

A Mathematical Model of MHD Micropolar Fluid Flow with Thermal-Diffusion and Diffusion-Thermo Effects

Ram Prakash Sharma

Department of Mathematics, JECRC University
Jaipur-303905, Rajasthan, India
Email: ramprakash0808@gmail.com

S. R. Mishra

Department of Mathematics
Siksha 'O' Anusandhan University
Khandagiri, Bhubaneswar-751030, Odisha, India
Email: satyaranjan_mshr@yahoo.co.in

(Received November 14, 2016)

Abstract: In this article, we have examined 2-dimensional steady magnetohydrodynamic (MHD) boundary layer flow of viscous micropolar fluid through a stretching surface. Simultaneous effects of thermal-diffusion (Soret) and diffusion-thermo (Dufour) are taken into account. Moreover, the effects of heat source/sink and first order chemical reaction are also considered. The governing flow problem is modelled by means of similarity transformation variables with their relevant boundary conditions. Finally, the reduced nonlinear coupled ordinary differential equations are solved numerically by means of nonlinear shooting technique. The effects of all the governing parameters are discussed for velocity, microrotation, temperature, concentration profiles, shear stress, transfer rate of heat and mass are presented with help of graphs. Numerical comparison is also presented with the existing published results as a special case of our study.

Keywords: Micropolar fluid; MHD; Soret and Dufour effect; Heat source; Chemical reaction.

1. Introduction

The thermal buoyancy caused due to heating/cooling of a vertical surface has a huge influence on flow and heat transfer characteristics. Convection heat transfer in the fluid flow is a phenomenon of considerable interest from both theoretical and practical point of perspectives because of its vast demands in countless engineering and geophysical fields. Combined

free and forced convection past a flat surface has been broadly investigated from both theoretical and experimental point of view through the over few years.

The impact of a magnetic field on natural convective transfer of heat on isothermal vertical surface has been discussed by Sparrow and Cess¹. Boundary layer natural convective flow of an electrically conducting fluid past a vertical surface in the presence of uniform surface heat flux and variable wall temperature with magnetic field has been investigated by Gupta², Char³, Chiam⁴, Liu⁵, Ishak et al.⁶⁻⁷ and Prasad et al.⁸ have analyzed the transfer of heat and flow properties past a stretching surface under the influence of a uniform magnetic field. The overhead analysis examined the motion entirely generated by a stretching surface saturated in a different state latent motion. Assorted convective laminar flow on a vertical sheet through porous medium under the influence of slip situation has been analyzed by Harris et al.⁹. The laminar slip motion past a flat surface in the presence of constant heat flux has been studied by Aziz¹⁰. Most recently Rohni et al.¹¹ analyzed numerically the unsteady assorted convective laminar motion close to 2-D stagnation point on a vertical porous surface immersed in a fluid-muddy porous medium with temperature slip effect and suction.

Excellent reviews of the mixed convection hydromagnetic flows in vertical channel have been investigated by many authors^{12,13,14-15,16-17,19}. Ishaket al.⁶⁻⁷ have studied magnetohydrodynamic motion of micropolar fluid toward stagnation point on a vertical surface. Steady assorted convective laminar motion of a micropolar fluid close to the stagnation point on a vertical sheet has been studied by Loket al.¹⁹. Ramachandran et al.²⁰ have also analyzed assorted convective in a stagnation flow close to vertical sheet. All the above recent studies are related to micropolar fluid over a vertical sheet. The MHD motion in a vertical curved permeable area with temperature-dependent heat source under the influence of slip-flow boundary condition has been examined by Srinivas and Muthuraj²¹. They have also analyzed the impact of MHD assorted convection peristaltic motion in a vertical permeable space under the influence of chemical reaction²².

Combined transfer of heat and mass by free convection in a porous medium has stimulated significant observation in the past many years, because of its huge prime engineering and geophysical practical utilities. Nield and Bejan²³, Ingham and Pop¹⁷⁻¹⁸, Bejan and Khair²⁴ and Trevisan and Bejan⁹ have studied an inclusive assessments on this area. However, in past few decades researchers worked on Dufour and Soret impact those cannot be neglected [Eckert and Drake²⁵]. In view of the significance of aforesaid effects, Kafoussias and Williams²⁶ investigated on heat and mass transfer

flow in presence of temperature dependent viscosity. Anghalet *al.*²⁷ have analyzed the Dufour and Soret effects on natural convection laminar flow over a vertical surface with saturated porous medium. Postelnicu²⁸⁻²⁹ have examined the effect of MHD and chemical reaction on an electrically conducting viscous fluid past over a vertical surfaces embedded in a porous media. Alam and Rahman³⁰ have studied the Dufour and Soret impact on assorted convective motion over a vertical porous flat plate in the presence of variable suction. The double dispersion on natural convective transfer of heat and mass from a vertical sheet saturated with non-Darcy electrically conducting fluid embedded permeable medium under the influence of Soret and Dufour effect has been investigated by Murthy *et al.*³¹. The impact of Soret and Dufour and partial slip on steady magnetohydrodynamic convective motion on account of a rotating disk has been analyzed by Rashidiet al.³². The impacts of heat and mass transfer on two-dimensional unsteady magnetohydrodynamic natural convective motion past a vertical porous surface in a permeable medium in the presence of Dufour effects have been presented by Mishra *et al.*³³.

