*Original Research Article*

# Natural Convective Mass Transfer MHD Flow of Chemically Reactive Micropolar Fluid past a Vertical Porous Plate

**ABSTRACT**

Magnetic field effects on a free convective mass transfer flow of chemically reactive micropolar fluid over a vertical porous plate are investigated in this work. A mathematical model related to the problem is developed from the basis of studying magnetohydrodynamics(MHD). A usual mathematical transformation is applied on the model to obtain a system of non-dimensional equations. Analytical solution of the problem is calculated by the use of perturbation technique. The computed numerical values of fluid velocity, angular velocity and species concentration are plotted in different figures. To observe the effects of various parameters on the above mentioned physical quantities, the results are discussed in detailed with the help of graphs. Finally, a conclusion is listed here.

*Keywords:* MHD, Micropolar fluid, Porous plate, Chemical reaction, Perturbation technique.

## 1. INTRODUCTION

The behaviors of fluid that contain suspended, metal or dust particles in many practical situations are first observed by the micropolar fluid theory (Eringen,1966) with internal structures in which coupling between the spin of each particle and the macroscopic velocity field is taken into account. Physically, the micropolar fluids contain dilute suspension of small, rigid, cylindrical macromolecules with individual motion and are influenced by spin inertia. Since the theory is used to investigate the flow character of polymeric fluids, colloidal suspension (Hadimoto and Tokioka, 1969; Kucaba-Pietal, 2004; Khedr, 2009), human and animal blood(Arimanet *et al.*, 1974; Muthu, 2008), liquid crystal (Lockwood *et al.*, 1987) and exotic lubricants so many scientists have been received a great interest to observe the micropolar fluid dynamics at present time.

The authors (Ferraro and Plumpton, 1996; Cramer and Pai, 1973; Raptis, 2011; Samiulhaq*et al.*, 2012 and Seth *et al.*, 2015) are notable for major contribution about MHD free convection flows and their significant application in the field of stellar and planetary magnetospheres, aeronautics, chemical engineering, electronics, and so on. In addition, many transport processes exist in industries andtechnology where the transfer of heat and mass occurs simultaneously as a result of thermal diffusion and diffusion ofchemical species. An extensive contribution on heat and mass transfer flow has been made (Gebhart, 1971) to highlight the insight on the phenomena. Thereafter, several authors, (Chamkha, 2000; Chaudhary, 2007; Haque and Alam, 2009; Samad and Mohebujjaman, 2009; Eldabe, 2011 and Seth, 2015) have paid attention to the study of MHD free convection and mass transfer flows.

The growing needs for chemical reactions in chemical and hydrometallurgical industries require the study of heat and mass transfer with chemical reaction. The effect of the first order homogeneous chemical reaction of an unsteady flow past a vertical plate with the constant heat and mass transfer has been investigated (Das *et al.*, 1994). The chemical reaction effects on an unsteady MHD free convection fluid flow past a semi-infinite vertical plate embedded in a porous plate with heat absorption have been studied by (Ibrahim *et al.*, 2008; Anand Rao *et al.*, 2012; Das, 2012; and Raju *et al.*, 2013).

The author (Peddision and McNitt, 1970; Bakr, 2011) has recognized the boundary layer situation for steady micropolar fluid flow past a semi-infinite flat plate due to its important role in a number of technical processes. The micro inertia effects on the flow of a micropolar fluid past a semi-infinite plate are investigated (Ahmadi, 1976; Kucaba-Pietal, 2004; Khedr *et al.*, 2009). The free convective micropolar fluid flow induced by the simultaneous action of buoyancy forces is of great interest in nature and in many industrial applications as drying processes, solidification of binary alloy as well as in astrophysics, geophysics and oceanography.

The processes of mass transfer play an important role in the production of materials in order to obtain the desired properties of a substance. Separation processes in chemical engineering such as the drying of solid materials, distillation, extraction and absorption are all affected by the process of mass transfer. Chemical reactions including combustion processes are often decisively determined by the mass transfer. The authors (Callahan and Marner1976; Bakr 2011) studied a free convective steady flow with mass transfer past a semi-infinite plate. An investigation on free convective steady flow with mass transfer past asemi-infinite vertical porous plate with constant suction has been completed (Soundalgekar and Wavre 1977; Ahmed and Das 2013). *Transient free convection flow on a semi-infinite vertical plate with mass transfer has been observed (*Soundalgekar and Ganesan1980).Hence our main goal is to investigate a free convective mass transfer steady flow of a chemically reactive micropolar fluid past a semi-infinite porous plate.

