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MHD FLOW OF AN OSCILLATORY MICROPOLAR ROTATING FLUID OVER A VERTICAL PLATE WITH SECOND – ORDER SLIP FLOW REGIME

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ABSTRACT This paper concerned with the study of an unsteady oscillatory flow of viscous, incompressible micropolar fluid above an infinite moving, vertical, permeable plate embedded in a porous medium in a rotating system with second-order slip flow incorporating Hall current, thermal radiation, chemical reaction and Soret effect. The leading equations are solved analytically to obtain the expressions for velocity, microrotation, temperature and concentration. The effects of various parameters involved in the movement problem are considered and portrayed by graph or table. It is perceived that the detected parameters have a noteworthy impact on the flow problem.

Keywords**: Micropolar fluid; Hall current; Chemical reaction; Second-order slip flow; Porous Medium.**

1. INTRODUCTION

Micropolar fluids are non-Newtonian fluids which comprise of arbitrarily oriented elements suspended in a viscid medium and display both translational and turning motions. Eringen [1] established the theory for micropolar fluids. Applications of micropolar fluids are found in the appraisals inscribed by Ariman et al. [2, 3]. Micropolar fluid flow with induced magnetic field has been found in many manufacturing applications such as solidifying of dual alloy, astrophysics, oceanography, geophysics and as aeration processes. Khonsari and Brewe [4] studied the possessions of viscous dissipation on the lubrication features of micropolar fluids. Bhargava and Takhar [5] analysed the behaviours of micropolar fluid numerically on thermal boundary layer near a stagnation point over moving boundaries. Kim and Lee [6] studied analytically the oscillatory flow problem of micropolar fluid on MHD flow about a vertical porous plate. Chamkha [7] considered the magneto hydrodynamic flow problems for micropolar fluids of unsteady naturally convective flow from a heated vertical porous plate incorporating with Joule heating, chemical reaction and thermal radiation. Gupta et al. [8] obtained finite element solution of an instable mixed convection flow of micropolar fluid above a porous lessening sheet.

The effect of Hall current cannot be ignored when the strength of the magnetic field is sturdy. In this context several authors (Keelson and Desseaux [9], Magdy [10], Mahmoud[11], Nadeem et al. [12], Srinivasachanya and Ramreddy [13], Omokhuale et al. [14], Oahimire and Olajuwon [15], Pal and Biswas [16], -----) analysed the consequence of Hall current with micropolar fluid.

In this study, an effort has been made to study a time dependent flow of viscous, incompressible micropolar fluid over an infinite, moving vertical plate embedded in a porous medium in a rotating system with second-order slip flow taking account of Hall current, thermal radiation, chemical reaction and Soret effect.

2. MATHEMATICAL FORMULATIONS

Consider an unsteady oscillatory flow of an incompressible, viscous, electrically conducting micropolar fluid over an infinite, moving, vertical permeable plate embedded in a porous medium in a rotating system with second order slip flow regime taking thermal reaction,

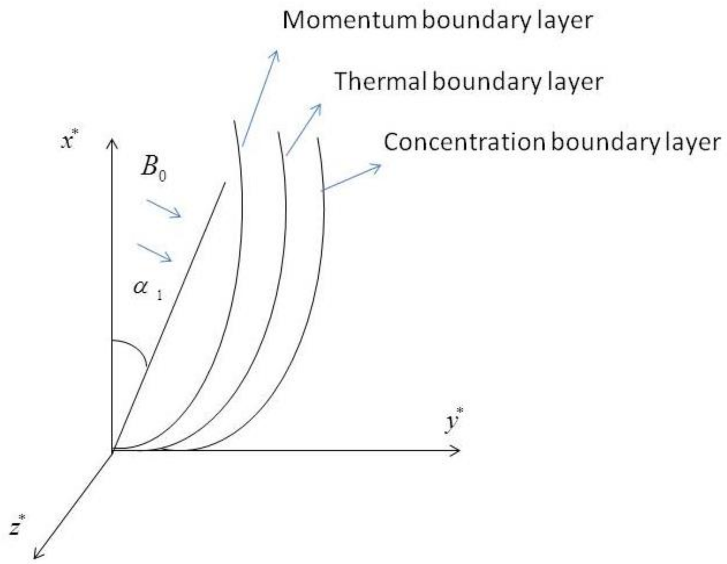

Figure 1: Physical diagram of flow configuration.