The novelty of the present study is to bring out the effect of thermal-diffusion and diffusion-thermo on the heat and mass transfer characteristic of free convective micropolar fluid past over a vertical surface. The results of Ishaket al.⁶⁻⁷, Ramchandran et al.²⁰ and Baag et al.³⁴ have been discussed as special cases of the present study. Another objective of the current study is the method of solution. The Runge-Kutta method followed by shooting technique is providing the similar result as that of the solution obtained by Ishaket al.⁶⁻⁷ which was solved by finite difference technique. Sharma and Singh³⁵⁻³⁶ have studied the influence of viscous dissipation and heat source/sink on steady MHD flow near a stagnation point on linearly stretching sheet subjected to different thermal boundary conditions. Sharma and Singh³⁸⁻³⁹ have analyzed the impact of variable thermal conductivity and heat source/sink on MHD flow near a stagnation point on a linearly stretching sheet. Sharma and Singh³⁷ have studied the influence Ohmic heating and viscous dissipation on steady MHD flow near a stagnation point on an isothermal stretching sheet. Sharma, Singh and Chamkha³⁸ have investigated the impact Mass transfer with chemical reaction in MHD mixed convective flow along a vertical stretching sheet. Sharma and Singh³⁹ have studied the influence Heat and mass transfer in the boundary layer flow along a vertical isothermal reactive plate near stagnation point: Existence of dual solution. Sharma and Yadav⁴⁰ have analyzed the impact heat source/sink on stagnation point flow over a stretching sheet.

2. Formulation of the Problem

The steady, 2-dimensional, viscous incompressible electrically conducting micropolar fluid close to a stagnation point on a vertical hot plane is considered (Fig.1).

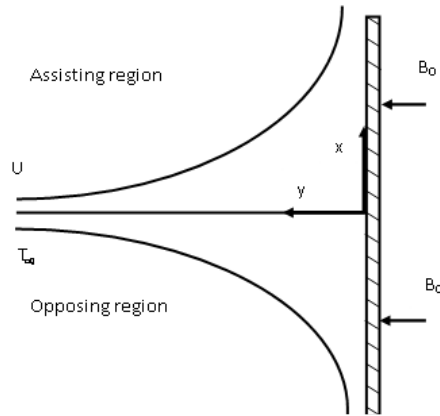


Fig.1 Physical model and coordinate system

Two equal and opposite forces are applied along x – axis so that the surface is stretched retaining the origin fixed. The magnetic Reynolds number of the conducting fluid is supposed to be very very small so that Hall effect and induced magnetic field may be neglected. Therefore, magnetic field effect in momentum is taken into account in the present study. Moreover, the flow domain is subject to uniform transverse magnetic field B_0 is applied normal to the sheet (Fig.1). Studies of magnetohydrodynamics boundary layer flow throughout flat plates and in the saturated region of bodies with transverse magnetic field demonstrate that the magnetic field reduces skin friction and heat transfer and increase the sock detachments distances. Following Bhattacharyya⁴¹ the governing boundary equations of momentum, energy and concentration for free convection under Boussinesq's approximation with boundary conditions are

$$(2.1) \quad \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0,$$

$$(2.2) \quad u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = U \frac{dU}{dx} + \left(\frac{\mu + \kappa}{\rho} \right) \frac{\partial^2 u}{\partial y^2} + \frac{\kappa}{\rho} \frac{\partial N}{\partial y} \\ + \frac{\sigma B_0^2}{\rho} (U - u) \pm g \beta_T (T - T_\infty) \pm g \beta_c (C - C_\infty),$$

$$(2.3) \quad \rho j \left(u \frac{\partial N}{\partial x} + v \frac{\partial N}{\partial y} \right) = \gamma \frac{\partial^2 N}{\partial y^2} - \kappa \left(2N + \frac{\partial u}{\partial y} \right),$$

$$(2.4) \quad u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2} + \frac{DK_T}{C_s C_p} \frac{\partial^2 C}{\partial y^2} + S' (T - T_\infty),$$

$$(2.5) \quad u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D \frac{\partial^2 C}{\partial y^2} + \frac{DK_T}{T_m} \frac{\partial^2 T}{\partial y^2} - k_c^* (C - C_\infty)$$

$$(2.6) \quad \begin{cases} u=0, v=0, N=-\frac{1}{2} \frac{\partial u}{\partial y}, T=T_w(x), C=C_w(x), \text{ at } y=0 \\ u \rightarrow U(x), N \rightarrow 0, T \rightarrow T_\infty, C \rightarrow C_\infty, \text{ as } y \rightarrow \infty \end{cases}$$

The equation of continuity (2. 1) is self-satisfied by the Cauchy-Riemann equations:

$$(2.7) \quad u = \frac{\partial \psi}{\partial y}, v = -\frac{\partial \psi}{\partial x},$$

where $\psi(x, y)$ is the stream function.

In sequence to transform Eqs. (2. 3) - (2. 5) into a set of ordinary differential equations, the following similarity transformation and dimensionless variables are introduced:

$$(2.8) \quad \left\{ \begin{array}{l} \eta = \left(\frac{a}{\nu} \right)^{1/2} y, f(\eta) = \frac{\psi}{(a\nu)^{1/2} x}, \omega(\eta) = \frac{N}{a \left(\frac{a}{\nu} \right)^{1/2} x}, \\ \theta(\eta) = \frac{T - T_\infty}{T_\omega - T_\infty}, \varphi(\eta) = \frac{C - C_\infty}{C_\omega - C_\infty}, M = \frac{\sigma B_0^2}{\rho a}, K_c = \frac{K_c^*}{a}, \\ \lambda = \frac{Gr}{Re_x^2}, Gr = \frac{g \beta_T (T_\omega - T_\infty) x^3}{\nu^2}, Gc = \frac{g \beta_c (C_\omega - C_\infty) x^3}{\nu^2}, \\ \delta = \frac{Gc}{Re_x^2}, l = \frac{\nu}{a}, Re_x = \frac{Ux}{\nu}, S = \frac{S'}{a}, Sc = \frac{\nu}{D}. \end{array} \right.$$

With the help of the above transformations, (2.1) is identically satisfied and (2.2)-(2.6) yield

$$(2.9) \quad (1+k)f''' + ff'' + 1 - f'^2 + K\omega' + M(1-f') \pm \lambda\theta \pm \delta\varphi = 0,$$

$$(2.10) \quad \left(1 + \frac{k}{2} \right) \omega'' + f\omega' - f'\omega - k(2\omega + f'') = 0,$$

$$(2.11) \quad \frac{1}{Pr} \theta'' + f\theta' - f'\theta + S\theta + Pr Du \varphi'' = 0,$$

$$(2.12) \quad \frac{1}{Sc} \varphi'' + f\varphi' - f'\varphi - Kc\varphi + Sr\theta'' = 0,$$

where

$$Du = \frac{DK_T(C_\omega - C_\infty)}{Cs Cp \nu (T_\omega - T_\infty)}, Sr = \frac{DK_T(T_\omega - T_\infty)}{T_m \nu (C_\omega - C_\infty)}, K = \frac{\kappa}{\mu}.$$

