\omega^*, \; t = \frac{t^* V_0^2}{\nu},$$

$$\theta = \frac{T^* - T_\infty^*}{T_w^* - T_\infty^*}, \; C = \frac{C^* - C_\infty^*}{C_w^* - C_\infty^*}, \; n = \frac{n^*\nu}{V_0^2}, \; \alpha = \frac{K^* V_0^2}{\nu^2}, \; J = \frac{V_0^2 J^*}{\nu^2},$$

$$M = \frac{\sigma B_0^2 \nu}{\rho V_0^2}, \; Gr = \frac{\nu \beta_f g (T_w^* - T_\infty^*)}{U_0^2 V_0^2}, \; Gc = \frac{\nu g \beta_c (C_w^* - C_\infty^*)}{V_0^2 U_0}, \quad Pr = \frac{\nu \rho C_p}{\kappa} = \frac{\nu}{\alpha}$$

$$Sc = \frac{\nu}{D^*}, \; S = \frac{S^* \nu}{V_0^2}, \; K_1 = \frac{K_{1_1}^* \nu}{V_0^2}, \; h = \frac{L_1^* V_0}{\nu} \quad S_r = \frac{(T_w^* - T_\infty^*)}{\nu (C_w^* - C_\infty^*)} \qquad \ldots(9)$$

Since, the spin-gradient viscosity γ, which gives some relationship between the coefficient of viscosity and microinertia, is defined as

$$\gamma = \left(\mu + \frac{1}{2}\Lambda\right)J^* = \mu J^*\left(1+\frac{1}{2}Bv\right),\ Bv = \frac{\Lambda}{\mu} \qquad \ldots(10)$$

where Bv denotes the dimensional viscosity ratio, and Λ is the coefficient of gyro-viscosity (or vortex viscosity).

In view of equations (8) – (10), the governing equations (2) – (5) reduces to the following dimensionless form

$$\frac{\partial u}{\partial t} - (1+\in B e^{nt})\frac{\partial u}{\partial y} = (1+Bv)\frac{\partial^2 u}{\partial y^2} + Gr\,\theta + Gc\,C + [M + \frac{1}{\alpha(1+A e^{nt})}] + 2Bv\frac{\partial \omega}{\partial y} \quad ..(11)$$

$$\frac{\partial \omega}{\partial t} - (1+\in B e^{nt})\frac{\partial \omega}{\partial y} = \frac{1}{\phi}\frac{\partial^2 \omega}{\partial y^2} \qquad \ldots(12)$$

$$\frac{\partial \theta}{\partial t} - (1+\in B e^{nt})\frac{\partial \theta}{\partial y} = (\frac{1}{Pr})\frac{\partial^2 \theta}{\partial y^2} + S\theta \qquad \ldots(13)$$

$$\frac{\partial C}{\partial t} - (1+\in B e^{nt})\frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 c}{\partial y^2} - K_1 C + S_r\frac{\partial^2 \theta}{\partial y^2} \qquad \ldots(14)$$

where $\phi = \dfrac{\mu J^*}{\gamma} = \dfrac{2}{2+Bv}$

with corresponding boundary conditions

$$u = 1 + h\frac{\partial u}{\partial y},\ \ \omega = -m\frac{\partial u}{\partial y}, \theta = 1+\varepsilon e^{nt}, C = 1+\varepsilon e^{nt} \ \text{ at } y=0 \qquad \ldots(15)$$

$$u \to 0,\ \ \omega \to 0,\ \theta \to 0, C \to 0 \qquad \text{as } y \to \infty \qquad \ldots(16)$$

NUMERICAL SOLUTION

The unsteady, nonlinear coupled equations(11-14) with conditions (15-16) are solved by using an explicit finite-difference scheme. Consider a rectangular region with *y* varying from 0 to y max(= 10), where *y* max corresponds to y = ∞ at which lies well outside the momentum and energy boundary layers. The region to be examined in (*y, t*) space is covered by a rectilinear grid with sides parallel to axes with y and Δt, the grid spacing in *y*, and *t* directions, respectively. The grid points (*y, t*) are given by ($i\Delta y, k\Delta t$). The finite-difference equations corresponding to (11-14) are given by

$$\frac{U_i^{k+1}-U_i^k}{\Delta t}-(1+\varepsilon B e^{nt_i^k})\frac{U_i^k-U_{i-1}^k}{\Delta y}=\frac{U_{i+1}^k-2U_i^k+U_{i-1}^k}{\Delta y^2}+Gr\theta_i^k+Gm\phi_i^k$$