## 2. ANALYSIS AND SOLUTION

### 2.1 MATHEMATICAL FLOW

A natural convective mass transfer steady flow of a chemically reactive micropolar fluid along a semi-infinite vertical porous plate is considered in the presence of a uniform magnetic field. The flow is assumed to be in the $x$-direction which is taken along the plate in the upward direction and $y$-axis is normal to it. Initially, we consider that the plate as well as the micropolar fluid particles is at rest at the same species concentration level $C\left(=C_\infty\right)$ at all points, where $C_\infty$ is species concentration of uniform flow. It is also assumed that a magnetic field $B$ of uniform strength is applied normal to the flow region. The physical configuration and co-ordinate system of the problem is presented in the following Fig.1.

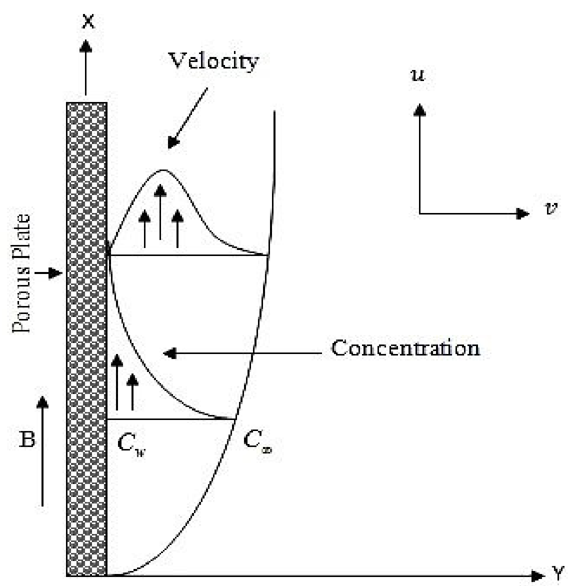


**Fig.1.** Physical configuration of the flow

Within the framework of the above stated assumption, the equations relevant to the problem are governed by the following system of coupled non-linear partial differential equations under the boundary-layer approximations,

Continuity Equation $\dfrac{\partial u}{\partial x}+\dfrac{\partial v}{\partial y}=0$

Momentum Equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=g\beta^{*}\left(C-C_{\infty}\right)+\left(\upsilon+\frac{\chi}{\rho}\right)\frac{\partial^{2}u}{\partial y^{2}}+\frac{\chi}{\rho}\frac{\partial\Gamma}{\partial y}-\frac{\sigma' uB_{0}^{2}}{\rho}-\frac{\upsilon}{K'}u$$

Angular Momentum Equation

$$u\frac{\partial\Gamma}{\partial x}+v\frac{\partial\Gamma}{\partial y}=\frac{\gamma}{\rho j}\left(\frac{\partial^{2}\Gamma}{\partial y^{2}}\right)-\frac{\chi}{\rho j}\left(2\Gamma+\frac{\partial u}{\partial y}\right)$$

Concentration Equation

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_{m}\frac{\partial^{2}C}{\partial y^{2}}-K_{c}\left(C-C_{\infty}\right)$$

with boundary condition,

$$u=0,\ \Gamma=-s\frac{\partial u}{\partial y},\ C=C_{w}\text{ at } y=0$$

$$u=0,\ \Gamma=0,\ C=C_{\infty}\text{ at } y\to\infty$$

where $u$ is the velocity component, $\Gamma$ is the velocity acting in $z$ - direction ( the rotation of $\Gamma$ is in the $x-y$ plane), $B_0$ is the magnetic field component, $g$ is local acceleration due to gravity, $\chi$ is the vortex viscosity, $\gamma$ is the spin gradient viscosity, $\beta^{*}$ is concentration expansion coefficient.