The boundary conditions (2.6) reduced to the following forms

$$(2.13) \quad \begin{cases} f(0) = 0, f'(0) = 0, \omega(0) = -\frac{1}{2}f''(0), \theta(0) = 1, \varphi(0) = 1, \text{ at } \eta = 0 \\ f'(\eta) \rightarrow 1, \omega(\eta) \rightarrow 0, \theta(\eta) \rightarrow 0, \varphi(\eta) \rightarrow 0 \text{ as } \eta \rightarrow \infty, \end{cases}$$

where prime denote differentiation with respect to η .

3. Physical Quantities of Interest

The major physical quantities of interest are defined as

$$(3.1) \quad \begin{cases} (i) \quad C_f = \frac{\tau_w}{\rho U_w^2/2}, (\text{skin friction coefficient}), \\ (ii) \quad Nu = \frac{xq_w}{k(T_w - T_\infty)}, (\text{Nusselt number}), \\ (iii) \quad Sh = \frac{xq_m}{D_m(C_w - C_\infty)}, (\text{Sherwood number}). \end{cases}$$

where surface shear stress, surface heat and mass flux are defined as

$$(3.2) \quad \tau_w = \left[(\mu + k) \frac{\partial u}{\partial y} + kN \right]_{y=0}, q_w = -k \left(\frac{\partial T}{\partial y} \right)_{y=0}, q_m = -D_m \left(\frac{\partial C}{\partial y} \right)_{y=0}$$

Employing the non-dimensional variables (2. 8), we obtain from Eqs. (3.1) and (3.2) as

$$(3.3) \quad \frac{1}{2} C_f \text{Re}_x^{1/2} = \left(1 + \frac{K}{2} \right) f''(0), \frac{Nu}{\text{Re}_x^{1/2}} = -\theta'(0), \frac{Sh}{\text{Re}_x^{1/2}} = -\phi'(0).$$

4. Results and Discussion

The robust Runge-Kutta method followed by shooting technique has been used to solve the coupled non-linear Eqs. (9) - (12) subject to boundary conditions Eq. (13) in the present discussion. The numerical solutions are obtained to exhibit the effects of emerging physical parameters on the momentum, angular momentum, temperature and concentration distributions through Figs.2-11. Further, the shear stress, for both the momentum profiles, transfer of rate of heat and mass are shown in Figs.12-15.

In the present study free convective steady motion of an electrically conducting micropolar fluid close to a stagnation point subject to transverse magnetic field with uniform heat source/sink and first order chemical reaction has been investigated. Main aim of the following analysis is to bring out the impacts of additional parameters introduced such as Soret (Sr), Dufour (Du) parameters besides the other parameters appear in the free convective diffusion problem. In all the figures, the dotted and the bold lines represent the opposing ($\lambda_1 = \lambda_2 = -1$) and assisting ($\lambda_1 = \lambda_2 = 1$) flows respectively. The present result is compared with that of Ishaket al.⁶⁻⁷, Lok et al.¹⁹, Ramchandran²⁰, Baag et al.³⁴. Moreover, the case of Newtonian fluid ($K = 0$) can also be derived as a particular case of Ramchandran²⁰ and Baaget al.³⁴.

Fig.2 dispenses the variation of material parameter on velocity profiles for both Newtonian and non-Newtonian fluid. It is clear to note that the velocity description reduces with an increase in K for both assisting and opposing cases. For $K = 0$, i.e. in case of Newtonian fluid velocity contributes its maximum value near the plate. In the present case the Soret and Dufour effects are withdrawn, so that the present result is compared with the earlier published result of Baaget al.³⁴ as well as Ramchandran²⁰ and found to be in good agreement.

Fig.3 presents the velocity, microrotation, temperature and concentration profiles in response to non-Newtonian parameter again in the absence of Soret and Dufour number. It is observed that the microrotation, temperature and the concentration profile enhance due to increase in material parameter whereas velocity profile reduces. It is interesting to note that the microrotation profiles intersects each other at $\eta = 0.75$ in opposing flow and $\eta = 1.25$ in assisting flow. This is a clear indication that the opposite effect

occurs in the layers from transient to free stream. Further, transient state is accelerated in case of opposing flow.

Fig.4 exhibits the microrotational effect which characterizes the micropolar fluid. It is to note that the magnetic parameter M enhance the velocity profile where as reverse effect is encountered for microrotation, temperature and concentration descriptions of the fluid under study subject to constant material properties ($K = 0.5$). Thus, it concluded that the additional forces due to the presence of magnetic field enhance the velocity profile.

The role of thermo-diffusion (Soret) and diffusion-thermo (Dufour) on the profiles are vital and interesting in the current study as shown in Figs.5 and 6. It clear to remarked that the velocity profile and microrotation profile have dual character with the variation of Dufour and Soret number. It is noticed that, in assisting flow the velocity profile reduces with the enhance in both Dufour and Soret numbers and reverse trend occurs in case of opposing flow. Further, the microrotation profile has also reverse trend as that of velocity profile (Figs.5 and 6). Another interesting finding is that because of enhancement in Dufour number the fluid temperature enhances significantly whereas the concentration profile reduces insignificantly in both assisting and opposing flows (Fig.5). Whereas in Fig.6, due to increase in Soret number the temperature of the fluid increases in opposing flow but reduces significantly in assisting flow. Thus, it is concluded that the dual Character of Dufour and Soret numbers in the velocity and microrotation profile are due to the inclusion of both magnetic and buoyancy parameters.