chemical reaction, Soret effect and Hall current into interpretation. The x^*-axis is selected along the upright plate, y^*-axis measured along normal to it (Fig.1). Let V_o be the suction velocity at the plate. Then the flow variables are functions of y^* and t^* only. The leading equations under the impact of transverse magnetic field (B_0) and using Wu's [17] second-order slip velocity model with Boussinesq approximations are:

$$\frac{\partial v^*}{\partial y^*} = 0, \tag{1}$$

$$\frac{\partial u^*}{\partial t^*} + v^*\frac{\partial u^*}{\partial y^*} - 2\Omega w^* = (\upsilon + \upsilon_r)\frac{\partial^2 u^*}{\partial y^{*2}} + \upsilon_r\frac{\partial N_1^*}{\partial y^*} + g\beta_T(T^* - T_\infty^*)\cos\alpha_1 - \upsilon\frac{u^*}{K^*}$$
$$+ g\beta_C(C^* - C_\infty^*)\cos\alpha_1 + \sigma\frac{B_0^2(mw^* - u^*)}{\rho(1+m^2)}, \tag{2}$$

$$\frac{\partial w^*}{\partial t^*} + v^*\frac{\partial w^*}{\partial y^*} + 2\Omega u^* = (\upsilon + \upsilon_r)\frac{\partial^2 w^*}{\partial y^{*2}} - \upsilon_r\frac{\partial N_1^*}{\partial y^*} - \sigma\frac{B_0^2(mw^* - u^*)}{\rho(1+m^2)} - \upsilon\frac{w^*}{K^*}, \tag{3}$$

$$\rho j^*\left(\frac{\partial N_1^*}{\partial t^*} + \upsilon^*\frac{\partial N_1^*}{\partial y^*}\right) = \gamma\frac{\partial^2 N_1^*}{\partial y^{*2}}, \tag{4}$$

$$\rho j^*\left(\frac{\partial N_2^*}{\partial t^*} + \upsilon^*\frac{\partial N_2^*}{\partial y^*}\right) = \gamma\frac{\partial^2 N_2^*}{\partial y^{*2}}, \tag{5}$$

$$\frac{\partial T^*}{\partial t^*} + v^*\frac{\partial T^*}{\partial y^*} = \frac{\kappa}{\rho C_p}\frac{\partial^2 T^*}{\partial y^{*2}} - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y^*} - \frac{Q^*}{\rho C_p}(T^* - T_\infty), \tag{6}$$

$$\frac{\partial C^*}{\partial t^*} + v^*\frac{\partial C^*}{\partial y^*} = D_M\frac{\partial^2 C^*}{\partial y^{*2}} - K_C(C^* - C_\infty) + \frac{D_M K_T}{T_m}\frac{\partial q_r}{\partial y^*}, \tag{7}$$

The boundary conditions are

$$u^* = u_p^* + A\frac{\partial u^*}{\partial y^*} + B\frac{\partial^2 u^*}{\partial y^{*2}}, v^* = 0, w^* = w_p^* + A\frac{\partial w^*}{\partial y^*} + B\frac{\partial^2 w^*}{\partial y^{*2}}, N_1^* = -n\frac{\partial u^*}{\partial y^*}, N_2^* = n\frac{\partial w^*}{\partial y^*},$$
$$T^* = T_\infty + (T_w - T_\infty)\exp(i^*\omega^* t^*), C^* = C_\infty + (C_w - C_\infty)\exp(i^*\omega^* t^*) \text{ at } y^* = 0;$$
$$u^* \to 0, v^* \to 0, w^* \to 0, N_1^* \to 0, N_2^* \to 0, T^* \to T_\infty, C^* \to C_\infty \text{ at } y^* \to \infty, \tag{8}$$

where u^*, v^* and w^* are components of velocity components along x^*, y^* and z^* axes respectively, N_1^* and N_2^* are microrotation components along x^* and y^* axes respectively, α_1 is inclination of the plate, ρ is density of the fluid, υ is kinematic viscosity, υ_r is kinematic microrotation viscosity , g is acceleration due to gravity, Q^* is heat absorption coefficient, A is constant, B is constant, n is a constant related to micro gyration vector and shear stress, T^* is dimensional temperature of the fluid, T_m is mean temperature, T_w and T_∞ denote temperature at the plate and temperature far away from the plate respectively .

Following the Roseland approximation, the radiative heat flux is

$$q_r = -\frac{4\sigma^*}{3K_1^*}\frac{\partial T^{*4}}{\partial y^*} \tag{9}$$

where σ^* is the Stefan-Boltzmann constant and K^* is the mean absorption co-efficient. Assuming that the differences in temperature within the flow are such that T^{*4} can be expressed as a linear combination of the temperature T^*, and neglecting the higher order terms of $(T^* - T_\infty)$, we have

$$T^{*4} = -3T_\infty^4 + 4T_\infty^3. \tag{10}$$

Introduce the following dimensionless quantities:

$$u = \frac{u^*}{V_0}, v = \frac{v^*}{V_0}, w = \frac{w^*}{V_0}, \eta = \frac{V_0 y^*}{\upsilon}, N_1 = \frac{\upsilon N_1^*}{V_0^2}, N_2 = \frac{\upsilon N_2^*}{V_0^2}, t = \frac{t^* V_0^2}{4\upsilon}, \omega = \frac{4\omega^*\upsilon}{V_0^2}, \theta = \frac{T^* - T_\infty}{T_w - T_\infty},$$

$$C = \frac{C^* - C_\infty}{C_w - C_\infty}, J = \frac{V_0^2 J^*}{\upsilon^2}, u_p = \frac{u_p^*}{V_0}, w_p = \frac{w_p^*}{V_0}. \tag{11}$$

