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Mixed Convective MHD Micro-Polar Fluid Flow in a Porous Medium with Radiation Absorption

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Abstract
An unsteady mixed convective flow of micro-polar fluid in a porous medium has been considered in presence of transverse magnetic field, Dufour effects and radiation. Effects of radiation absorption and heat source/sink are taken into account. The Buoyancy force leads to free convection and oscillatory free stream velocity is responsible for forced convection. Partial differential equations governed by conservation principles of mass, momentum and energy are solved analytically using perturbation scheme. Effects of various parameters on the governing fluid motion are shown graphically and numerically in tabular form.

Keywords- Micro-polar fluid, Dufour effect, Radiation, Shear stress, Couple shear stress.

1. Introduction

Generalization of classical fluid dynamics considering non symmetric stresses leads to the theory of micro-polar fluid (fluids with micro-rotations). Major equations of motion of micro-polar fluids are guided by conservation principles of linear momentum, angular momentum and constitutive equation (Eringen, 1964; 1966; 1972). Applications of micro-polar fluid are observed in polymeric fluids, liquid crystal, lubricants etc. Due to its extensive application in science and engineering, it has drawn the attentions various scientists and researchers (Modather et al., 2009; Hsiao, 2010; Rani and Tomar, 2010; Haque et al., 2012; Babu et al., 2013; Reddy et al., 2014; Gupta et al., 2014; Pal and Biswas, 2016) to study the micro-polar fluid flows.

Again, mechanics of combined heat and mass transfer under the influence of magnetic field with or without chemical reaction occurs in various engineering and industrial purposes. Simultaneous heat and mass transfer effects (Seddeek et al., 2007; Ibrahim et al., 2008; Pal and Talukdar, 2010; Rout et al., 2014; Acharya et al., 2014, Singh et al., 2018; Ahuja and Gupta, 2019) on fluid flow problems have been studied.

The objective this study is to come across the influences of radiation absorption, radiation and slip parameter on micro-polar fluid flow through a porous medium under the influence of Lorentz force and constant suction.

2. Mathematical Formulations

A time dependent flow problem of micro-polar fluid guided by free and forced convection with Lorentz force through porous medium has been studied with radiation absorption and chemical reaction consequences. The surface of the medium is characterized by an infinite vertical porous plate in slip flow regime. The lesser electrical conductivity reduces the strength of induced magnetic field, so to stabilize the system; transverse magnetic field may be applied. Application of transverse magnetic field generates Lorentz force and its mathematical form under usual notation is $\sigma B_0^2 u'$. Using equation of state and Boussinesq approximation, the pressure gradient term is replaced by $g\beta(T'-T_\infty)+g\beta^*(C'-C_\infty)+\left(\sigma B_0^2+\frac{\nu+\nu_r}{k}\right)U$. Effects of radiation, heat source/sink and diffusion thermo have been taken into consideration in the energy equation. First order chemical reaction has been taken in the species continuity equation. The geometry of the problem is given by Figure 1. With these assumptions, the governing equations of motion are given as follows

$$\frac{\partial v'}{\partial y'}=0 \Rightarrow v'=-V_0 \tag{1}$$

where, negative sign indicates that suction is towards the plate and V_0 is magnitude of suction velocity at the surface

$$\frac{\partial u'}{\partial t'}+v'\frac{\partial u'}{\partial y'}=(\nu+\nu_r)\frac{\partial^2 u'}{\partial y'^2}+2\nu_r\frac{\partial \omega'}{\partial y'}+g\beta(T'-T_\infty)+g\beta^*(C'-C_\infty)-\left(\frac{\sigma B_0^2}{\rho}+\frac{\nu+\nu_r}{k}\right)(u'-U) \tag{2}$$

$$\frac{\partial \omega'}{\partial t'}+v'\frac{\partial \omega'}{\partial y'}=\gamma\frac{\partial^2 \omega'}{\partial y'^2} \tag{3}$$

$$\frac{\partial T'}{\partial t'}+v'\frac{\partial T'}{\partial y'}=\alpha\frac{\partial^2 T'}{\partial y'^2}-\frac{1}{\rho C_p}\frac{\partial q_r'}{\partial y'}+\frac{D_m K_T}{C_s C_p}\frac{\partial^2 C'}{\partial y'^2}-\frac{Q}{\rho C_p}(T'-T_\infty)+\frac{Q_1'}{\rho C_p}(C'-C_\infty) \tag{4}$$

$$\frac{\partial C'}{\partial t'}+v'\frac{\partial C'}{\partial y'}=D\frac{\partial^2 C'}{\partial y'^2}-Kr'(C'-C_\infty) \tag{5}$$