$$+[M+\frac{1}{\alpha(1+\varepsilon B e^{nt_i^k})}]U_i+2B\nu(\frac{\omega_i^k-\omega_{i-1}^k}{\Delta y})$$

$$\frac{\omega_i^{k+1}-\omega_i^k}{\Delta t}-(1+\varepsilon B e^{nt_i^k})\frac{\omega_i^k-\omega_{i-1}^k}{\Delta y}=\frac{1}{\varphi}\frac{\omega_{i+1}^k-2\omega_i^k+\omega_{i-1}^k}{\Delta y^2}$$

$$\frac{\theta_i^{k+1}-\theta_i^k}{\Delta t}-(1+\varepsilon B e^{nt_i^k})\frac{\theta_i^k-\theta_{i-1}^k}{\Delta y}=\left[\frac{1}{\Pr}\right]\frac{\theta_{i+1}^k-2\theta_i^k+\theta_{i-1}^k}{\Delta y^2}+S\theta_i^k$$

$$\frac{C_i^{k+1}-C_i^k}{\Delta t}-(1+\varepsilon B e^{nt_i^k})\frac{C_i^k-C_{i-1}^k}{\Delta y}=\frac{1}{Sc}\frac{C_{i+1}^k-2C_i^k+C_{i-1}^k}{\Delta y^2}-K_1C_i^k+Sr(\frac{\theta_{i+1}^k-2\theta_i^k+\theta_{i-1}^k}{\Delta y^2})$$

The finite-difference equations at every internal nodal point on a particular *n*-level constitute a tri-diagonal system of equations. These equations are solved by using the Thomas algorithm. Computations are carried out until the steady-state solution is assumed to have been reached when the absolute difference between the values of velocity as well as temperature at two consecutive time steps are less than 10^{-6} at all grid points.

RESULTS AND DISCUSSIONS

For different values of the chemical reaction parameter(K_1), viscosity ratio parameter (B_v), permeability parameter (α), the translational velocity u and microrotation profiles ω are plotted in Figs. 1 and 2, respectively. Figures reveal that on increasing the values of the permeability parameter (α) the profiles of u and the magnitude of ω, across the boundary layer, tend to increase. It is noted that translational velocity increases with decreasing chemical reaction parameter, while, reverse effect is observed for microrotation profile. Moreover, figure reveals that on increasing the values of the permeability parameter (α) and Soret number the profile of u , across the boundary layer, tend to increase. The velocity distribution decreases with increasing B_v. The phenomenon reflects the fact that the effect of increase in the value of B_v will result in an enhancement of the total viscosity in fluid flow because B_v is directly proportional to vortex viscosity which makes the fluid flow more viscous and so weakens the convection currents. In addition, the magnitude of ω increases as B_v

increases. Figure reveals that on increasing the values of the permeability parameter (α) and Soret number the magnitude of ω, across the boundary layer, tend to decrease.

Variations of the temperature profiles $\theta(y)$ along the span-wise coordinate y are shown in Fig. 3 for different values of Prandtl number (Pr =0.71, for air at 20^0C and 1 atmospheric pressure, Pr =1.0 for electrolytic solution, at 20^0C and 1 atmospheric pressure), heat source Parameter (S) and suction parameter (B). The numerical results show that the temperature decreases with increase in the Prandtl number. This is due to the fact that a fluid with high Prandtl number has a relatively low thermal conductivity which results in the reduction of the thermal boundary layer thickness. Also, the figure indicates that the temperature reduces with increase in heat source parameter (S), suction parameter (B) and heat source for air while reverse effect is observed for electrolytic solution.

Fig. 4 depicts the species concentration for different gases. The values of Schmidt number (Sc) are chosen to represent the most common diffusing chemical species like Hydrogen (Sc = 0.22), Oxygen (Sc = 0.66), and Ammonia (Sc = 0.78) at a temperature of 25^0C and 1 atmospheric pressure. A comparison of curves in the figure shows a decrease in concentration distribution $C(y)$ with an increase in Schmidt number because the smaller values of Sc are equivalent to increasing chemical molecular diffusivity (D). Hence the concentration of the species is higher for small values of Sc and lower for larger values of Sc. The concentration profiles also decrease with increase in suction parameter (B). There is a fall in the concentration due to increasing values of the chemical reaction parameter. This shows that the diffusion rates can tremendously be altered by chemical reaction. There is a rise in the concentration due to increasing values of the Soret number. Both the temperature and the concentration profiles attain their maximum values at the wall and decrease exponentially with y and finally tend to zero as $y \to \infty$.