Substituting equation (11) into equations (2)-(8) and using (1), (9), (10) yields the following non-dimensional equations:

$$\frac{1}{4}\frac{\partial u}{\partial t} - \frac{\partial u}{\partial \eta} - Rw = (1+\beta)\frac{\partial^2 u}{\partial \eta^2} + \beta\frac{\partial N_1}{\partial \eta} + Gr\theta\cos\alpha_1 + GcC\cos\alpha_1 - \frac{M}{(1+m^2)}(mw+u) - \frac{u}{K}, \tag{12}$$

$$\frac{1}{4}\frac{\partial w}{\partial t} - \frac{\partial w}{\partial \eta} + Ru = (1+\beta)\frac{\partial^2 w}{\partial \eta^2} - \beta\frac{\partial N_2}{\partial \eta} - \frac{M}{(1+m^2)}(w-mu) - \frac{w}{K}, \tag{13}$$

$$\frac{1}{4}\frac{\partial N_1}{\partial t} - \frac{\partial N_1}{\partial \eta} = L\frac{\partial^2 N_1}{\partial \eta^2}, \tag{14}$$

$$\frac{1}{4}\frac{\partial N_2}{\partial t} - \frac{\partial N_2}{\partial \eta} = L\frac{\partial^2 N_2}{\partial \eta^2}, \tag{15}$$

$$\frac{1}{4}\frac{\partial \theta}{\partial t} - \frac{\partial \theta}{\partial \eta} = \frac{1}{\Pr}(1+Nr)\frac{\partial^2 \theta}{\partial \eta^2} - \frac{Q}{\Pr}\theta, \tag{16}$$

$$\frac{1}{4}\frac{\partial C}{\partial t} - \frac{\partial C}{\partial \eta} = \frac{1}{Sc}\frac{\partial^2 C}{\partial \eta^2} - \alpha C + Sr\frac{\partial^2 \theta}{\partial \eta^2}, \tag{17}$$

The boundary conditions become

$$u = u_p + A\frac{\partial u}{\partial \eta} + B\frac{\partial^2 u}{\partial \eta^2}, v = 0, w = w_p + A\frac{\partial w}{\partial \eta} + B\frac{\partial^2 w}{\partial \eta^2}, N_1 = -n\frac{\partial u}{\partial \eta}, N_2 = n\frac{\partial w}{\partial \eta},$$

$$\theta = \exp(i\omega t), C = \exp(i\omega t) \text{ at } y = 0;$$

$$u \to 0, v \to 0, w \to 0, N_1 \to 0, N_2 \to 0, \theta \to 0, C \to 0 \text{ at } y \to \infty, \tag{18}$$

where $\beta = \frac{\upsilon_r}{\upsilon}$ is dimensionless viscosity, $Nr = \frac{16T_\infty^3\sigma^*}{3K_1^*\kappa}$ is thermal radiation parameter, $M = \frac{\sigma B_0^2\theta}{\rho V_0^2}$ is magnetic field parameter, $Gr = \frac{g\upsilon\beta_T(T_w^* - T_\infty)}{V_0^2}$ is Grashof number, $Gc = \frac{g\upsilon\beta_C(C_w^* - C_\infty)}{V_0^2}$ is modified Grashof number, $\Pr = \frac{\rho C_p\upsilon}{\kappa}$ is Prandtl number,

$Sc = \dfrac{\upsilon}{D_M}$ is Schmidt number, $Sr = \dfrac{D_M K_T (T_w^* - T_\infty)}{T_m \upsilon (C_w^* - C_\infty)}$ is Soret number, $\alpha = \dfrac{K_C \upsilon}{V_0^2}$ is chemical reaction parameter, $\alpha = \dfrac{2\Omega\upsilon}{V_0^2}$ is rotational parameter, $L = \dfrac{\upsilon V_0^2}{\rho \upsilon^3 j}$ is the material parameter, $Q = \dfrac{4\upsilon Q^*}{V_0^2}$ is heat absorption parameter, $K = \dfrac{V_0^2 K^*}{\upsilon^2}$ is permeability parameter.

The equations (12)-(17) by introducing $q = u + iw$ and $p = N_1 + iN_2$ can be written as

$$\frac{1}{4}\frac{\partial q}{\partial t} - \frac{\partial q}{\partial \eta} + iRq = (1+\beta)\frac{\partial^2 q}{\partial \eta^2} + i\beta\frac{\partial p}{\partial \eta} + Gr\theta\cos\alpha_1 + GcC\cos\alpha_1 - \frac{M}{(1+m^2)}(1-im)q - \frac{q}{K}, \tag{19}$$

$$\frac{1}{4}\frac{\partial p}{\partial t} - \frac{\partial p}{\partial \eta} = L\frac{\partial^2 p}{\partial \eta^2}, \tag{20}$$

$$\frac{1}{4}\frac{\partial \theta}{\partial t} - \frac{\partial \theta}{\partial \eta} = \frac{1}{\Pr}(1+Nr)\frac{\partial^2 \theta}{\partial \eta^2} - \frac{Q}{\Pr}\theta, \tag{21}$$

$$\frac{1}{4}\frac{\partial C}{\partial t} - \frac{\partial C}{\partial \eta} = \frac{1}{Sc}\frac{\partial^2 C}{\partial \eta^2} - \alpha C + Sr\frac{\partial^2 \theta}{\partial \eta^2}, \tag{22}$$