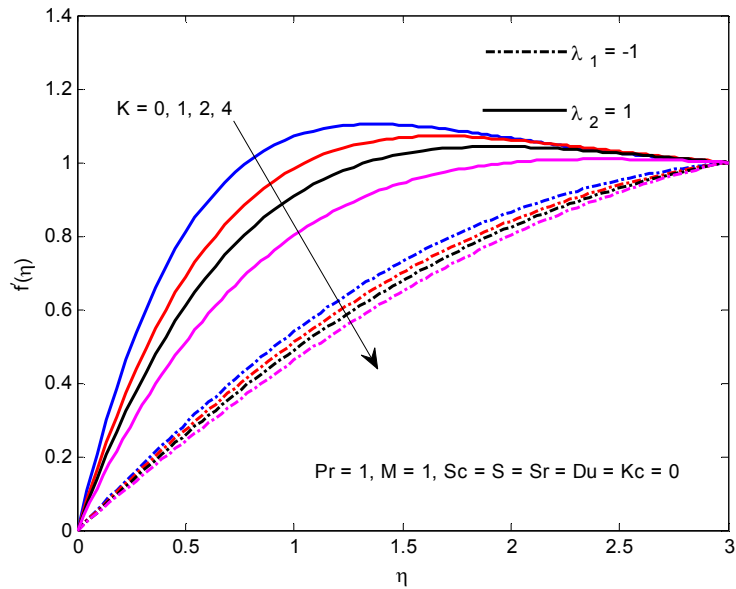
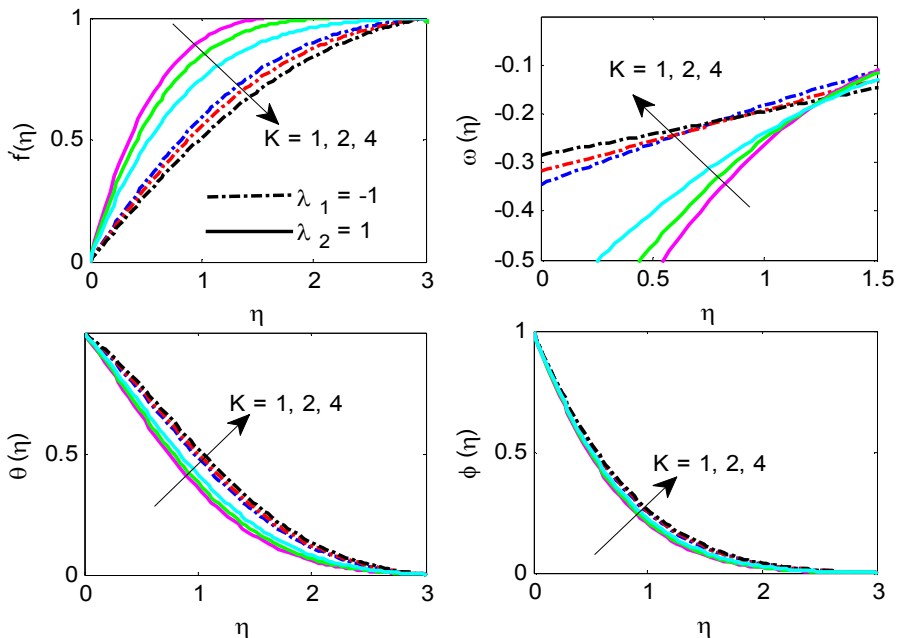
Fig.7 exhibits the presence of heat source/sink on the temperature profile of micropolar fluid. This clearly indicates that an increase in heat source strength enhances the temperature of the fluid in both the assisting and opposing flow whereas heat sink reduces it. Whereas destructive chemical reaction has a retarding effect on the concentration profile and incase of constructive the profile enhances significantly (Fig.8). One striking result is that the constructive reaction combines with opposing buoyancy force produce a higher rate of increase in the concentration profile. Thus, constructive chemical reaction inclusion with opposing force is favorable to increase the concentration profile at all points in its boundary layer.

Figs. 9-11 present the variation of different parameters on the skin friction, couple stress, rate of heat and mass transfer. Fig. 9 presents the effect of thermal buoyancy parameter with variation of magnetic parameter. It is noticed that the skin friction coefficient, couple stress and rate of heat transfer increases with the increase in thermal buoyancy parameter as magnetic parameter increases whereas rate of mass transfer decreases significantly. In this regards thermo-diffusion plays a vital role which

contributes a fall in rate of mass transfer. Fig.10 illustrates the variation of both the buoyant parameters with the variation of Soret number. It is observed is similar to that of Fig.9 but one striking feature is that the rate of mass transfer has a dual character with different values of Soret number within the range 0 to 1. From $Sr = 0$ to 0.75 rate of mass transfer increases with the increasing value of buoyant parameters whereas after that the profile decreases. This clear observation is remarked from Fig.11. It is seen that the variation of mass buoyancy parameter with the enhance in thermal buoyancy within the range 0 to 1. Thus, it is concluded that the interaction of buoyant parameters, Soret and Dufour number enhances the properties of micropolar fluid which is clear in this study.

5. Conclusion

1. Dual Character of diffusion-thermo (Dufour) and thermal-diffusion (Soret) effects exhibit in the velocity and microrotation profile due to inclusion of magnetic parameter.
2. Increase in heat source strength enhances the temperature of the fluid in both the assisting and opposing flow whereas heat sink reduces it.
3. For reducing skin friction, diffusion of foreign species initiating destructive reaction is a suggestive measure. On the other hand foreign species and assisting mass buoyancy increases skin friction substantially in aqueous medium and the presence of heat source.
4. Thermo-diffusion plays a vital role which contributes a fall in rate of mass transfer.
5. Lighter diffusive species favouring constructive reaction are suitable for reducing mass transfer rate at the bounding surface.