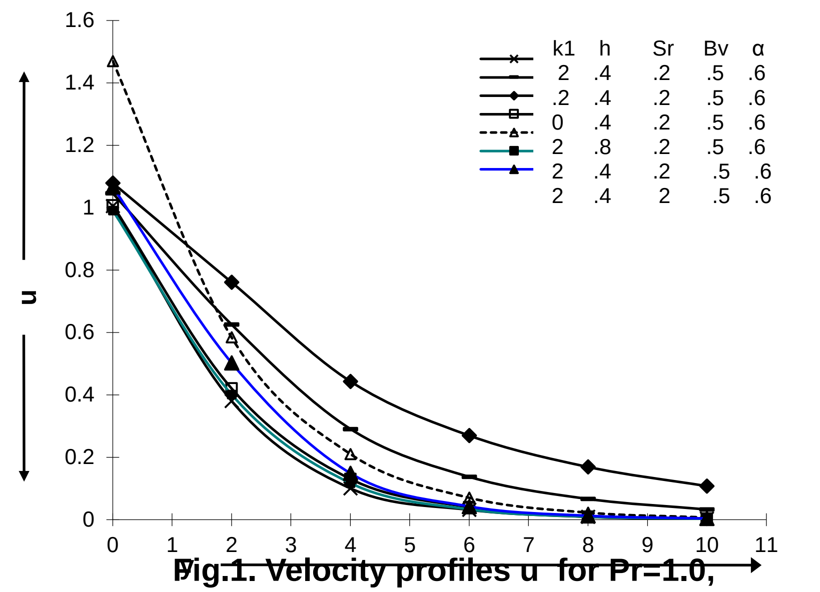

Fig.1. Velocity profiles u for Pr=1.0, M=1,Gr=2,S=1,m=.5,Sc=.22

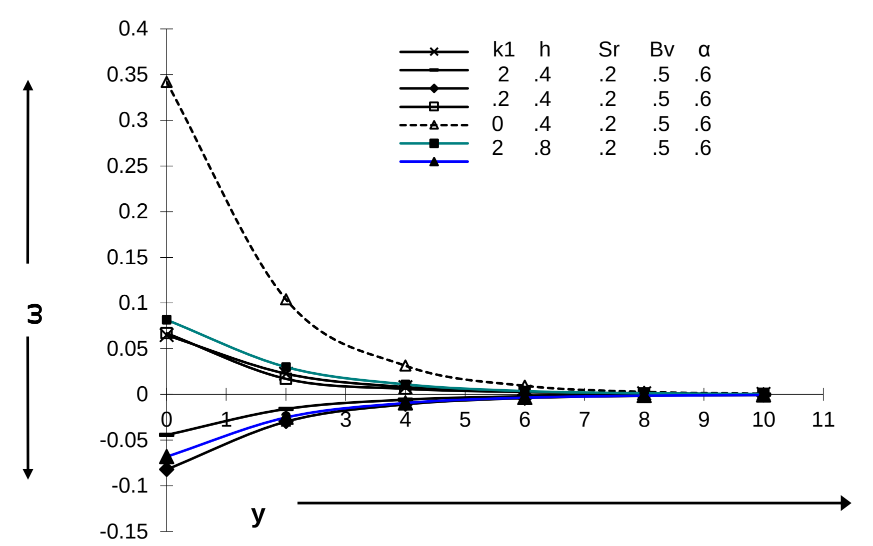

Fig.2. Micro rotation profiles ω for Pr=1.0, M=1,Gr=2,S=1,m=.5,Sc=.22

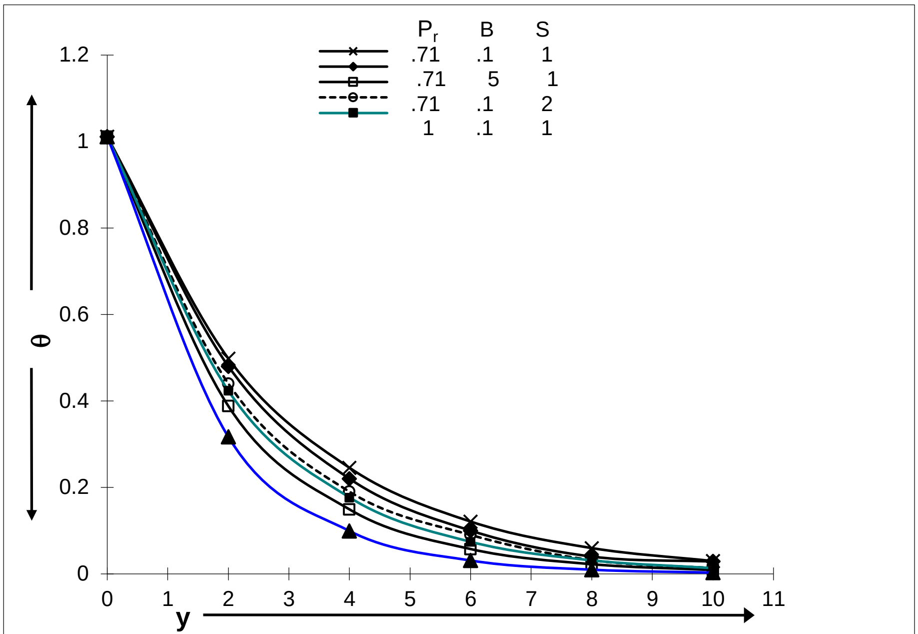

Fig.3. Temperature profiles for ε=.01, n=.1,t=1

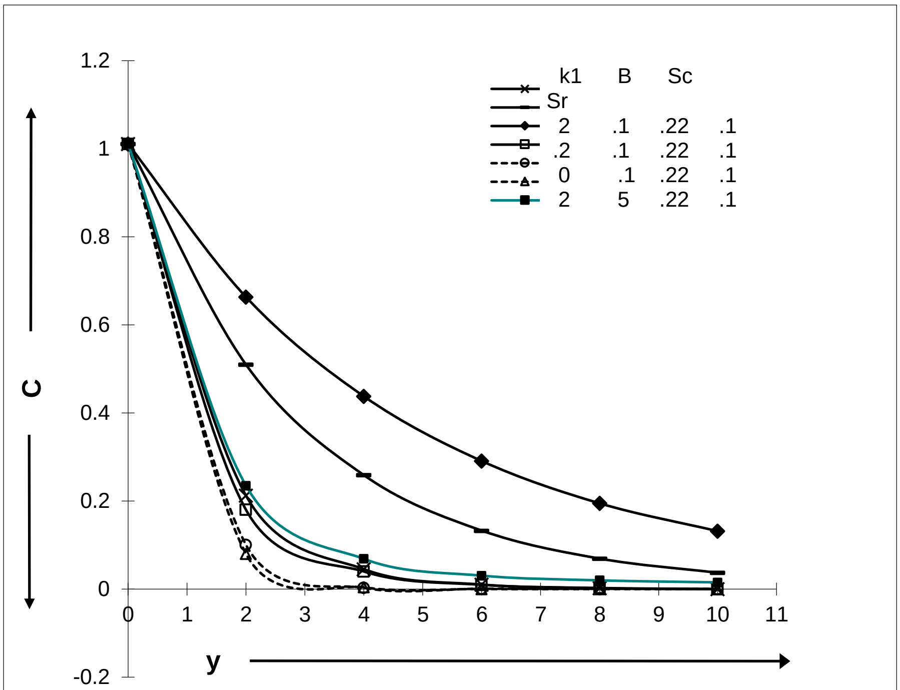

Fig.4. Concentration profiles for ε=.01, n=.1,t=1

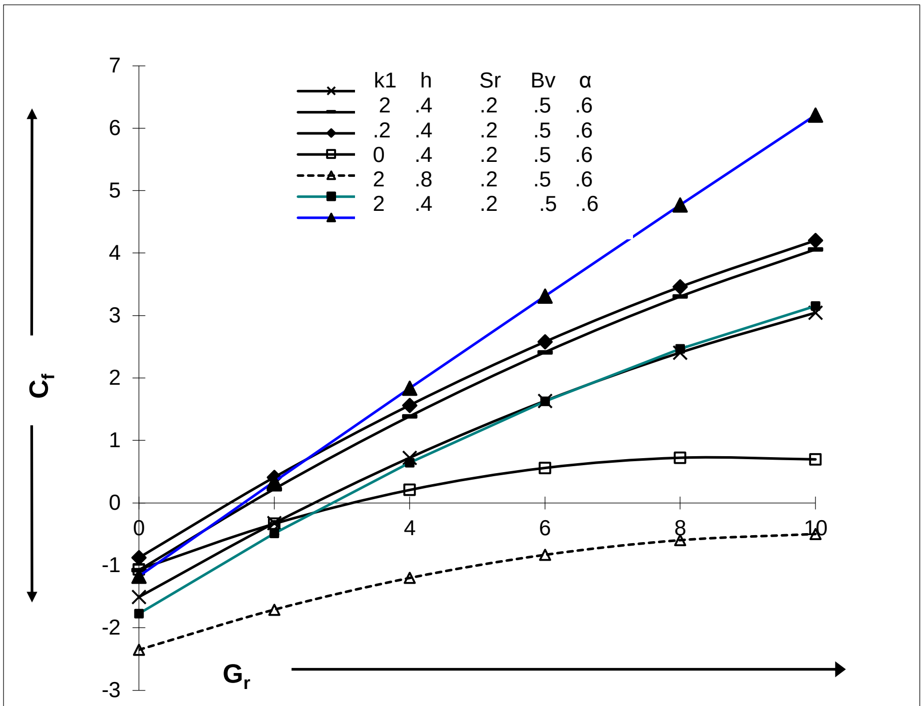