The boundary conditions become

$$q = q_p + A\frac{\partial q}{\partial \eta} + B\frac{\partial^2 q}{\partial \eta^2},\ p = in\frac{\partial q}{\partial \eta},\ \theta = \exp(i\omega t), C = \exp(i\omega t) \text{ at } y = 0;$$

$$q \to 0,\ p \to 0, \theta \to 0, C \to 0 \text{ at } y \to \infty. \tag{23}$$

3. METHOD OF SOLUTION

To solve the equations (19) - (22), we assume

$$q = q_0(\eta)\exp(i\omega t),\ p = p_0(\eta)\exp(i\omega t), \theta = \theta_0(\eta)\exp(i\omega t), C = C_0(\eta)\exp(i\omega t). \tag{24}$$

Using (24), the equations (19)-(22) reduces to

$$a_1 q_0'' + q_0' - a_2 q_0 = -i\beta p_0' - Gr\theta_0\cos\alpha_1 + GcC_0\cos\alpha_1, \tag{25}$$

$$Lp_0'' + p_0' - \frac{i\omega}{4}p_0 = 0, \tag{26}$$

$$a_3\theta_0'' + \theta_0' - a_4\theta_0 = 0, \tag{27}$$

$$C_0'' + ScC_0' - a_5 C + SrSc\theta_0'' = 0, \tag{28}$$

where $a_1 = 1+\beta, a_2 = \dfrac{1}{K} + i\left(R + \dfrac{\omega}{4} - \dfrac{Mm}{1+m^2}\right) + \dfrac{M}{1+m^2}, a_3 = \dfrac{1}{\Pr}(1+Nr), a_4 = \dfrac{Q}{\Pr} + \dfrac{i\omega}{4}, a_5 = \alpha + \dfrac{i\omega}{4}.$

The corresponding boundary conditions become

$$q_0 = U_p + A\frac{\partial q_0}{\partial \eta} + B\frac{\partial^2 q_0}{\partial \eta^2}, p_0 = in\frac{\partial q_0}{\partial \eta},\ \theta_0 = 1, C_0 = 1 \text{ at } y = 0;$$

$$q_0 \to 0,\ p_0 \to 0, \theta_0 \to 0, C_0 \to 0 \text{ at } y \to \infty. \tag{29}$$

The solution of the equations (25)-(28) with boundary condition (29) is obtained as

$$q = \{A_8\exp(-r_1\eta + A_9\exp(-r_2\eta) + A_{10}\exp(-r_3\eta) + A_{11}\exp(-r_4\eta)\}\exp(i\omega t), \tag{30}$$

$$p = A_1\exp(i\omega t - r_1\eta), \tag{31}$$

$$\theta = A_2\exp(i\omega t - r_2\eta), \tag{32}$$

$$C = A_2\exp(i\omega t - r_3\eta) + A_4\{\exp(i\omega t - r_2\eta) - \exp(i\omega t - r_3\eta)\}, \tag{33}$$

where

$$r_1 = \frac{1+\sqrt{1+iL\omega}}{2L}, r_2 = \frac{1+\sqrt{1+4a_3a_4}}{2a_3}, r_3 = \frac{Sc+\sqrt{Sc^2+4_5 Sc}}{2}, r_4 = \frac{1+\sqrt{1+4a_1a_2}}{2a_1}.$$

The Local skin friction co-efficient (C_f) is given by

$$C_f = \frac{\tau_w^*}{\rho V_0^2} = \{1+(1-n)L\}q'(0)$$

$$= -\{1+(1-n)L\}(r_1A_8 + r_2A_9 + r_3A_{10} + r_4A_{11})\exp(i\omega t). \quad (34)$$

The couple stress co-efficient $\overline{C}_w$ at the plate is written as $\overline{C}_w = \frac{M_w^*}{\upsilon V_0^3} = -A_1 r_1 \exp(i\omega t),$ (35)

where M_w^* is the wall couple stress.

The rate of heat transfer at the surface in terms of the Nusselt number (Nu) is given by

$$Nu\,\mathrm{Re}_x^{-1} = -\theta'(0) = r_2\exp(i\omega t), \qquad \text{where } \mathrm{Re}_x = \frac{xV_0}{V}. \quad (36)$$

The rate of mass transfer at the surface of the local Sherwood number is given by

$$Sh\,\mathrm{Re}_x^{-1} = -C'(0) = r_3A_3\exp(i\omega t) + r_2A_4\exp(i\omega t). \quad (37)$$

The constants (A_i) are not presented here for the sake of brevity.