Fig.2 Effect of K on velocity profile

Fig.3 Velocity, microrotation, temperature and concentration profile for $Pr = M = Sc = Kc = 1, S = 0.5, Du = Sr = 0$

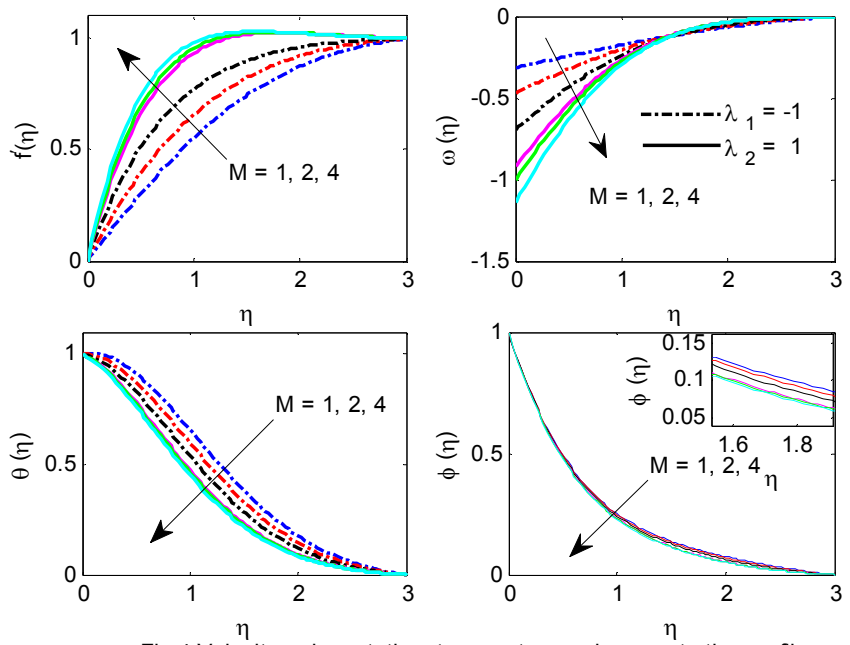


Fig.4 Velocity, microrotation, temperature and concentration profile for $Pr = K = Sc = S = Kc = 1, S = Du = Sr = 0.5$

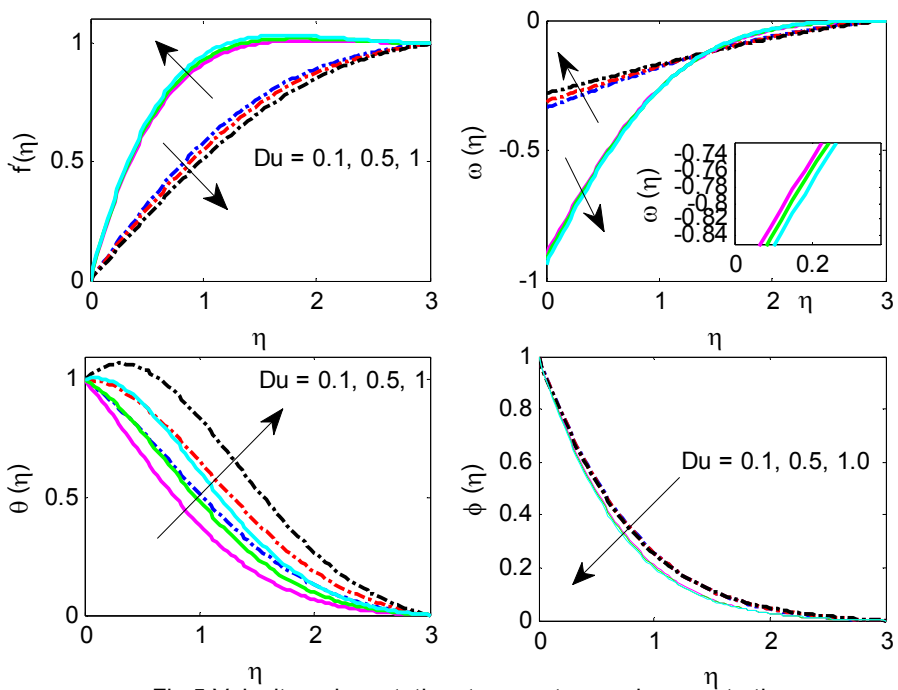


Fig.5 Velocity, microrotation, temperature and concentration for $Pr = M = K = Sc = Kc = 1, S = 0.5, Sr = 0.1$

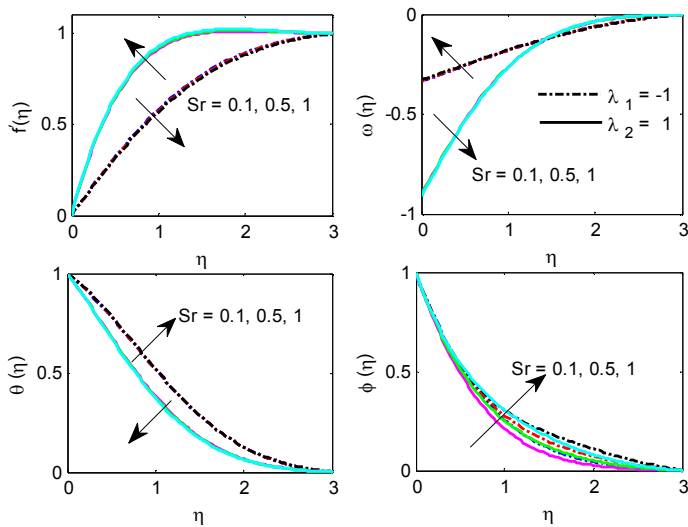


Fig.6 Velocity, microrotation, temperature and concentration for $Pr = M = Sc = Kc = K = 1$, $S = 0.5$, $Du = 0.1$