### 2.2 MATHEMATICAL FORMULATION

Since our goal is to attain analytical solutions of the problem so we introduce the following dimensionless variables,

$$\eta=y\sqrt{\frac{U_{0}}{2\upsilon x}},\psi=\sqrt{2\upsilon U_{0}x}\,f(\eta),u=\frac{\partial\psi}{\partial y}\text{ and } v=-\frac{\partial\psi}{\partial x},\ \phi(\eta)=\frac{C-C_{\infty}}{C_{w}-C_{\infty}}\text{ and }\Gamma=\sqrt{\frac{U_{0}^{3}}{2\upsilon x}}g\left(\eta\right)$$

The dimensionless equations are,

$$\left(1+\Delta\right)f'''\left(\eta\right)+\Delta g'\left(\eta\right)+f\left(\eta\right)f''\left(\eta\right)+G_{M}\varphi\left(\eta\right)-\left(K+M\right)f'\left(\eta\right)=0 \quad (4)$$

$$\wedge g''\left(\eta\right)+f'\left(\eta\right)g\left(\eta\right)+f\left(\eta\right)g'\left(\eta\right)-2\lambda g\left(\eta\right)-\lambda f''\left(\eta\right)=0 \quad (5)$$

$$\varphi''\left(\eta\right)+S_{c}f\left(\eta\right)\varphi'\left(\eta\right)-S_{c}C_{r}\varphi\left(\eta\right)=0 \quad (6)$$

with boundary conditions

$$f\left(\eta\right)=f_{w},\ f'\left(\eta\right)=0,\ g\left(\eta\right)=-sf''\left(\eta\right),\ \varphi\left(\eta\right)=1\ \eta=0$$

$$f'\left(\eta\right)=0,\ g\left(\eta\right)=0,\ \varphi\left(\eta\right)=0\ \eta\to\infty$$

Where, micro-rotational number $\Delta=\frac{\chi}{\rho\upsilon}$, modified Grashof number, $G_{m}=\frac{g\beta^{*}\left(C_{w}-C_{\infty}\right)2x}{U_{0}^{2}}$ permeability of porous plate, $K=\frac{2\upsilon x}{K'U_{0}}$, magnetic force number, $M=\frac{\sigma B_{0}^{2}2x}{U_{0}\rho}$, Spin Gradient number, $\wedge=\frac{\gamma}{\upsilon\rho j}$, Vortex viscosity, $\lambda=\frac{2x\chi}{\rho jU_{0}}$, Schmidt number, $S_{c}=\frac{\upsilon}{D_{m}}$, chemical reaction parameter, $C_{r}=K_{c}\frac{2x}{U_{0}}$.

### 2.3 MATHEMATICAL ANALYSIS

Since the solution is sought for the large suction further transformation can be made as,

$$\xi=\eta f_{w} \quad (1)$$

$$f\left(\eta\right)=f_{w}F\left(\xi\right) \quad (2)$$

$$\phi\left(\eta\right)=f_{w}^{2}G\left(\xi\right) \quad (3)$$

$$g(\eta) = f_w{}^3 H(\xi) \tag{4}$$

Model with small quantity,

$(1+\Delta)F''' + \Delta H' + FF'' + \varepsilon G_M G - (K+M)\varepsilon F' = 0$ (4.3.8)

$\wedge H'' + F'H + FH' - 2\lambda\varepsilon H - \lambda\varepsilon F'' = 0$ (4.3.9)

$$G'' + S_c G'F - \varepsilon S_c C_r G = 0 \tag{5}$$

with boundary conditions

$F(\xi) = 1,\ F'(\xi) = 0,\ G(\xi) = \varepsilon,\ H(\xi) = -sF''(\xi)$ at $\xi = 0$

$F'(\xi) = 0,\ G(\xi) = 0,\ H(\xi) = 0$ at $\xi \to \infty$

## 2.4 SOLUTION

Now for the large suction $(f_w > 1)$, $\varepsilon$ will be very small. Therefore following **Bestman**(1990), $F$, $G$ and $H$ can be expended in terms of the small perturbation quantity $\varepsilon$,

$$F(\xi) = 1 + \varepsilon F_1(\xi) + \varepsilon^2 F_2(\xi) + \varepsilon^3 F_3(\xi) + \ldots\ldots \tag{6}$$

$$G(\xi) = \varepsilon G_1(\xi) + \varepsilon^2 G_2(\xi) + \varepsilon^3 G_3(\xi) + \ldots\ldots \tag{7}$$

$$H(\xi) = \varepsilon H_1(\xi) + \varepsilon^2 H_2(\xi) + \varepsilon^3 H_3(\xi) + \ldots\ldots \tag{8}$$