Fig.5. Skin-friction coefficient for Pr=1.0, M=1,S=1,m=.5,Sc=.22

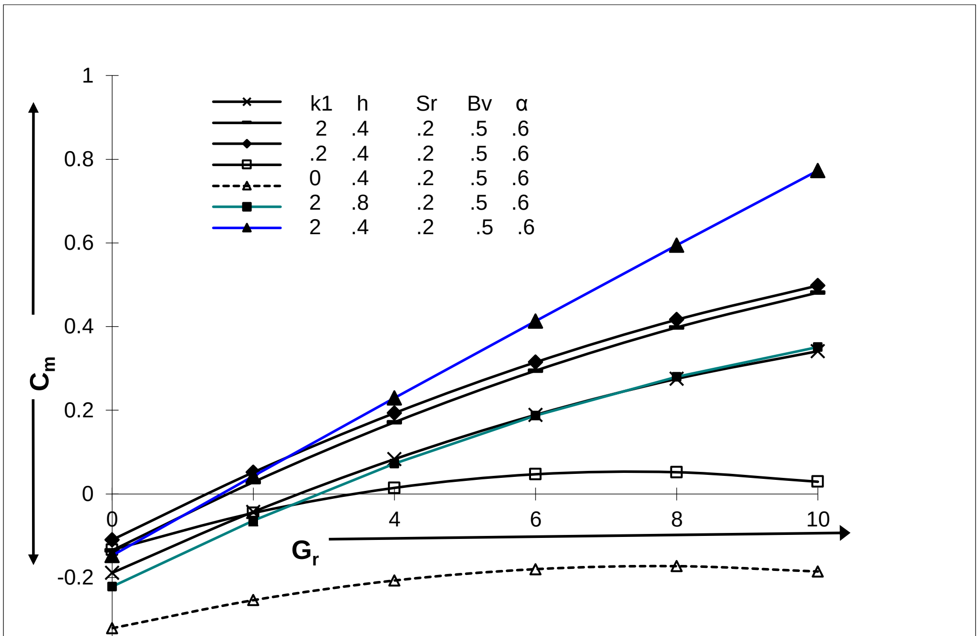

Fig.6. Couple Stress coefficient for Pr=1.0, M=1,S=1,m=.5,Sc=.22

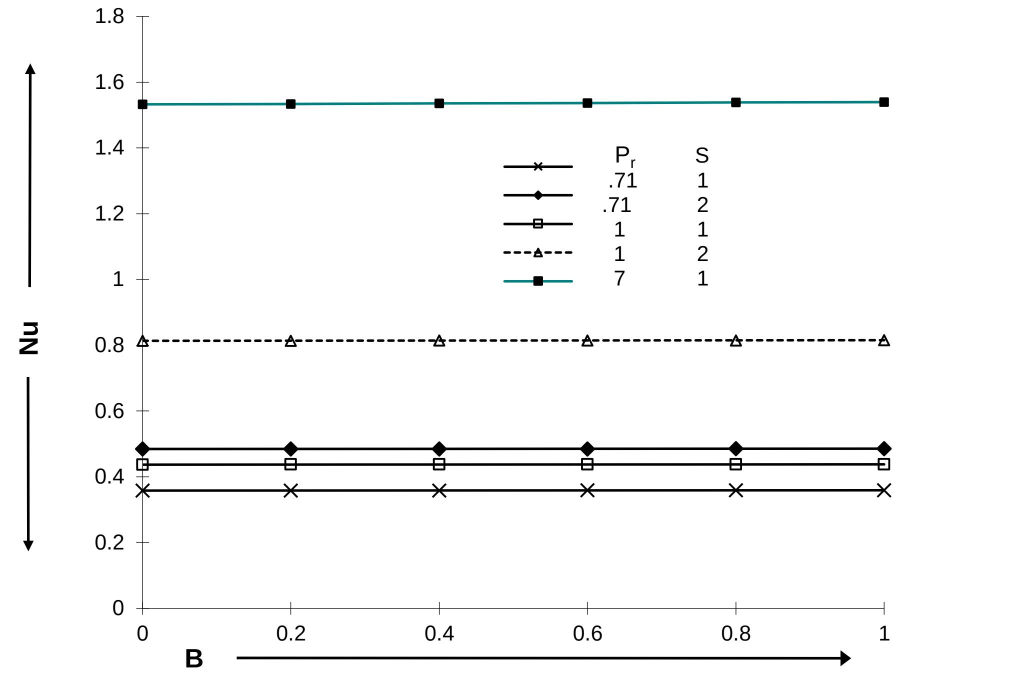

Fig.7. Rate of heat transfer ε=0.01, n=0.1,t=1

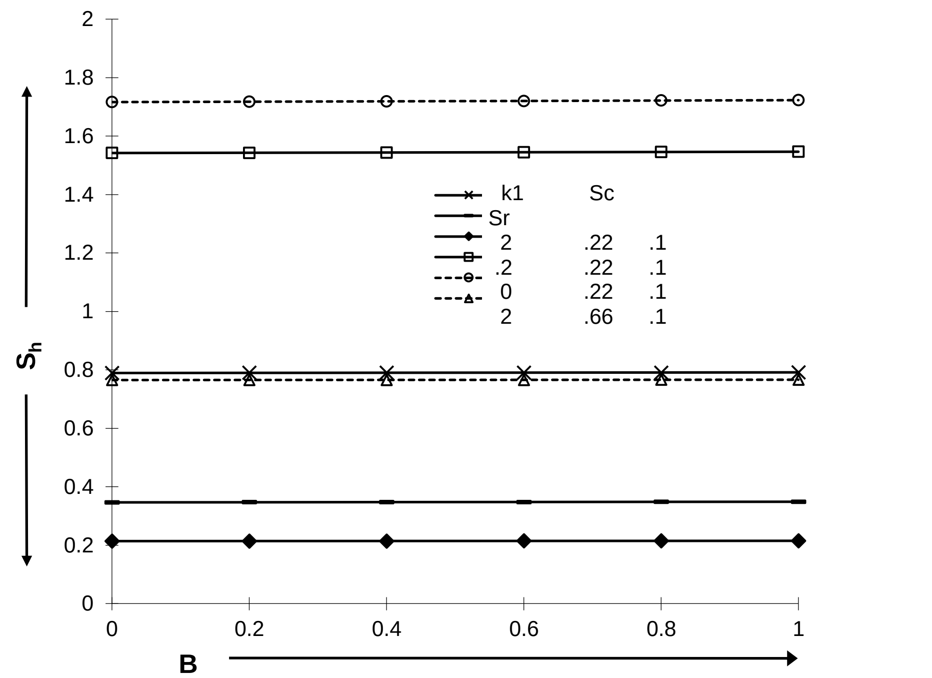

Fig.8. Rate of mass transfer for ε=.01, n=.1,t=1

Given the velocity field in the boundary layer, the skin friction coefficient (C_f) at the wall can be calculated, which is given by

$$\tau_{\omega} = (\mu + \Lambda)\frac{\partial u^*}{\partial y^*}\bigg|_{y^*=0} + \Lambda\,\omega^*\Big|_{y^*=0}$$

$$C_f = \frac{2T_w^*}{\rho U_0 V_0} = 2[1+(1-n)\beta]u'(0)$$

the couple stress coefficient (C_m) at the plate is written as

$$C\omega = \gamma\,\frac{\partial \omega^*}{\partial y^*}\bigg|_{y^*=0}$$

$$C_m = \frac{M_w}{\mu J U_0} = \left(1+\frac{\beta}{2}\right) w'(0)$$

The rate of heat transfer in terms of Nusselt number is given by

$$Nu = \frac{q_w^*\,\nu}{\kappa\, U_0^*(T_w^* - T_\infty^*)}$$

where $q = -\kappa\,\frac{\partial T^*}{\partial y^*}\bigg|_{y^*=0}$

in non-dimensional form it is given by

$$Nu = -\frac{\partial \theta}{\partial y}\bigg|_{y=0}$$

The rate of mass transfer is given by

$$J^*(\text{Diffusion flux}) = -\rho D^* \frac{\partial C^*}{\partial y^*}\bigg|_{y^*=0}$$