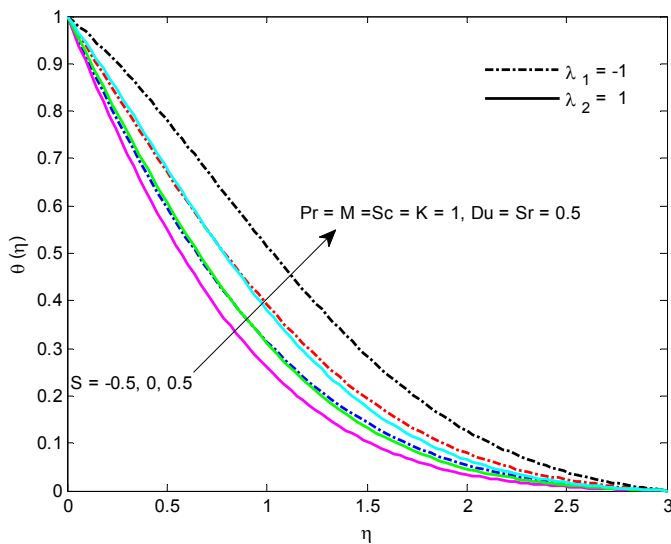


Fig.7 Temperature profile for different values of source / sink parameter (S)

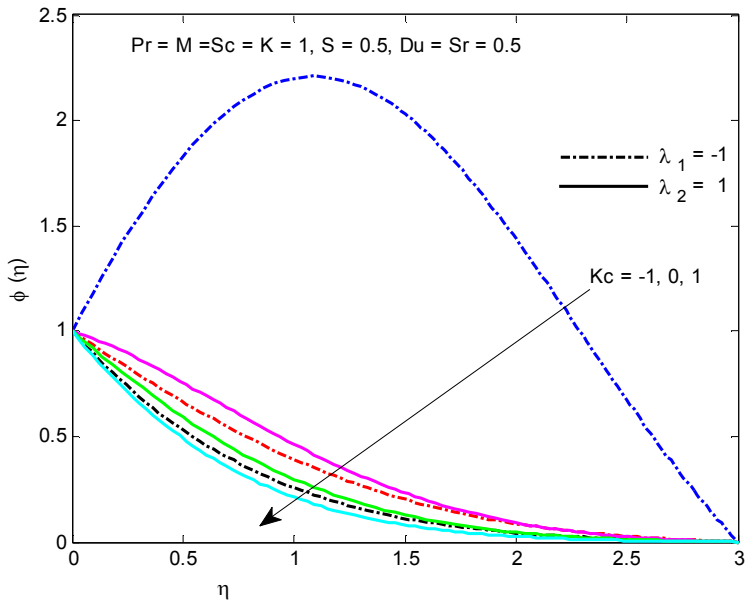


Fig.8 Effect of Chemical reaction (Kc) on concentration profile

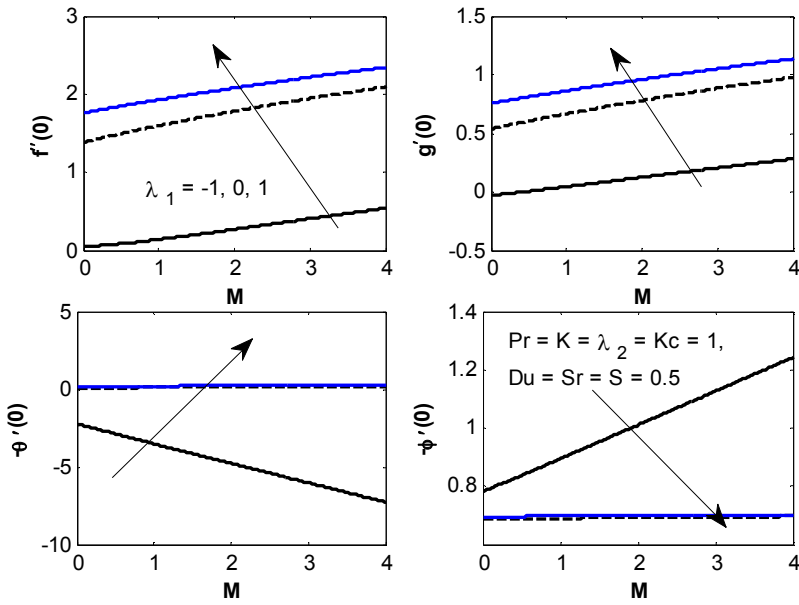


Fig.9 Effect of M and λ_1

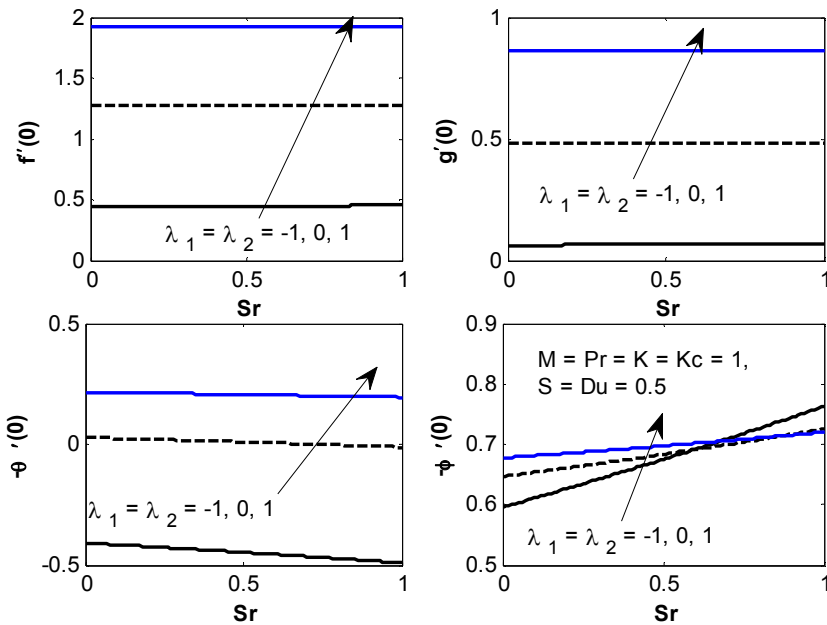


Fig.10 Effect of Sr , λ_1 and λ_2

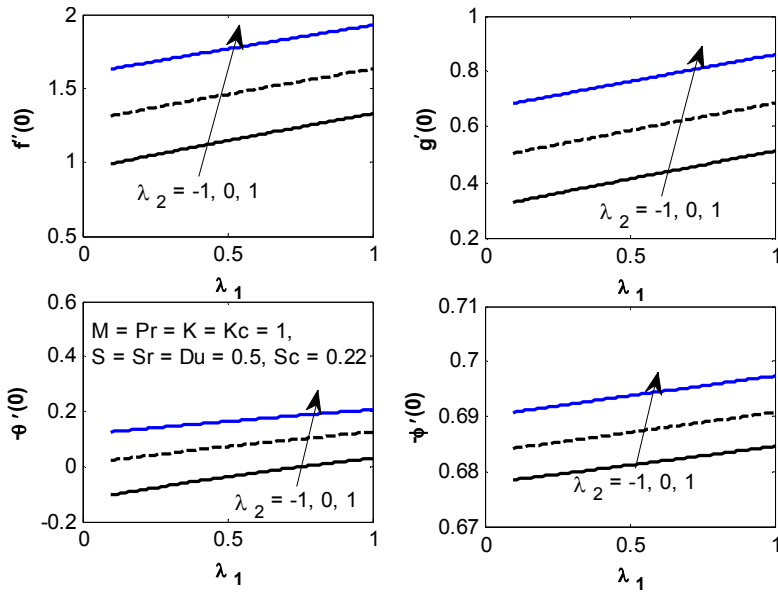


Fig.11 Effect of λ_1 and λ_2

References

1. E. M. Sparrow and R. D. Cess, The effect of a magnetic field on free convection heat transfer, *International Journal of Heat and Mass Transfer*, **3** (1961) 267-274.
2. A. S. Gupta, Laminar free convection flow of an electrically conducting fluid from a vertical plate with uniform surface heat flux and variable wall temperature in the presence of a magnetic field, *Zeitschrift für angewandte Mathematik und Physik ZAMP*, vol. **13** (1963) 324-333.
3. M. I. Char, Heat transfer in a hydromagnetic flow over a stretching sheet, *Heat Mass Transfer*, **29** (1994) 495-500.
4. T. C. Chiam, Magnetohydrodynamic heat transfer over a non- isothermal stretching sheet, *Acta Mechanica*, **122** (1997) 169-179.
5. I. C. Liu, Flow and heat transfer of an electrically conducting fluid of second grade over a stretching sheet subject to a transverse magnetic field, *International Journal of Heat and Mass Transfer*, **47** (2004) 4427-4437.
6. A. Ishak, R. Nazar and I. Pop, Hydromagnetic flow and heat transfer adjacent to a stretching vertical sheet, *Heat Mass Transfer*, **44** (2008) 921-927.
7. A. Ishak, R. Nazar and I. Pop, Magnetohydrodynamic (MHD) flow of a micropolar fluid towards a stagnation point on a vertical surface, *Computers & Mathematics with Applications*, **56** (2008) 3188-3194.

8. K. V. Prasad, D. Pal and P. S.Datti, MHD power-law fluid flow and heat transfer over a non-isothermal stretching sheet, *Communications in Nonlinear Science and Numerical Simulation*, **14** (2009) 278-2189.
9. S. D. Harris, B. D. Ingham and I. Pop, Mixed convection boundary-layer flow near the stagnation point on a vertical surface in a porous medium: Brinkman model with slip, *Transport of Porous Media*, **77** (2009) 267–285.