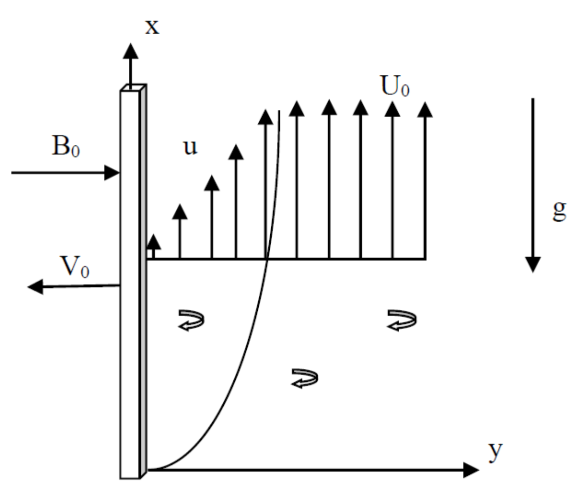

Figure 1. Physical description of the problem

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The boundary conditions of the problem are

$$\left.\begin{array}{l} y'=0: u'=L'\dfrac{\partial u'}{\partial y'}, \omega'=-n_1\dfrac{\partial u'}{\partial y'}, T'=T_w, C'=C_w \\ u'\to U=U_0(1+\varepsilon e^{in't'}), \omega'\to 0, T'\to T_\infty, C'\to C_\infty \end{array}\right\} \tag{6}$$

Following Cogley et al. (1968), the heat fluctuation due to radiation is given by

$$\frac{\partial q'_r}{\partial y'}=-16\frac{T'^3_\infty \sigma'}{3k'}\frac{\partial^2 T'}{\partial y'^2} \tag{7}$$

where, u' velocity of fluid particle; ω' micro-rotation components of fluid particles; T' temperature of fluid; C' concentration of fluid; T_w & C_w fluid temperature and concentration at the surface respectively; T_∞ & C_∞ fluid temperature and concentration at free stream region; ε amplitude of oscillation; ρ density of fluid; g acceleration due to gravity; β, β* co-efficients of volume expansions; σ electrical conductivity; B_0 strength of magnetic field; α thermal diffusivity; D molecular diffusivity; Kr' first order chemical reaction; Q' external heat agent; Q_1' radiation absorption parameter; C_p specific heat at constant pressure; j' micro-inertia density; σ' Stefan-Boltzman constant; k' mean absorption coefficient; D_m coefficient of mass diffusivity; K_T thermal conductivity; ν, ν_r kinematic and kinematic micro-rotation viscosity; γ spin gradient viscosity; k permeability of porous medium.

3. Method of Solution

We introduce dimensionless variables to make equations (2) - (5) dimensionless and these are given as follows

$$y=\frac{V_0 y'}{\nu}, t=\frac{t'V_0^2}{\nu}, u=\frac{u'}{U_0}, \omega=\frac{\nu\omega'}{U_0 V_0}, \theta=\frac{T'-T_\infty}{T_w-T_\infty}, \phi=\frac{C'-C_\infty}{C_w-C_\infty}, n=\frac{\nu n'}{V_0^2}, j=\frac{V_0^2 j'}{\nu^2},$$

where, u, ω, y, t, n, θ, ϕ, j are dimensionless velocity, micro-rotation component, displacement variable, time, frequency of oscillation, temperature, concentration and micro-inertia density respectively.

The equations of motion in dimensionless forms are:

$$\frac{\partial u}{\partial t}-\frac{\partial u}{\partial y}=(1+b)\frac{\partial^2 u}{\partial y^2}+2b\frac{\partial \omega}{\partial y}+Gr\theta+Gm\phi-M(u-1-\varepsilon e^{\text{int}})-\frac{1+b}{K_p}(u-1-\varepsilon e^{\text{int}}) \tag{8}$$

$$\frac{\partial \omega}{\partial t}-\frac{\partial \omega}{\partial y}=\frac{1}{\eta}\frac{\partial^2 \omega}{\partial y^2} \tag{9}$$

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$$\frac{\partial\theta}{\partial t}-\frac{\partial\theta}{\partial y}=\frac{(1+Nr)}{\Pr}\frac{\partial^2\theta}{\partial y^2}+Du\frac{\partial^2\phi}{\partial y^2}-\frac{Q}{\Pr}\theta+Q_1\phi \tag{10}$$

$$\frac{\partial\phi}{\partial t}-\frac{\partial\phi}{\partial y}=\frac{1}{Sc}\frac{\partial^2\phi}{\partial y^2}-Kr\phi \tag{11}$$