4. RESULTS AND DISCUSSION

For numerical calculation, the values of the parameters are considered as

$$t=1, n=0.5, A=0.5, B=0.5, U_p=0.6, \omega=0.01, Nr=0.5, M=0.5, m=0.2, L=1, Gr=1,$$

$$Gc=1, n=0.5, K=0.5, R=0.3, \alpha=0.2, \beta=0.5, Sr=0.3, Sc=0.63, Q=0.5, \alpha_1=\frac{\pi}{4}.$$

Figures 2-11 represent the velocity profiles for different values of Soret number (Sr), heat absorption parameter (Q), chemical reaction parameter (α), Hall current (m), radiation parameter (Nr), permeability of the medium (K), U_p, A, B and α_1, respectively. From Figure 2, it is seen that velocity increases with an increasing values of Soret number from $Sr=0.3$ to $Sr=1.5$ through $Sr=0.9$. From Figure 3, it is observed that velocity decreases with increasing values of Q i.e., heat absorption of fluid reduces the velocity of the fluid.

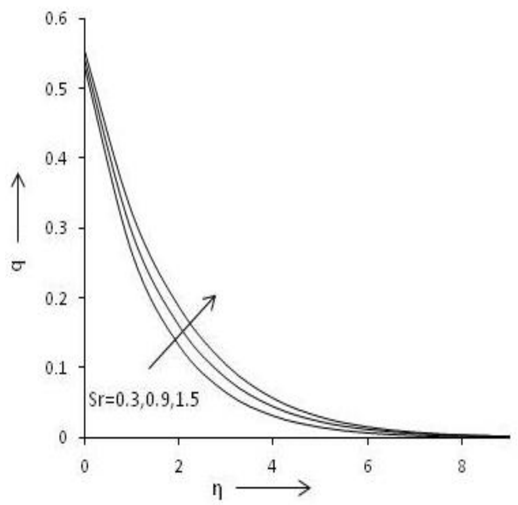

Figure 2: Variation of velocity for Sr.

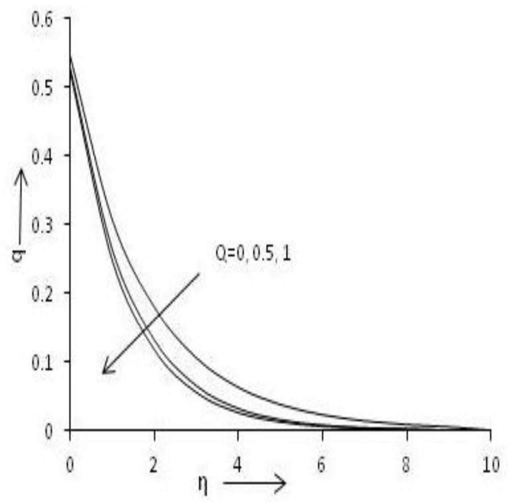

Figure 3: Variation of velocity for Q.

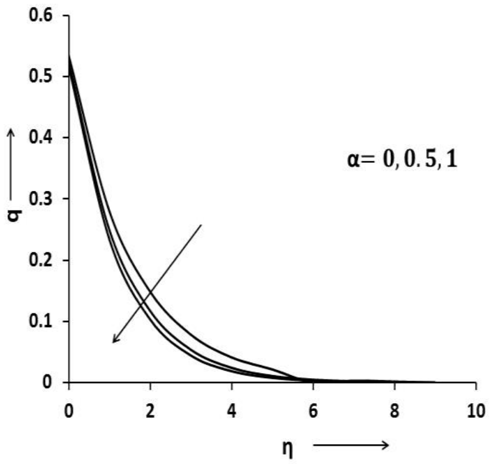

Figure 4: Variation of velocity for α.

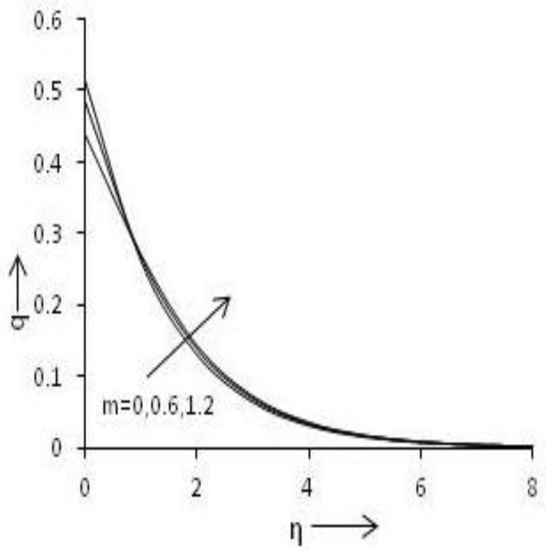

Figure 5: Variation of velocity for m.