10. A. Aziz, Hydrodynamic and thermal slip flow boundary layers over a flat plate with constant heat flux boundary condition, *Communications in Nonlinear Science and Numerical Simulation*, **15** (2010) 573-580.
11. A. M. Rohni, S. Ahmad, I. Pop and J. H. Merkin, Unsteady mixed convection boundary-layer flow with suction and temperature slip effects near the stagnation point on a vertical permeable surface embedded in a porous medium, *Transport of a Porous Media*, **92** (2012) 1-14.
12. L. N. Tao, On combined free and forced convection in channel, *ASME Journal of Heat Transfer*, **82** (1960) 233-238.
13. W. Aung and G. Worku, Developing flow and flow reversal in a vertical channel with symmetric wall temperatures, *ASME Journal of Heat Transfer*, **108** (1986) 299-304.
14. O. V. Trevisanand A. Bejan Combined heat and mass transfer by natural convection in a porous medium, *Advances in Heat Transfer*, **20** (1990) 315-352.
15. C. H. Cheng, H. S. Kou and W. H. Huang, Flow reversal and heat transfer of fully developed mixed convection in vertical channels, *Journal of Thermophysics and Heat Transfer*, **4(3)** (1990) 375-383.
16. A. Barletta, Laminar mixed convection with viscous dissipation in a vertical channel, *International Journal of Heat and Mass Transfer*, **41** (1998) 3501–3513.
17. D. B. Ingham and I. Pop, *Transport Phenomena in Porous Media*, I. Pergamon, Oxford, 1998.
18. D. B. Ingham and I. Pop, *Transport Phenomena in Porous Media II*, Pergamon, Oxford, 2002.
19. Y. Y. Lok, N. Amin, D. Campean and I. Pop, Steady mixed convection flow of a micropolar fluid near the stagnation point on a vertical surface, *International Journal of Numerical Methods for Heat & Fluid Flow*, **15** (2005) 654–670.
20. N. Ramachandran, T. S. Chen and B. F.Armaly, Mixed convection in a stagnation flows adjacent to vertical surfaces, *ASME Journal of Heat Transfer*, **110** (1988) 373-377.
21. S. Srinivas and R. Muthuraj, MHD flow with slip effects and temperature-dependent heat source in a vertical wavy porous space, *Chemical Engineering Communications*, **197** (2010) 1387-1403.
22. S. Srinivas and R. Muthuraj, Effects of chemical reaction and space porosity on MHD mixed convective flow in a vertical asymmetric channel with peristalsis, *Mathematical and Computer Modelling*, **54** (2011)pp. 1213-1227.