where, $M=\frac{\sigma B_0^2\nu}{\rho V_0^2}$: Hartmann number; $b=\frac{\nu_r}{\nu}$: ratio of viscosities; $Gr=\frac{g\beta(T_w-T_\infty)\nu}{U_0V_0^2}$: Grashoff number of heat transfer; $Gm=\frac{g\beta^*(C_w-C_\infty)}{U_0V_0^2}$: Grashoff number for mass transfer; $K_p=\frac{kV_0^2}{\nu^2}$: dimensionless permeability; $\eta=\frac{\rho\nu^3 j}{\gamma V_0^2}$: dimensionless micro-rotation density; $Nr=\frac{16T_\infty^3\sigma'}{3kk'}$: raditation parameter; $\Pr=\frac{\nu}{\alpha}$: Prandtl number; $Du=\frac{DmK_T(C_w-C_\infty)}{\nu C_s C_p(T_w-T_\infty)}$: Dufour number; $Q=\frac{Q'\nu^2}{V_0^2K_T}$: external heat agent; $Kr=\frac{Kr'\nu}{V_0^2}$: dimensionless chemical reaction parameter; $Q_1=\frac{Q_1'(C_w-C_\infty)\nu}{(T_w-T_\infty)}$: dimensionless radiation absorption co-efficient.

Relevant boundary conditions are:

$$\left.\begin{aligned} y=0: u=h\frac{\partial u}{\partial y}, \omega=-n_1\frac{\partial u}{\partial y}, \theta=\phi=1 \\ y\to\infty: u=1+\varepsilon e^{\mathrm{int}}, \omega=\theta=\phi\to 0 \end{aligned}\right\},$$

where, h is the dimensionless slip parameter and n_1 relates to angular velocity and velocity gradient at the surface. The coupled differential equations are solved analytically using perturbation scheme; the velocity, micro-rotation, temperature and concentration in the neighbourhood of the surface are assumed as follows

$$\left.\begin{aligned} u=u_0+\varepsilon e^{\mathrm{int}}u_1+o(\varepsilon^2), \omega=\omega_0+\varepsilon e^{\mathrm{int}}\omega_1+o(\varepsilon^2) \\ \theta=\theta_0+\varepsilon e^{\mathrm{int}}\theta_1+o(\varepsilon^2), \phi=\phi_0+\varepsilon e^{\mathrm{int}}\phi_1+o(\varepsilon^2) \end{aligned}\right\} \tag{12}$$

where, $\varepsilon \ll 1$ is perturbation parameter and it characterizes the amplitude of variation of periodical free stream velocity. Smaller values of ε indicate the system as laminar otherwise the flow becomes turbulent.

Using (12) in (8) - (11), equating the like powers of ε, we get the following set of ordinary differential equations:

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$$-u_0' = (1+b)u_0'' + 2b\omega_0' + Gr\theta_0 + Gm\phi_0 - M\left(u_0 - 1\right) - \frac{1+b}{K_p}(u_0 - 1) \tag{13}$$

$$inu_1 - u_1' = (1+b)u_1'' + 2b\omega_1' + Gr\theta_1 + Gm\phi_1 - M\left(u_1 - 1\right) - \frac{1+b}{K_p}(u_1 - 1) \tag{14}$$

$$\omega_0'' + \eta\omega_0' = 0 \tag{15}$$

$$\omega_1'' + \eta\omega_1' - i\eta^2\omega_1 = 0 \tag{16}$$

$$-\theta_0' = \frac{1+Nr}{\Pr}\theta_0'' + Du\phi_0'' - \frac{Q}{\Pr}\theta_0 + Q_1\phi_0 \tag{17}$$

$$i\eta\theta_1 - \theta_1' = \frac{1+Nr}{\Pr}\theta_1'' + Du\phi_1'' - \frac{Q}{\Pr}\theta_1 + Q_1\phi_1$$

(18)

$$-\phi_0' = \frac{1}{Sc}\phi_0'' - Kr\phi_0 \tag{19}$$

$$i\eta\phi_1 - \phi_1' = \frac{1}{Sc}\phi_1'' - Kr\phi_1 \tag{20}$$

Solutions of the equations are

$$\omega_0 = C_1 + C_2 e^{-\eta y}, \omega_1 = C_3 e^{-\alpha_1 y} + C_4 e^{\alpha_2 y}, \phi_0 = C_5 e^{-\alpha_3 y} + C_6 e^{\alpha_4 y}, \phi_1 = C_7 e^{-\alpha_5 y} + C_6 e^{\alpha_6 y}$$

$$\theta_0 = C_9 e^{-\alpha_9 y} + A_1 e^{-\alpha_3 y}, u_0 = C_{13} e^{-\alpha_{11} y} + A_3 e^{-ny} - A_4 e^{-\alpha_7 y} - A_5 e^{-\alpha_3 y} + 1,$$

$$\theta_1 = C_{11} e^{-\alpha_9 y} + A_2 e^{-\alpha_5 y}, u_1 = C_{15} e^{-\alpha_{13} y} + A_6 e^{-\alpha_1 y} - A_7 e^{-\alpha_9 y} - A_8 e^{-\alpha_5 y} + 1,$$

and the constants of the solutions are not presented here for the sake of brevity.