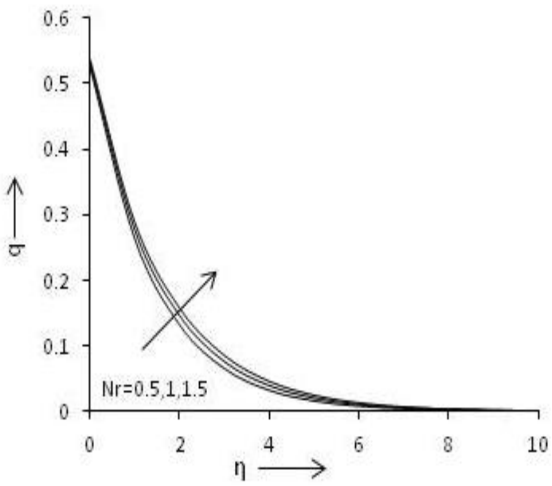

Figure 6: Variation of velocity for Nr.

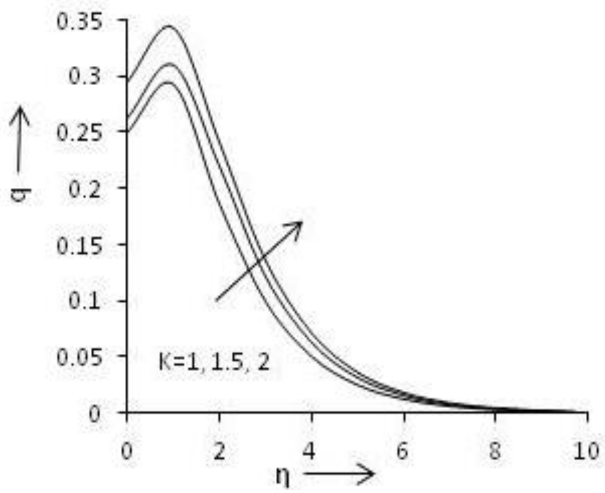

Figure 7: Variation of velocity for K.

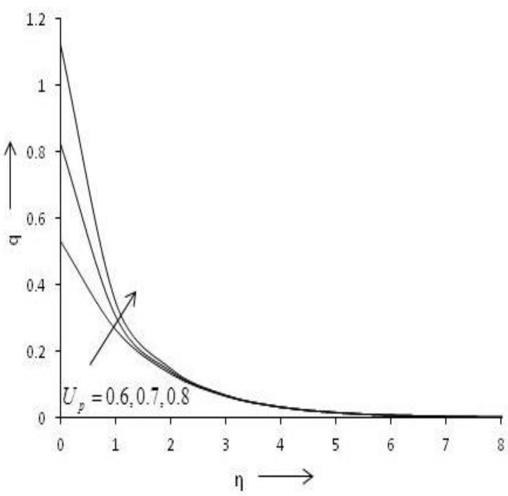

Figure 8: Variation of velocity for U_p.

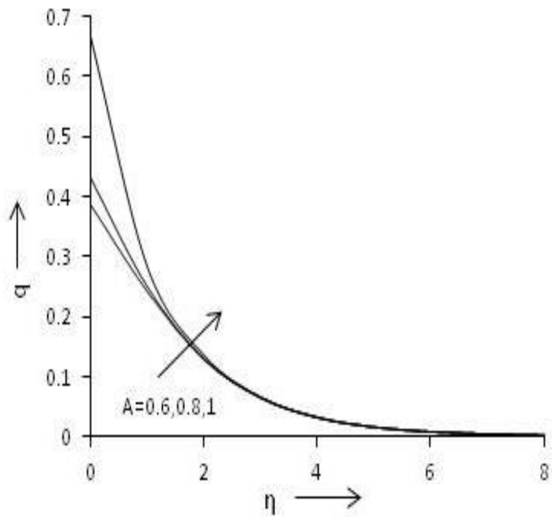

Figure 9: Variation of velocity for A.

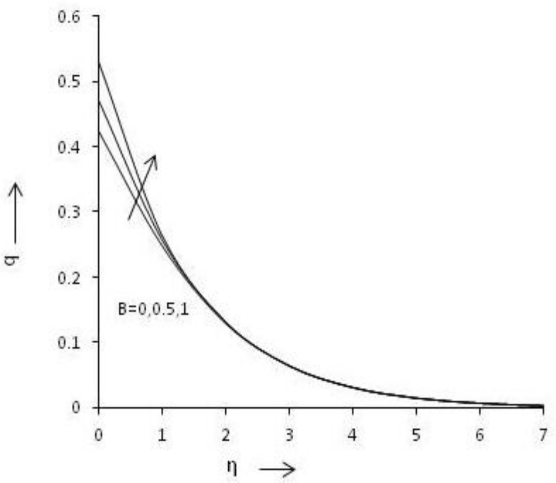

Figure 10: Variation of velocity for B.

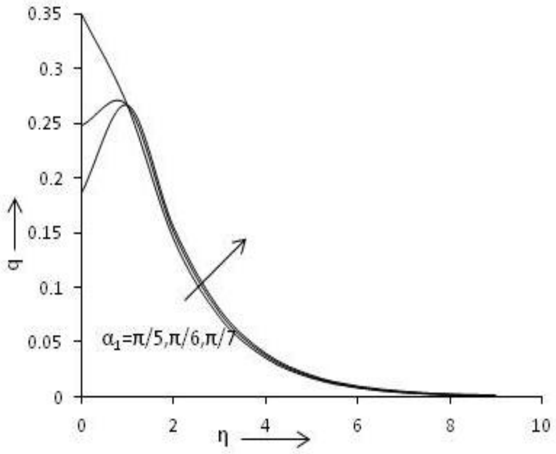

Figure 11: Variation of velocity for α_1.