The coefficient of mass transfer which is generally known as Sherwood number S_h is given by

$$S_h = \frac{J^*\nu}{V_0\,\rho D^*(C_w^* - C_\infty^*)} = -\frac{\partial C}{\partial y}\bigg|_{y=0}$$

Figs. 5 and 6 show the variations of skin friction coefficient C_f and couple stress coefficient Cm for various values of K_1, B_v and α against G_r. It is observed that higher values of chemical reaction parameter lead to a reduction in the skin friction coefficient and couple stress coefficient. It is noted that C_f and C_m decrease with increasing B_v, because with increasing B_v offer a greater resistance to the fluid motion. It is concluded that C_f and C_m increase with increasing the values of α. Further, C_f and C_m increase as the buoyancy parameter G_r increases. The reason for this is that an increase in the buoyancy effect in mixed convection flow leads to an acceleration of the fluid flow, which increases the friction factor.

Numerical values of rate of heat for selected values of the Prandtl number (Pr) , heat source parameter(S) taking $\varepsilon = 0.01$, $n = 1$ and $t = 1$ are presented in Fig. 7. It is important to note that the heat transfer rate is enhanced as the Prandtl number increase. This is due to the fact that there would be a decrease of thermal boundary layer thickness with the increase of Prandtl number. It is also observed that the Nusselt number increases with an increase in S.

Fig. 8 displays the rate of mass transfer at the porous plate for Hydrogen (Sc = 0.22), Oxygen (Sc = 0.66) and Ammonia (Sc = 0.78) at a temperature 25^0C and 1 atmospheric pressure taking $\varepsilon = 0.01$, $n = 1$ and $t = 1$. It is clear that increasing values of Schmidt number or chemical reaction parameter enhance the mass transfer rate. Physically, the increase of Sc means decrease of molecular diffusivity (D), that results in decrease of concentration boundary layer. Hence, the concentration of the species is higher for values of Sc and lower for larger values of Sc. Also, the figure indicates that the rate of mass transfer reduce with increase in Soret number.

Nomenclature

A Positive constant

B Suction parameter

Bv Dimensionless viscosity ratio

Cp Specific at constant pressure

Cf Skin-friction coefficient

Cm Couple stress coefficient

C Dimensionless concentration

C^* Species concentration in the fluid

C^*_w Species concentration near the plate

C^*_∞ Species concentration with fluid away from the plate

D^* Chemical molecular diffusivity

D_T^* Thermal diffusivity

g Acceleration due to gravity

Gr Grashof number

Gc Modified Grashof number

h Rarefactor parameter

J^* Microinertia density

$K^*(t^*)$ Permeability of the porous medium

k Thermal conductivity of the fliud

K_1 Chemical reaction parameter

n Exponential index

n^* Dimensionless exponential index

M Magnetic parameter

Nu Nusselt number

Pr Prandtl number

S Heat source parameter

S_r Soret number

Sc Schmidt number

Sh Sherwood number

t Time

t^* Dimensionless time

T^* Temperature of the fluid near the plate

T^*w Temperature of the plate

$T^*\infty$ Temperature of the fluid far away from the plate

$U0$ Plate velocity in the direction of flow

U^*, v^* Components of dimensional velocities along x^* and y^* direction respectively

u, v Dimensionless velocities along x and y direction respectively

x^*, y^* Coordinate axis along and normal to the porous plate respectively

x, y Dimensionless Coordinate axis along and normal to the porous plate respectively

Greek symbols

α Dimensionless permeability parameter

β Coefficient of volumetric thermal expansion of the fluid

βc Volumetric Coefficient of expansion with concentration

σ Electrical conductivity of the fluid

θ Dimensionless temperature

ρ Density

μ Dynamic viscosity

v Kinematic viscosity

vr Kinematic rotational viscosity

γ Spin- gradient viscosity

Λ Vortex viscosity

Ω^* Component of the angular velocity vector normal to the x^*-y^* plane

ω Dimensionless component of the angular velocity vector normal to the x-y plane

Subscripts

w wall condition.

∞ free stream condition.

Superscripts

$*$ dimensional properties

REFERENCES:

[1] Eringen, A.C. (1964): Simple microfluids. Int. J. Engng. Sci. 2, 205-217.

[2] Eringen, A.C. (1966): Theory of micropolar fluids. J. Math. Mech., 16, 1-18.

[3] Eringen, A.C. (1972): Theory of Termomicrofluids. J. Math. Anal. Appl. 38, 480-496.