4. Results and Discussions

Wall shear stress is given by

$$\sigma = \frac{\tau_w}{\rho U_0 V_0} = A_9 + \varepsilon A_{10}\cos(nt) + i\varepsilon\sin(nt)$$

(21)

The wall couple stress is given by

$$C_s = \frac{M_w}{\frac{\gamma U_0 V_0^2}{\nu^2}} = C_2\eta - \varepsilon C_3\alpha_1\left[\cos(nt) + i\varepsilon\sin(nt)\right] \tag{22}$$

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The rate of heat transfer (Nusselt number) is given by

$$Nu\,\mathrm{Re}^{-1} = -\theta'(0) = C_9\alpha_7 + A_1\alpha_3 + \left(C_4\alpha_9 + A_2\alpha_5\right)\left[\cos(nt) + i\sin(nt)\right] \tag{23}$$

The rate of mass transfer (Sherwood number) is given by

$$Sh\,\mathrm{Re}^{-1} = -\phi'(0) = C_5\alpha_3 + C_7\alpha_5\left[\cos(nt) + i\sin(nt)\right] \tag{24}$$

The objective of the paper is to find out the effects of flow parameters on oscillatory micro-polar fluid flow past a vertical plate with heat and mass transfer from analytical results. Numerical values are computed using MATLAB software. In this problem, values of some physical parameters are kept fixed as Pr = 5; M = 2; S = 2; e = 0.001; Kp = 0.3; Gr = 5; Gm = 0.3. Prandtl number (Pr) characterizes ratio of viscosity to thermal diffusivity and its value nearly '4' or '5' is generally for various refrigerants. Further, Hartmann number (M) characterizes the combined influence of magnetic viscosity and ordinary viscosity. Again, Schmidt number (S) signifies the ratio momentum diffusion to molecular diffusion, Kp; reflects the nature of permeability of the porous medium, Gr and Gm are free convection parameters for heat and mass transfers due to buoyancy force. Positive values of Gr and Gm signify that temperature and concentration of fluid at the surface is higher than their free stream values.

Figures 2 to 6 represent the velocity and angular velocity profiles against the displacement variable y. In the discussion, 'b = 0' (ratio of viscosities) characterizes the flow of Newtonian fluid and 'b > 0' characterizes the flow of micro-polar fluid. The Figure 2 reveals that the fluid flow reaches its free stream velocity at the region y > 2, thus the effect of friction is prominent at the region y < 2. Further, it is also seen that velocity starts from a minimum non-zero value (due to slip) at the surface and then it increases to reach a maximum value and finally it tends to free stream value. Also, we can conclude that there is an acceleration with increasing values of b. Figure 3 notifies that there is a reduction in micro-rotation of fluid with increasing values of 'b'.

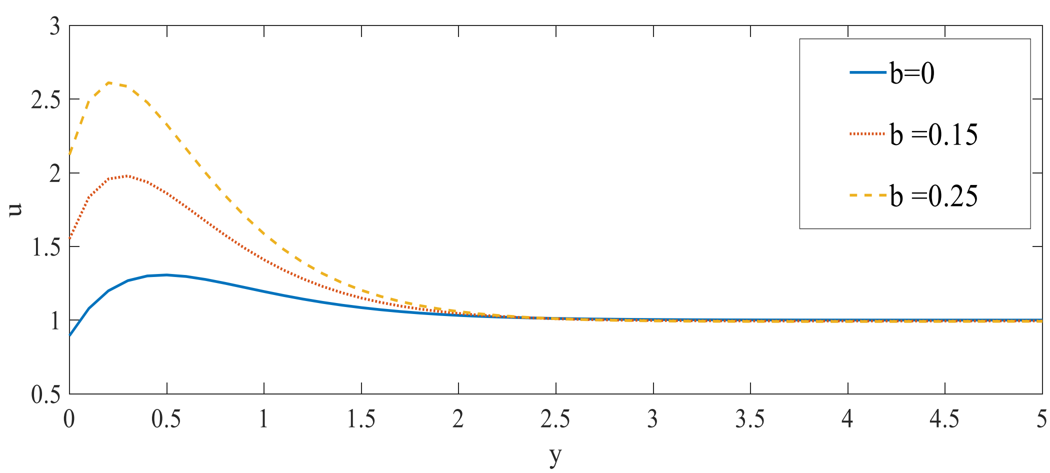

Figure 2. Velocity profile against displacement variable y for Nr=0.1, Pr=5, M=2, Sc=2, Kr=0.5, Du=0.5, Q=0.2, Q1=0.3, e=0.001, eta(η) =0.2, n=0.1, Kp=0.3, Gr=5, n_1=0.2, h=0.4, Gm=0.3 at t=0.5