Figure 4 shows that that the velocity of the fluid increases with an increase in the chemical reaction parameter from $\alpha = 0$ to $\alpha = 1$ through $\alpha = 0.5$. From Figure 5, it is seen that due to the effect of Hall current (m), the fluid velocity increases up to $\eta = 0.9$ (nearly) after that reverse effect is seen and then gradually it approaches to the value 0. Figure 6 shows that the velocity of the fluid increases with the increasing values of radiation parameter. Figure 7 shows that an increasing in K increases the fluid velocity. Figures 8-10, shows that the fluid velocity increases with an increase in U_p, A and B. Figure 11 show that an increase in α_1 increases the fluid velocity near the plate but small reverse effect is seen away from the plate and finally approaches to zero velocity.

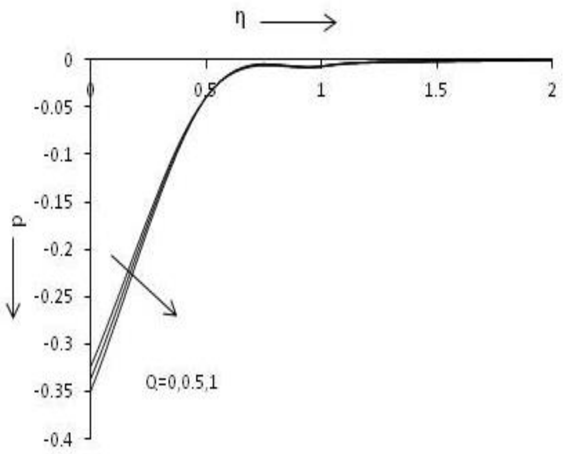

Figure 12: Variation of microrotation for Q.

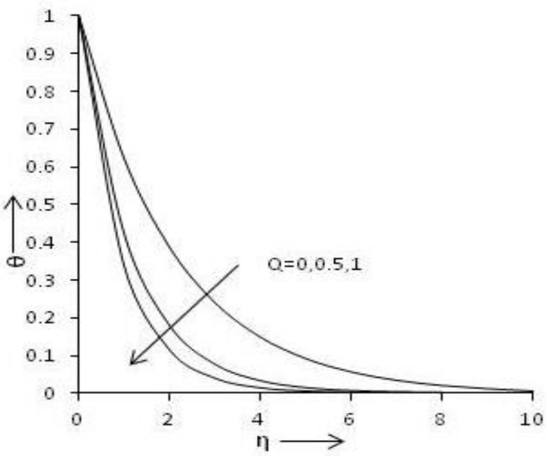

Figure 13: Variation of temperature for Q.

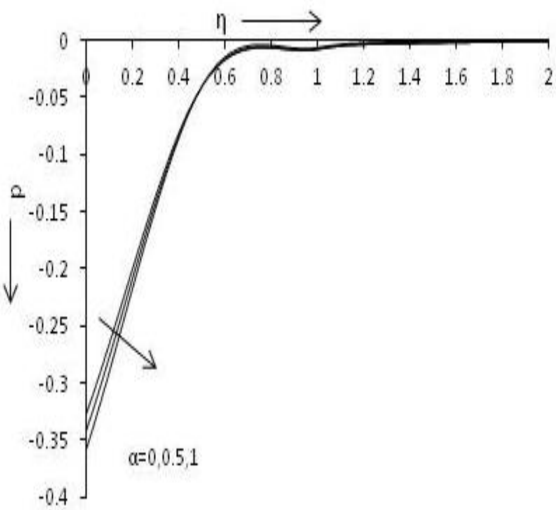

Figure 14:Variation of microrotation α.

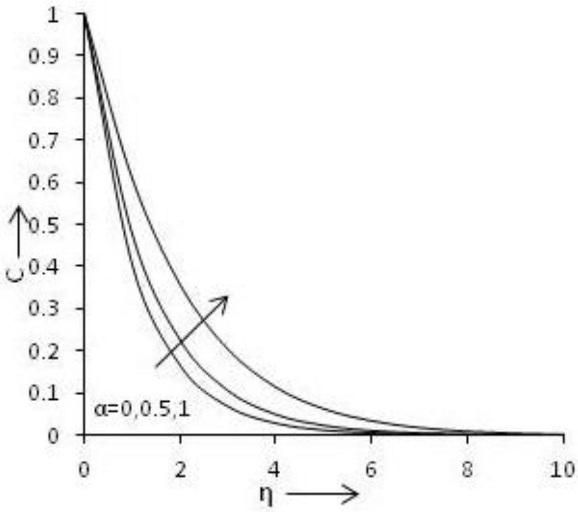

Figure 15: Variation of concentration for α.