23. D. A. Nield and A. Bejan, *Convection in Porous Media*, 2nd Edition, Springer, New York, 1999.
24. A. Bejan and K. R. Khair, Heat and mass transfer by natural convection in a porous medium, *International Journal of Heat and Mass Transfer*, **28** (1985) 909-918.
25. E. R. G. Eckert and R. M. Drake, *Analysis of Heat and Mass Transfer*, McGraw-Hill, New York, 1972.
26. N. G. Kafoussias and E. M. Williams, Thermal-diffusion and diffusion-thermo effects on mixed free-forced convective and mass transfer boundary layer flow with temperature dependent viscosity, *International Journal of Engineering Science*, **33** (1995) 1369-1383.
27. M. Anghel, H. S. Takhar and I. Pop, Dufour and Soret effects on free convection boundary-layer over a vertical surface embedded in a porous medium, *Studia Universitatis Babes-Bolyai, Mathematica*, **4** (2000) 11-21.
28. A. Postelnicu, Influence of a magnetic field on heat and mass transfer by natural convection from vertical surfaces in porous media considering Soret and Dufour effects, *International Journal of Heat and Mass Transfer*, **47** (2004) 1467-1472.
29. A. Postelnicu, Influence of chemical reaction on heat and mass transfer by natural convection from vertical surfaces in porous media considering Soret and Dufour effects, *Heat Mass Transfer*, **43** (2007). 595-602.
30. M. S. Alam and M. M. Rahman, Dufour and Soret effects on mixed convection flow past a vertical porous flat plate with variable suction, *Nonlinear Analysis: Modelling and Control*, **11** (2006) 3-12.
31. P. V. S. N. Murthy, M. K. Partha and G. P. Raja Sekhar, Soret and Dufour effects in a non-Darcy porous medium, *Journal of Heat Transfer*, **128** (2006) 605-610.
32. M. M. Rashidi, T. Hayat, E. Erfani, S. A. Mohimani Pour and A. H. Awatif, Simultaneous effects of partial slip and thermal-diffusion and diffusion-thermo on steady MHD convective flow due to a rotating disk, *Communications in Nonlinear Science and Numerical Simulation*, **16** (2011) 4303-4317.
33. S. R. Mishra, G. C. Dash and M. Acharya, Free convective flow of visco-elastic fluid in a vertical channel with Dufour effect, *World Applied Sciences Journal*, **28**(2013) 1275-1280.
34. S. Baag, S. R. Mishra, G. C. Dash and M. R. Acharya, Numerical investigation on MHD micropolar fluid flow towards a stagnation point on a vertical surface with heat source and chemical reaction, *Journal of King Saud University-Engineering Sciences*, DOI: 10.1016/j.jksues.2014.06.002, (2014).
35. P. R. Sharma and Gurminder Singh, Effects of viscous dissipation and heat source/sink on steady MHD flow near a stagnation point on linearly stretching sheet subjected to different thermal boundary conditions. Modeling Measurement & Control 'B', *AMSE J.*, France, **77**(1) (2008) 35-53.

36. P.R.Sharma and Gurminder Singh, Effects of variable thermal conductivity and heat source/sink on MHD flow near a stagnation point on a linearly stretching sheet, *J. Applied Fluid Mechanics*, Iran, **2(1)** (2008) 13-21.
37. P.R.Sharma and Gurminder Singh, Effects of Ohmic heating and viscous dissipation on steady MHD flow near a stagnation point on an isothermal stretching sheet, *Thermal Science*, **13(1)**(2009) 05-12.
38. P.R.Sharma, Gurminder Singh and A.J.Chamkha Mass transfer with chemical reaction in MHD mixed convective flow along a vertical stretching sheet, *Int. J. Energy Technology*, **4(20)** (2012) 01-12 (ISSN: 2035-911X).
39. P.R.Sharma and Gurminder Singh, Heat and mass transfer in the boundary layer flow along a vertical isothermal reactive plate near stagnation point: Existence of dual solution, *J. Applied Fluid Mechanics*, Iran, **7(1)** (2014) 25-33.
40. P.R.Sharma and R.S.Yadav, Effects of heat source/sink on stagnation point flow over a stretching sheet, *Int. J. Engineering Research & Technology*, **3(5)** (2014) 594-601.
41. K. Bhattacharyya, Dual solutions in boundary stagnation-point flow and mass transfer with chemical reaction past a stretching/ shrinking sheet, *International Communications in Heat and Mass Transfer*, **38** (2011) 917-922.
42. M. K. Jain, S. R. K. Iyengar, and R. K. Jain, *Numerical Methods for Scientific and Engineering Computation*, Wiley Eastern Ltd., New Delhi, India, 1985.
42. A. J. Chamkha, T. Grosan and I. Pop, Fully developed free convection of a micropolar fluid in a vertical channel, *International Communications in Heat and Mass Transfer*, **29** (2002) 1119-1127.

Nomenclature

C fluid Concentration	D coefficient of the mass diffusivity
Du Dufour number	Pr Prandtl number
Sr Soret number	g acceleration due to gravity
M magnetic parameter	K material parameter
C_p specific molecular diffusivity	Greek symbols
Sc Schmidt number	$\theta(\eta)$ dimensionless temperature
T fluid temperature	μ dynamic viscosity
T_∞ fluid temperature at infinity	δ solutal buoyancy parameter
Gc Grashof number for mass transfer	α thermal diffusivity
B_0 magnetic flux density	σ Electrical conductivity
Sh Sherwood number	λ thermal buoyancy or mixed convection parameter
κ thermal conductivity	ρ density of the fluid
Nu Nusselt number	ν kinematic viscosity
Kc chemical reaction parameter	η similarity variable
Gr Grashof number for heat transfer	β_T thermal expansion coefficient
C_∞ species concentration at infinity	β_c concentration expansion coefficient
k_c^* reaction rate of the solute	γ spin gradient viscosity
N angular Velocity	$\phi(\eta)$ non-dimensional concentration parameter
u, v velocity components along x- and y-direction	
j micro-inertia density	
k vortex viscosity or microrotation viscosity	
C_w stretching sheet concentration	
Ec Eckert number	
T_w stretching sheet temperature	
x, y coordinates	