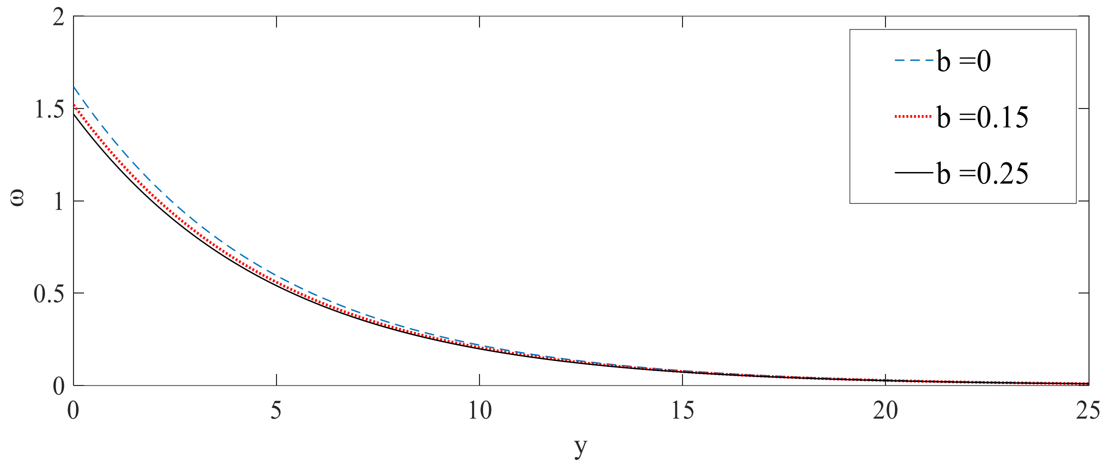

Figure 3. Angular velocity profile against displacement variable y for Nr=0.1, Pr=5, M=2, Sc=2, Kr=0.5, Du=0.5, Q=0.2, Q_1=0.3, e=0.001, eta(η) =0.2, n=0.1, Kp=0.3, Gr=5, n_1=0.2, h=0.4, Gm=0.3 at t=0.5

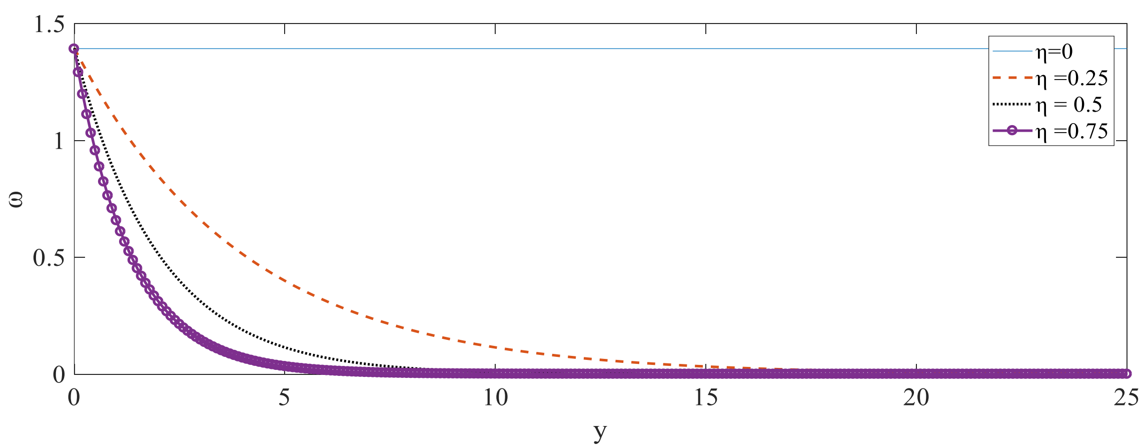

Figure 4. Angular velocity profile against displacement variable y for Nr=0.1, Pr=5, b=0.5, M=2, Sc=2, Kr=0.5, Du=0.5, Q=0.2, Q_1=0.3, e=0.001, n=0.1, Kp=0.3, Gr=5, n_1=0.2, h=0.4, Gm=0.3 at t=0.5

Parameter eta (η) symbolizes micro-inertia per unit mass and its zero (η = 0) value indicates that there is no change in micro-rotation (Figure 4) and gradually it experiences a deceleartion with the increase of η. Again, the parameter which connects micro-rotation with shear stress at the surface is given by n1. Its zero values reflects that there is no rotation at the surface. The Figure 5 states that the parameter has a positive impact on the micro-rotation velocity.