The first order equations,

$$\left.\begin{aligned} &(1+\Delta)F_1''' + \Delta H_1' + F_1'' = 0 \\ &\wedge H_1'' + H_1' = 0 \\ &G_1'' + S_c G_1' = 0 \end{aligned}\right\} \tag{9}$$

with boundary conditions

$F_1 = 0,\ G_1 = 1,\ H_1 = 0$ at $\xi = 0$

$F_1' = 0,\ G_1 = 0,\ H_1 = 0$ at $\xi \to \infty$

The second order equations,

$$\left.\begin{aligned} &(1+\Delta)F_2''' + \Delta H_2'(\xi) + F_1F_1'' + F_2'' + G_M G_1(\xi) - (K+M)F_1' = 0 \\ &\wedge H_2'' + F_1'H_1 + F_1H_1' + H_2' - 2\lambda H_1 - \lambda F_1'' = 0 \\ &G_2'' + S_c G_2' + S_c G_1'F_1 - S_c C_r G_1 = 0 \end{aligned}\right\} \tag{10}$$

with boundary conditions

$F_2 = 0,\ G_2 = 0,\ H_2 = 0$ at $\xi = 0$

$F_2' = -\dfrac{1}{\varepsilon^2},\ G_2 = 0,\ H_2 = 0$ at $\xi \to \infty$

Also the third order equations,

$$\left.\begin{aligned} &(1+\Delta)F_3''' + \Delta H_3' + F_2F_1'' + F_1F_2'' + F_3'' + G_M G_2 - (K+M)F_2' = 0 \\ &\wedge H_3'' + F_2'H_1 + F_1'H_2 + F_2H_1' + F_1H_2' + H_3' - 2\lambda H_2 - \lambda F_2'' = 0 \\ &G_3'' + S_c G_3' + S_c G_2'F_1 + S_c G_1'F_2 - S_c C_r G_2 = 0 \end{aligned}\right\} \tag{11}$$

with boundary conditions

$F_3 = 0,\ G_3 = 0,\ H_3 = 0$ at $\xi = 0$

$F_3' = \dfrac{1}{\varepsilon^3},\ G_3 = 0,\ H_3 = 0$ at $\xi \to \infty$

From Equation (4.4.4) we get first order solutions,

$F_1 = 0,\ G_1 = e^{-S_c\xi},\ H_1 = 0$

From Equation (10) we get second order solutions,

$$F_2 = \frac{1}{A_2\varepsilon^2} - \frac{\xi}{\varepsilon^2} - \frac{1}{A_2\varepsilon^2} e^{-A_2\xi} + A_3 e^{-S_c\xi}, \; H_2 = 0 \text{ and } G_2 = -C_r e^{-S_c\xi}$$

From Equation (4.4.6) we get third order solutions,

$$F_3 = -\frac{1}{A_2\varepsilon^3} + \frac{\xi}{\varepsilon^3} + \frac{1}{A_2\varepsilon^3} e^{-A_2\xi} + A_{15} e^{-A_2\xi} + A_{16} e^{-S_c\xi} + A_{17} e^{-S_c\xi} + A_{18} e^{-A_2\xi} - A_{19} e^{-S_c\xi}$$

$$H_3 = A_8 e^{-A_2\xi} + A_9 e^{-S_c\xi}$$

$$G_3 = A_4 e^{-S_c\xi} - A_5 e^{-S_c\xi} + A_6 \xi e^{-S_c\xi} - A_7 e^{-(S_c+A_2)\xi} + A_{20} e^{-2S_c\xi}$$

From the Equation (9), (10) and (11) we have series for the solution. Putting the equations of first, second and third order solution in the Equations (9), (10) and (11), we get the values of *F*, *H* and *G*. Substituting the values of *F*, *H* and *G* to the equation.

The fluid velocity equation,

$$f = f_w F(\xi)$$

$$\Rightarrow f = f_w + \left(\varepsilon^2 f_w A_3 + \varepsilon^3 f_w A_{16} + \varepsilon^3 f_w A_{17} e^{-S_c\xi} - \varepsilon^3 f_w A_{19}\right) e^{-S_c\xi} + \left(\varepsilon^3 f_w A_{15} + \varepsilon^3 f_w A_{18}\right) e^{-A_2\xi}$$

$$\Rightarrow f' = \left(-S_c\varepsilon^2 f_w A_3 - S_c\varepsilon^3 f_w A_{16} - S_c\varepsilon^3 f_w A_{17} e^{-S_c\xi} + S_c\varepsilon^3 f_w A_{19}\right) e^{-S_c\xi}$$

$$-\left(A_2\varepsilon^3 f_w A_{15} + A_2\varepsilon^3 f_w A_{18}\right) e^{-A_2\xi}$$