[4] ´Lukaszewicz G. (1999): Micropolar Fluids – Theory and Applications, Birkha¨user, Boston.

[5] Ariman, T., Turk, M.A. and Sylvester, N.D. (1973): Microcontinuum fluid mechanics – areview. Int. J. Engng. Sci. 11, 905-930.

[6] Gorla, R.S.R. (1992): Mixed convection in a micropolar fluid from a vertical surface with uniform heat flux. Int. J. Engng. Sci. 30, 349-358.

[7] Rees, D.A.S. and Pop, I. (1998): Free convection boundary layer flow of a micropolar fluid from a vertical flat plate. IMAJ. Appl. Math., 61, 179-197.

[8] Yucel, A. (1989): Mixed convection in micropolar flow over a horizontal plate with surface mass transfer, Int. J. Eng. Sci. 27, 1593–1602.

[9] Gorla R. S. R., Slaouti, A. S. and Takhar,H. S. (1998): Free convection in micropolar fluids over a uniformly heated vertical plate, Int. J. Heat and Fluid Flow. 8, 504–518.

[10] Gorla, R. S. R., Mohammedan A. A., Mansour, M. and Hussein, I (1995): Unsteady natural convection from a heated vertical plate in micropolar fluid, Numerical Heat Transfer, Part A 28, 253–262.

[11] Hiremath, P.S. and Patil, P.M. (1993): Free convection effects on oscillatory flow of couple stress field through a porous medium. Acta Mech. 98, 143-158.

[12] Raptis A. and Takhar, H. S. (1999): Polar fluid through a porous medium, Acta Mechanica 135, 91–93.

[13] Sharma, B. K. , Chaudhary, R. C. and Sharma , P. K. (2007): Fluctuating mass transfer on three-dimensional flow through a porous medium with variable permeability. Advances in Theoretical and Applied Mathematics. Vol. 2(3), 257-267.

[14] Helmy, K.A. (1998): MHD unsteady free convection flow past a vertical porous plate, ZAMM, 98, 255-270.

[15] Chaudhary, R. C. and Sharma, B. K. (2006): Combined heat and mass transfer by laminar mixed convection flow from a vertical surface with induced magnetic field. Journal of Applied Physics.Vol. 99, 34901-10.

[16] El-Hakiem, M. A. Mohammadein,A. A. El-Kabeir, S. M. M. and Gorla, R. S. R. (1999): Joule heating effects on magnetohydrodynamic free convection flow of a micropolar fluid. Int. Comm. Heat Mass Tran. 26(2), 219-227.

[17] El-Amin, M.F. (2001): Magnetohydrodynamic free convection and mass transfer flow in micropolar fluid with constant suction. J. Magn. Mater. 234, 567-574.

[18] Cussler, E.L. (1998): Diffusion mass transfer in fluid systems. 2nd ed. Cambridge University Press.

[19] Das, U.N., Deka, R.K. and Soundalgekar, V.M. (1994): Effects of mass transfer on flow past an impulsively started infinite vertical plate with constant heat flux and chemical reaction, Forschung im Engenieurwesen Engineering Research Co., 284-287.

[20] Muthucumarswamy, R. and Ganesan, P. (2001): First order chemical reaction

on flow past an impulsively started vertical plate with uniform heat and mass flux. Acta. Mech. 147, 45-57.

[21] Muthucumarswamy, R. (2002): Effects of a chemical reaction on moving isothermal vertical surface with suction. Acta. Mech. 155, 65-70.

[22] Sharma B.K., Agarwal M. and Chaudhary R.C. (2006): MHD fluctuating free convective flow with radiation embedded in porous medium having variable permeability and heat source/sink. – Journal of Technical Physics, vol.47(1), pp.47-58.

[23] Sharma B.K., Jha A.K. and Chaudhary R.C. (2006): Radiation effect with simultaneous thermal and mass diffusion in MHD mixed convection flow from a vertical surface with ohmic heating. – Romania Journal of Physics, vol.51(7-8), pp.715-727.

[24] Kandasamy R., Periasamy K. and Prashu Sivagnana K.K. (2005): Effects of chemical reaction, heat and mass transfer along wedge with heat source and concentration in the presence of suction or injection. – Int. J. Heat Mass Transfer, vol.48, pp.1388-1394.

[25] Sharma, B.K., Singh, A.P., Yadav, K., Chaudary, R.C. (2013) Effects of chemical reaction on magnetomicropolar fluid flow from a radiative surface with variable permeability. Int. J. Appl. Mech. Eng., 18 (3), 833–851.