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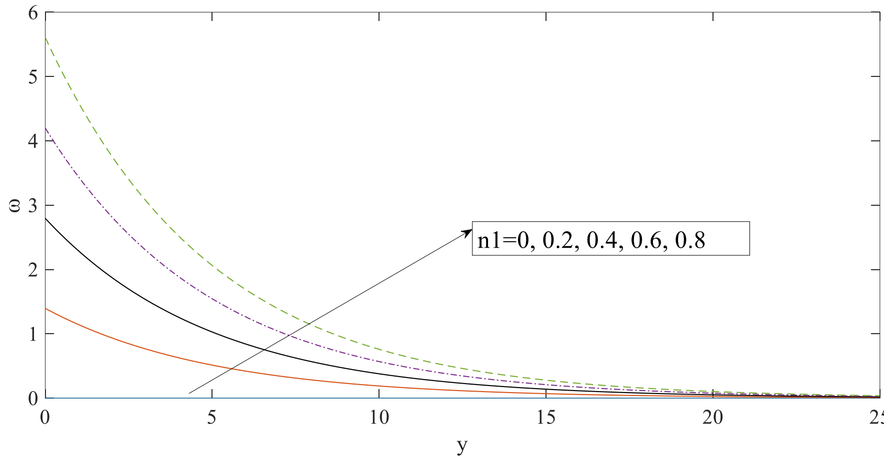

Figure 5. Angular Velocity profile against displacement variable y for Nr=0.1, Pr=5, M=2, b=0.5, Sc=2, Kr=0.5, Du=0.5, Q=0.2, Q1=0.3, e=0.001, (η) =0.2, n=0.1, Kp=0.3, Gr=5, h=0.4, Gm=0.3 at t=0.5

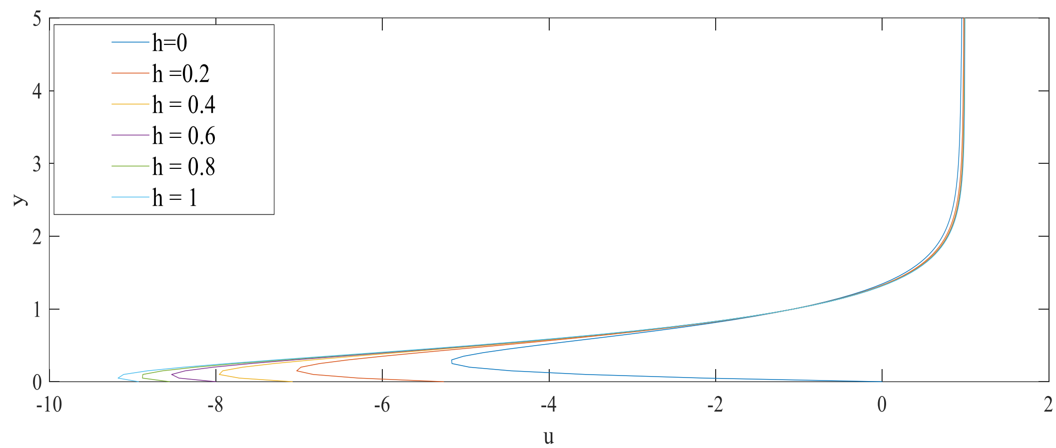

Figure 6. Velocity profile against displacement variable y for Nr=0.1, Pr=5, M=2, b=0.5, Sc=2, Kr=0.5, Du=0.5, Q=0.2, Q1=0.3, e=0.001, eta(η) =0.2, n=0.1, Kp=0.3, Gr=5, n_1=0.2, Gm=0.3 at t=0.5

The parameter (h) symbolizes the slip parameter and its zero value indicates that there is no slip and this physical situation is noticed in figure 6. It is noticed that the fluid experiences a back flow in the vicinity of the surface due to the presence of slip. Increasing values of h increases the speed of motion but it experiences a back flow.