The fluid angular velocity equation,

$$g(\eta) = f_w^3 H(\xi)$$

$$\Rightarrow g(\eta) = \varepsilon^3 f_w^3 A_8 e^{-A_2\xi} + \varepsilon^3 f_w^3 A_9 e^{-S_c\xi}$$

The fluid concentration equation,

$$\phi(\eta) = f_w^{\,2} G(\xi)$$

$$\Rightarrow \varphi(\eta) = f_w^{\,2} \varepsilon e^{-S_c\xi} - \varepsilon^2 f_w^{\,2} C_r e^{-S_c\xi} + \varepsilon^3 f_w^{\,2} A_4 e^{-S_c\xi} - \varepsilon^3 f_w^{\,2} A_5 e^{-S_c\xi} + \varepsilon^3 f_w^{\,2} A_6 \xi e^{-S_c\xi}$$

$$-\varepsilon^3 f_w^{\,2} A_7 e^{-(S_c+A_2)\xi}$$

## 3. RESULT AND DISCUSSION

To discuss the results of the problem, the analytical solutions are obtained by using the perturbation technique. In order to analyze the physical situation of the model, we have computed the numerical values of the flow variables for different values of Modified grashof number $G_m$ ,Suction parameter $f_w$, Magnetic force number *M*, permeability of porous plate *K*, Micro-rotational number $\Delta$, Vortex viscosity $\lambda$, Spin gradient viscosity number $(\wedge)$, Schmidt number $S_c$ and Chemical reaction parameter $C_r$. The fluid velocity, angular velocity and concentration versus the non-dimensional coordinate variable $\eta$ are displayed in Figures.

The increase values of magnetic parameter create a drug force known as Lorent force. The velocity profiles are illustrated in Fig. 1. As it is observed, the velocity profiles curve climb up at the increase of magnetic force number. Afterwards, the suction parameter stabilize the boundary layer growth. So the velocity profiles curve decline with go up suction parameters. And same behavior is shown for Schmidt number, modified Grashof number. The velocity profiles curve go down for permeability of prous plate. Then with increase of vortex viscosity, the velocity profiles plunge. The angular velocity profiles are displayed in Fig. 2. Firstly, angular velocity profiles curve decline with rise of suction parameter. Afterthat, it increases at the modified Grashof number. But in Fig. 2(c) angular velocity profiles show flactutution for Schmidt number. Then at the upsurge of micro-rotational number the angle velocity increase.at the end of the list of figure, angular velocity decline due to soar of spin gradient viscosity number and vortex viscosity.

Schmidt number decrease the molecular diffusivity. Fig. 3 describes the concentration profiles. As it is noticed, concentration profiles curve with increase of suction parameter, Schmidt number, chemical number and micro-rotational number.