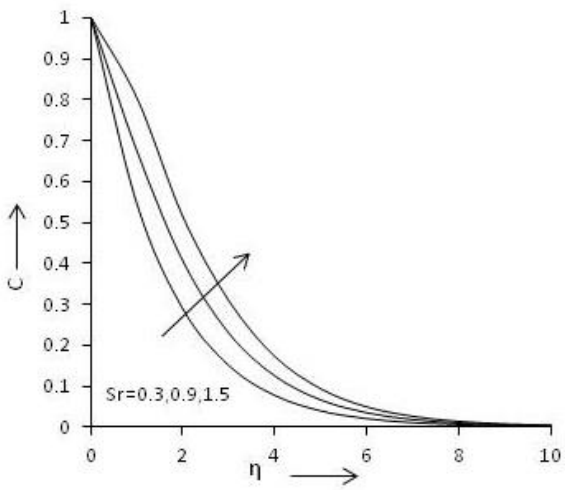

Figure 16: Variation of concentration for Sr.

Figure 12, and Figure 13, represents the effect of heat absorption parameter (Q) on micro-rotational velocity and temperature profile, respectively. It is seen that both micro-rotational velocity and thickness of the thermal boundary layer decreases with the increasing values of heat absorption parameter. Figure 14, and Figure 15, represents the effect of chemical reaction parameter (α) on micro-rotational velocity and concentration profile, respectively. It is seen that chemical reaction decreases the micro-rotational velocity whereas concentration profile increases. Figure 16 indicate that concentration increase with an increasing value of Soret number.

Table 1: Effect of Sr, Q, α on C_f and $\overline{C}_w$.

Sr	Q	α	C_f	$\overline{C}_w$
0.3	0.5	0.2	1.6312	0.0267
0.9	0.5	0.2	4.0107	0.1738
1.5	0.5	0.2	6.3903	0.3210
0.3	1.0	0.2	0.9718	-0.0250
0.3	1.5	0.2	0.8410	-0.0329
0.3	0.5	1.0	1.1358	-0.0910
0.3	0.5	1.5	0	-0.0669
0.3	0.5	2.0	-0.2490	-0.0583

Table 2: Effect of parameter $Q, Nr, \Pr, \omega$ on $Nu \operatorname{Re}_x^{-1}$.

Q	Nr	$\Pr$	ω	$Nu \operatorname{Re}_x^{-1}$
0	0.5	0.71	0.01	0.4733
0.5	0.5	0.71	0.01	0.8606
1	0.5	0.71	0.01	1.0867
0.5	1.0	0.71	0.01	0.7080
0.5	1.5	0.71	0.01	0.6112
0.5	0.5	0.025	0.01	0.5857
0.5	0.5	7.0	0.01	4.7368
0.5	0.5	0.71	0.02	0.8604
0.5	0.5	0.71	0.03	0.8602
0.5	0.5	0.71	0.04	0.8598

Table: 3: Effect of α parameter on $Sh \operatorname{Re}_x^{-1}$.

α	$Sh \operatorname{Re}_x^{-1}$
0	0.9782
0.5	1.1716
1	1.2955

The numerical results for skin friction co-efficient, couple stress co-efficients, Nusselt number and Sherwood number are shown in the tables 1-3, respectively.

Table 1 show that the local skin friction coefficient (C_f) and couple stress coefficient $(\overline{C}_w)$ increases with an increasing values of Sr whereas they are decreases with an increase in Q. Also, the values of C_f decreases with an increase in chemical reaction parameter, but reverse effect is seen for $\overline{C}_w$.

Table 2 shows the effect of the parameters $Q, N_r, \Pr, \omega$ on Nusselt Number.

From Table 2 it is observed that the values of Nusselt number increases with the increasing values of Q and $\Pr$ whereas reverse effect is seen for Nr and ω.

Table 3 show the effect of chemical reaction parameter on Sherwood number. It is seen that Sherwood number increase with an increase in α.

5. CONCLUSIONS

The following conclusions can be drawn from the above study

(i) An increase in Soret number increases the fluid velocity, local skin friction coefficient and couple stress coefficient.

(ii) Fluid velocity increases with an increase in radiation parameter, chemical reaction parameter and permeability of the porous medium.

(iii) Fluid velocity decreases due to Heat absorption of fluid.

(iv) An increasing value of heat absorption parameter decreases the micro-rotational velocity and thickness of the thermal boundary layer.

(v) An increase in chemical reaction parameter decreases the micro-rotational velocity, but increases concentration profile.

(vi) Skin friction coefficient and couple stress coefficient increases with an increasing values of Soret number, but they decrease with an increase in heat absorption parameter. Also, with an increase in chemical reaction parameter the value of Skin friction coefficient decrease, but reverse effect is seen for couple stress coefficient.

(vii) Nusselt number increases with an increasing values of heat absorption parameter and $\Pr$ whereas it decreases for Nr and ω.

(viii) Sherwood number increase with an increase in chemical reaction parameter.

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