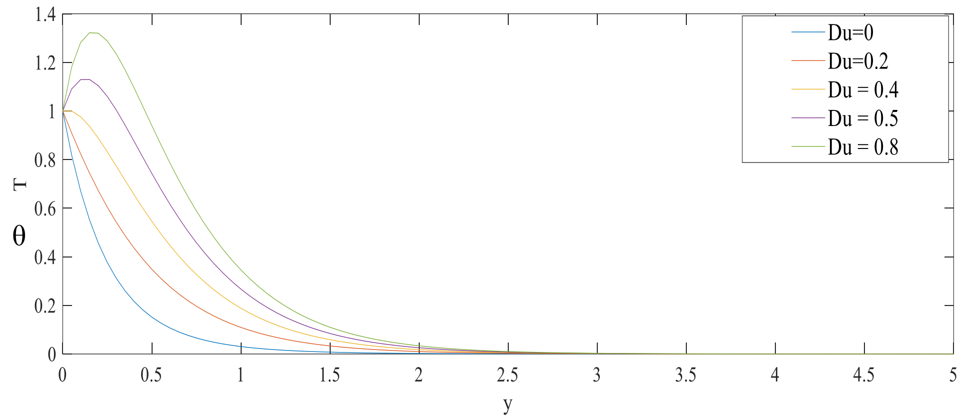

Figure 7. Temperature profile against displacement variable y for Nr=0.1, Pr=5, M=2, b=0.5, Sc=2, Kr=0.5, Q=0.2, Q1=0.3, e=0.001, eta(η) =0.2, n=0.1, Kp=0.3, Gr=5, n_1=0.2, h=0.4, Gm=0.3 at t=0.5

Temperature profiles against the displacement variable are shown by figure 7 and 8 with a special emphasis is given on Dufour number (Du) and radiaion absorption (Q_1). It is seen that fluid reaches its thermal equilibrium at the region $y \geq 2.5$. Further, Dufour number signifies the energy flux due to concentration gradient and it is noticed that there is a significant growth in temperature during the enhancement of Dufour number. Figure 8 reveals that the radiation absorption parameter has a positive impact on the temperature.

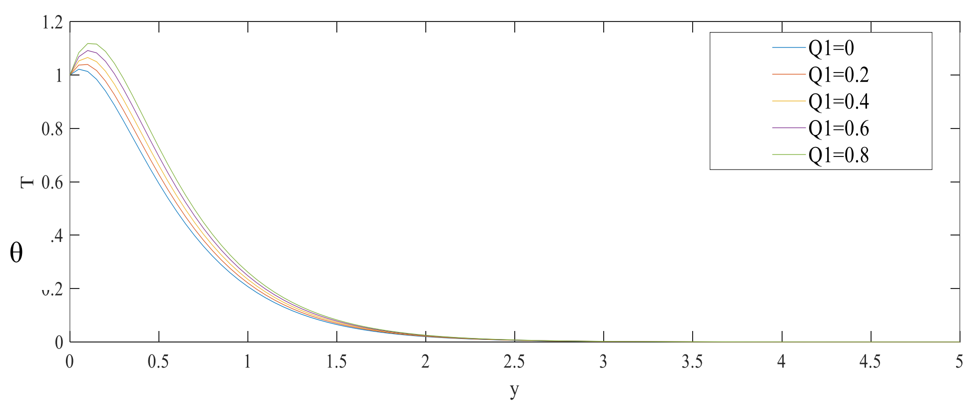

Figure 8: Temperature profile against displacement variable y for Nr=0.1, Pr=5, M=2, b=0.5, Sc=2, Kr=0.5, Du=0.5, Q=0.2, e=0.001, eta(η) =0.2, n=0.1, Kp=0.3, Gr=5, n_1=0.2, h=0.4, Gm=0.3 at t=0.5

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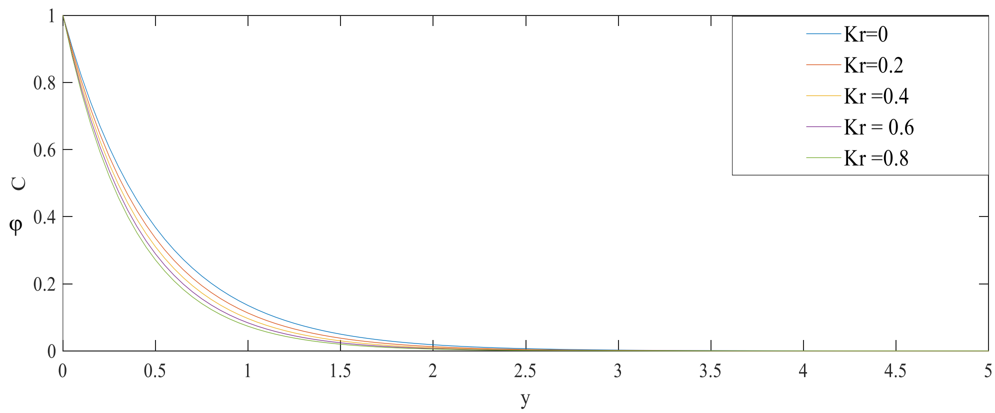

Figure 9: Concentration profile against displacement variable y for Nr=0.1, Pr=5, M=2, b=0.5, Sc=2, Du=0.5, Q=0.2, Q1=0.3, e=0.001, eta(η) =0.2, n=0.1, Kp=0.3, Gr=5, n_1=0.2, h=0.4, Gm=0.3 at t=0.5

Influence of chemical reaction parameter (Kr) on the concentration of fluid flow is shown by Figure 9. It is observed that concentration is higher in the neighbourhood of the surface. Further, it is seen that the concentration is reduced with the increase of chemical reaction parameter.