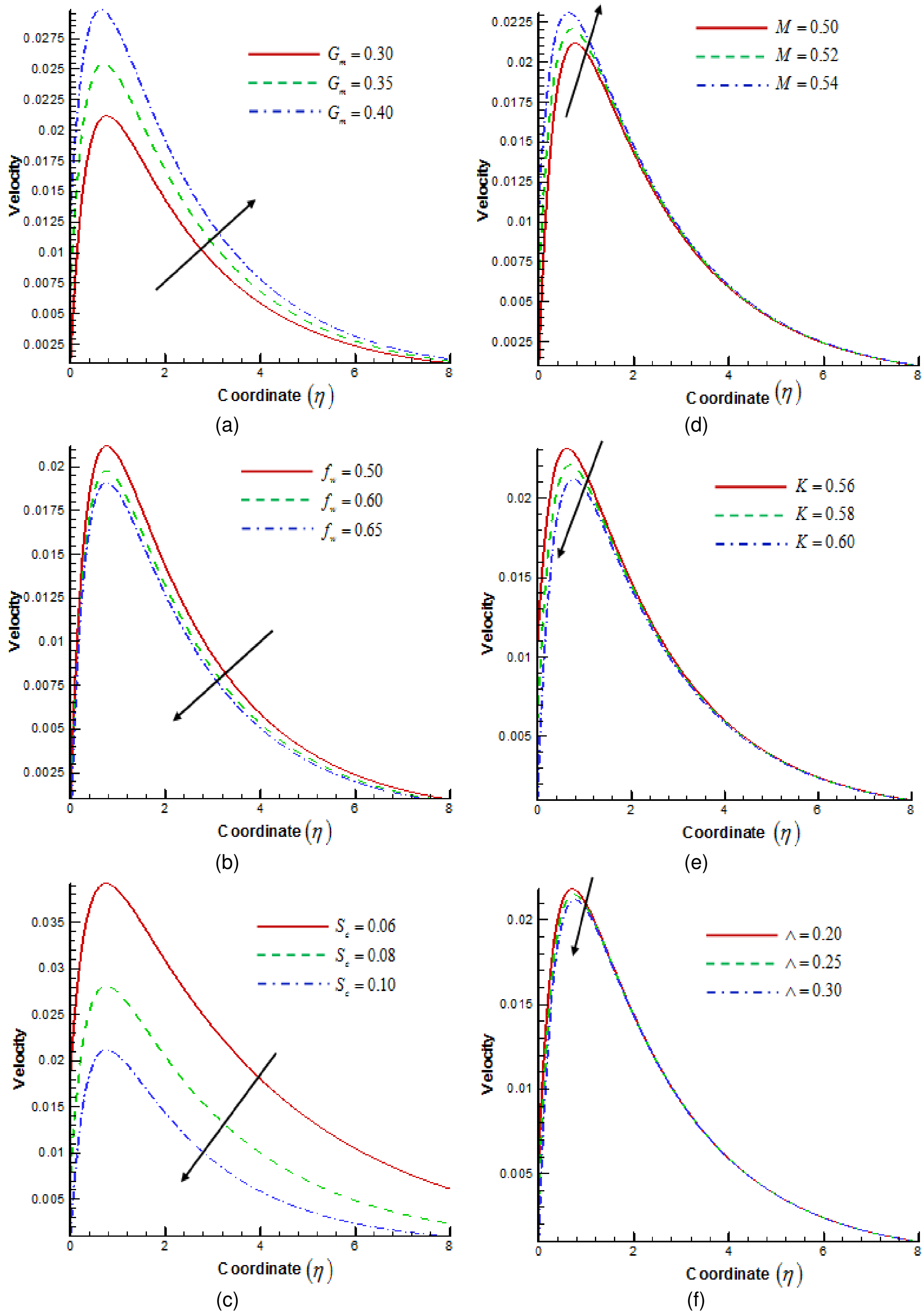


Fig. 1. Velocity profiles for different values of (a) modified Grashof number (b) suction parameter (c) Schmidt number (d) magnetic force number (e) permeability of porous plate (f) spin gradient viscosity number.

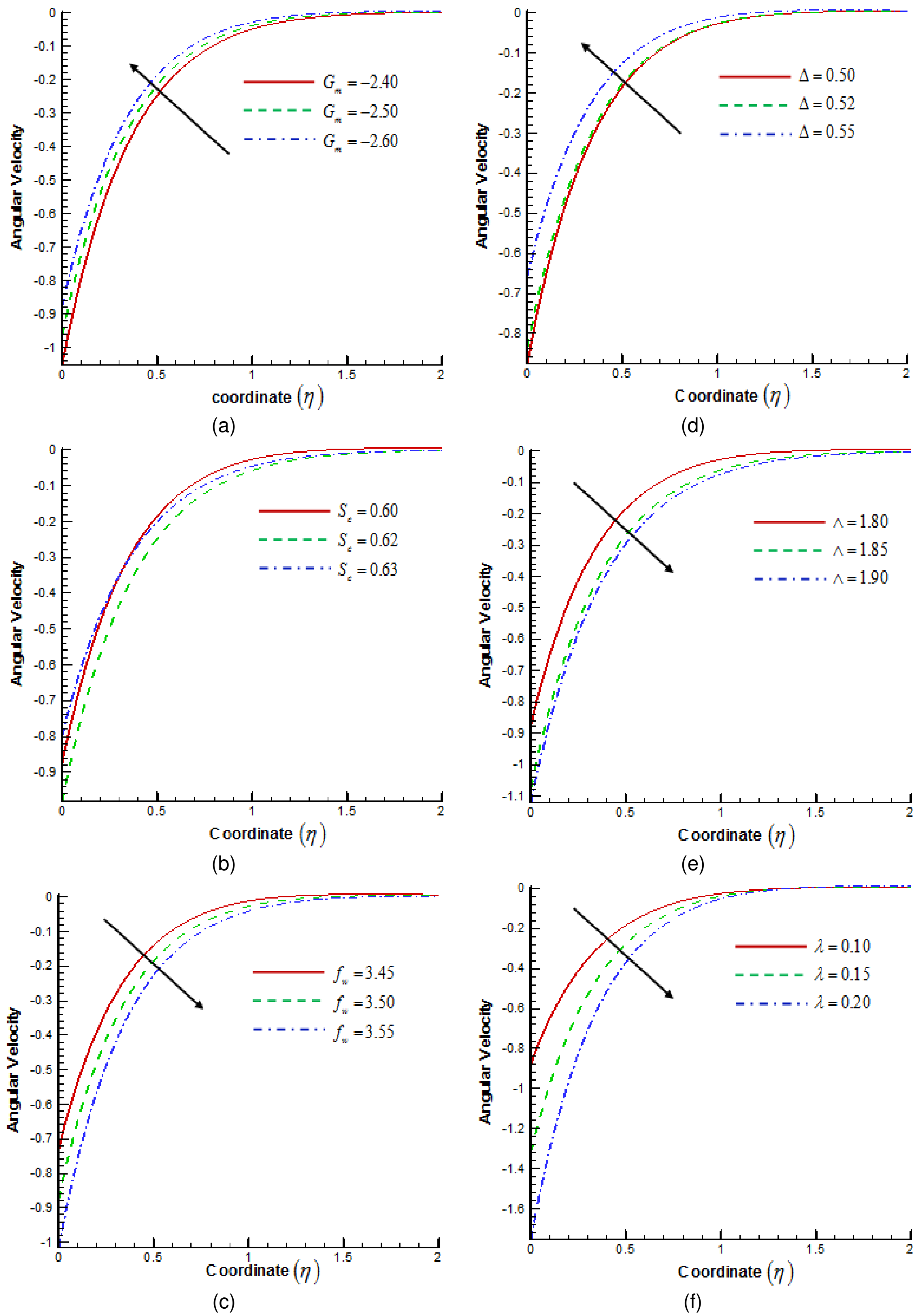


Fig. 2. Angular velocity profiles for different values of (a) modified Grashof number (b) Schmidt number (c) suction parameter (d) micro-rotational number (e) spin gradient viscosity number (f) vortex viscosity.