Viscous drag or shear stress at the surface is exhibited through the parameter Sh and influences of various parameters on Sh are given by Table 1. We should frame the model in such a way that there should be lesser wear and tear at the surface and for that, shear stress must be lesser. The table states that the factors responsible for increasing shearing stress are slip parameter (h), radiation absorption (Q_1), ratio of viscosity (b) and Dufour number (Du). The parameters help to reduce the shear stress are Nr (radiation parameter), external heat agent (Q).

Table 1 also shows the magnitude of couple shear stress at the surface for various flow parameters involved in the problem. Couple shear stress is reduced by the increment of slip parameter, external heat agent and ratio of viscosity but reverse pattern is experienced during the growth of radiation parameter, radiation absorption and Dufour number. Nusselt number and Sherwood number characterize rate of heat and mass transfers at the surface of the fluid flow. Our intention is to find out the mechanism for controlling rate of heat and mass transfers at the surface. From the above table, it is seen that at any given time t, there is an increment in rate of heat transfer during growth of radiation absorption parameter and chemical reaction parameter with fixed values of Prandtl number and radiation parameter. Radiation parameter and Du (Dufour number) also boost the rate of heat transfer.

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Table 1. Shear stress, couple shear stress, rate of heat transfer and rate of mass transfer for Pr=5, M=2, Sc=2, e=0.001, eta (η)=0.2, n=0.1, Kp=0.3, Gr=5, n_1=0.2, Gm=0.3 at t=0.5

H	Q_1	b	Du	Nr	Q	Kr	σ	Cs	$\theta'(0)$	$\phi'(0)$
0	0.2	1	0.4	0.1	0.2	0.5	92.1563	0.5624		
0.2							96.5012	0.2911		
0.4							98.0002	0.1974		
0.6							98.7596	0.1500		
0.8							99.2184	0.1214		
0.4	0	1	0.4	0.1	0.2	0.5	87.8588	0.2615	0.8131	
	0.2						93.6208	0.2812	1.1835	
	0.4						99.3829	0.3009	1.5538	
	0.6						105.1449	0.3206	1.9242	
	0.8						116.6689	0.3403	2.2946	
0.4	0.2	0	0.4	0.1	0.2	0.5	16.4899	0.3832		
		0.2					24.6192	0.3640		
		0.4					42.5727	0.3473		
		0.6					104.6206	0.3323		
		0.8					645.2982	0.3187		
0.4	0.2	1	0	0.1	0.2	0.5	12.5433	0.0040	4.0295	
			0.2				46.1267	0.1188	1.8703	
			0.4				79.7101	0.2337	0.2890	
			0.6				113.2935	0.3485	2.4483	
			0.8				146.8769	0.4633	4.6076	
0.4	0.2	1	0.4	0	0.2	0.5	107.4731	0.3242	2.9836	
				0.2			106.6264	0.3307	1.2702	
				0.4			105.3948	0.3397	0.0463	
				0.6			103.3605	0.3540	0.8716	
				0.8			99.1972	0.3826	0.5856	
0.4	0.2	1	0.4	0.1	-0.5	0.5	108.9068	0.3352	1.8762	
					0		99.7374	0.3025	1.5061	
					0.5		92.0371	0.2753	1.1724	
0.4	0.2	1	0.4	0.1	0.2	0			0.5404	2.0000
						0.2			0.9016	2.1832
						0.4			1.2207	2.3416
						0.6			1.5103	2.4832
						0.8			1.7775	2.6125

There is a significant growth in Sherwood number during the enhancement of chemical reaction. It may be interpreted that the rate of mass accumulation is accelerated with the increment in chemical reaction parameter.

5. Conclusions

In the work (Reddy et al., 2014), oscillatory flow problem is characterized by only buoyancy driven convection, but in this paper, an attempt has been made to find out the combined effects of free (buoyancy driven) and forced (non-zero free stream velocity) convections. Results are computed using series expansion, known as perturbation technique for smaller values of ε (amplitude of oscillations). From the above study, following points are concluded:

- Friction plays a dominant role in the region $y < 2$.
- Presence of slip at the surface creates an area of adverse pressure gradient (region of back flow).
- Concentration of fluid flow declines with chemical reaction.
- Slip parameter, radiation absorption and Dufour number increase the viscous drag or shear stress at the surface.

Conflict of Interests

The author does not have any conflict of interest regarding the publication of paper.

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