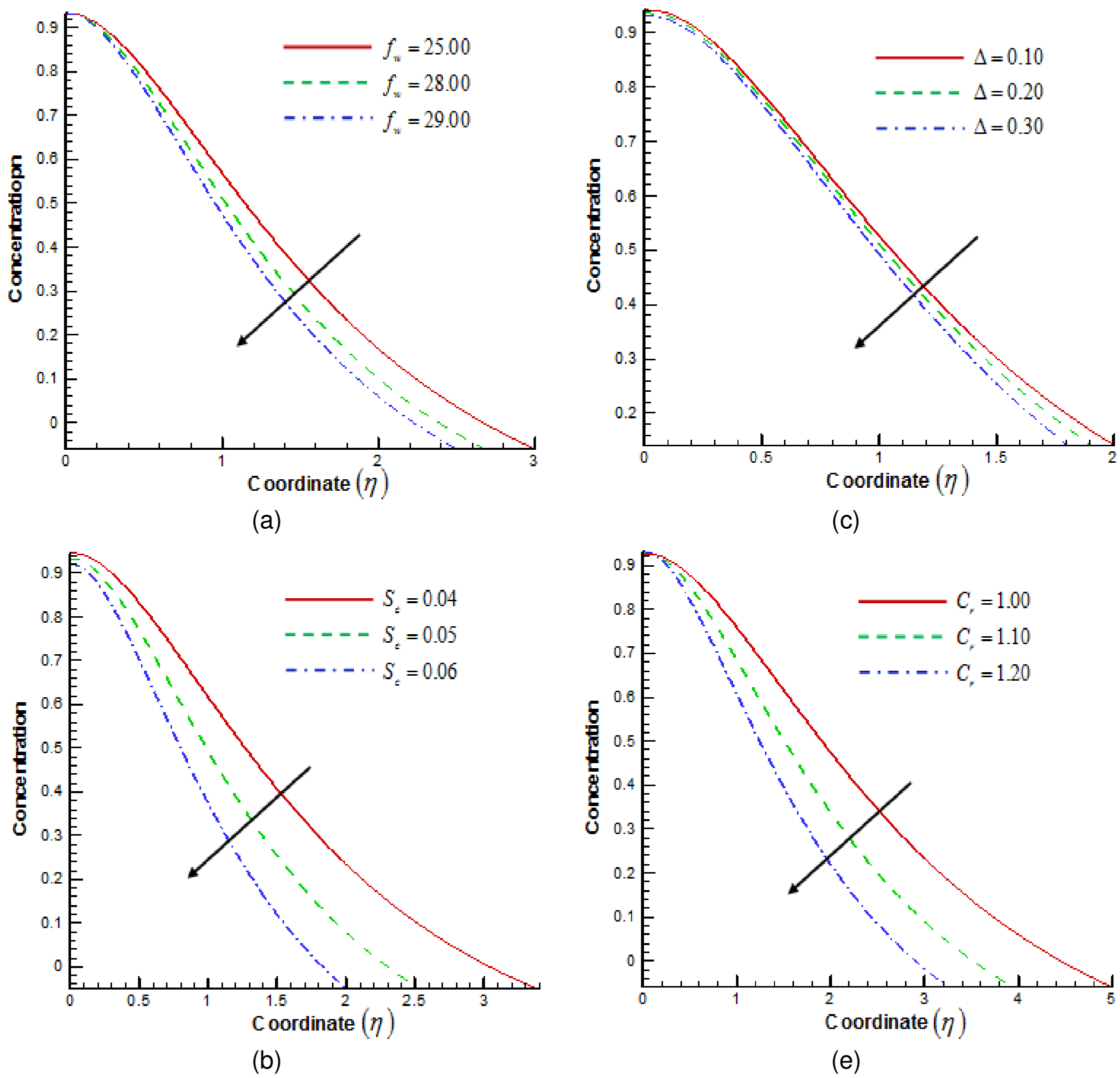


Fig. 3. Concentration profiles for different values of (a) suction parameter (d) Schmidt number (c) micro-rotational number (d) chemical reaction parameter.

## 4. CONCLUTION

Some of the important findings of the present work obtained from the graphical representation of the results are listed below:

1. The fluid velocity and angular velocity profiles decreases with the increase of Modified grashof number.
2. The velocity and angular velocity profiles decreases with the increase of Suction parameter and also the concentration profile decreases with the increase of Suction parameter.
3. The velocity profile decreases and angular velocity profiles decreases with the increase of Schmidt number and also the concentration profile decreases with the increase of Schmidt number.
4. The velocity profile go up with Magnetic force number.
5. The velocity profiles decreases with the increase of Permeability of porous plate.
6. The concentration profile decreases with the increase of Chemical reaction parameter.

7. The angular velocity profile increases with the increase of Micro-rotational number and the concentration profile decreases with the increase of Micro-rotational number.
8. The angular velocity profile decreases with the increase of Spin gradient viscosity number.
9. The angular velocity profile decreases with the increase of Vortex viscosity.

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## APPENDIX

$$A_1 = \frac{1}{\wedge}, \quad A_2 = \frac{1}{1+\Delta}, \quad A_3 = \frac{-A_2 G_M}{\left(-S_c{}^3 + A_2 S_c{}^2\right)}, \quad A_5 = \frac{S_c}{A_2 \varepsilon^2}, \quad A_6 = \frac{S_c}{\varepsilon^2}$$

$$A_7 = \frac{S_c^2}{A_2 \varepsilon^2 \left(A_2{}^2 + S_c A_2\right)}, \quad A_{20} = \frac{A_3}{2}, \quad A_8 = \frac{-\dfrac{A_2 \lambda}{\varepsilon^2}}{\left(A_2^2 - A_1 A_2\right)}, \quad A_9 = \frac{A_3 \lambda S_c^2}{S_c^2 - A_1 S_c}, \quad A_{10} = \Delta A_2{}^2 A_8$$

$$A_{11} = \Delta A_2 A_9 S_c, \quad A_{12} = G_m C_r A_2, \quad A_{13} = \frac{A_2\left(K+M\right)}{\varepsilon^2}, \quad A_{14} = A_2 S_c A_3 \left(K+M\right), \quad A_{15} = \frac{A_{10}}{A_2{}^2}$$

$$A_{16} = \frac{A_{11}}{\left(-S_c^3 + S_c^2 A_2\right)}, \quad A_{17} = \frac{A_{12}}{\left(-S_c^3 + S_c^2 A_2\right)}, \quad A_{18} = \frac{A_{13}}{A_2{}^2}, \quad A_{19} = \frac{A_{14}}{\left(-S_c^3 + S_c^2 A_2\right)}$$