ORIGINAL PAPER

HEAT ANNIHILATION AND VISCOUS DISSIPATION EFFECTS OVER THERMAL AND MASS DIFFUSION IN MHD MIXED CONVECTION FLOW OF MICROPOLAR FLUID IN PRESENCE OF CHEMICAL REACTION

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Abstract. *This article analyze the chemically reacting free convection MHD micropolar flow, heat and mass transfer past an infinite vertical plate with heat annihilation and viscous dissipation. The non-linear coupled partial differential equations are solved by using multi parameter perturbation technique. The results for transverse velocity, angular velocity and temperature are obtained and effects of various parameters on these functions are presented graphically. The numerical discussion with physical interpretations of various parameters also presented.*

Keywords: *Heat sink, Magnetic field, micropolar fluid, mixed convection, chemical reaction, viscous dissipation.*

1. INTRODUCTION

Flows arising from temperature difference have great significance not only for their own but also for the applications to the geophysics and engineering. There are many interesting aspects of such flows, so analytical solutions of such problem are presented by many authors. Gebhart and Pera [1], Sparrow et al. [2], Soundalgekar [3], Acharya et al. [4], Singh and Chand [5] are some of them.

A reactor, in which chemical transformations take place, has to carry out several functions like bringing reactants into intimate contact, providing an appropriate environment (temperature and concentration fields) for adequate time and allowing for removal of products. Fluid dynamics play a pivotal role in establishing the relationship between reactor hardware and reactor performance. For a specific chemical catalyst, the reactor performance is a complex function of the underlying transport processes. The first step in any reaction engineering analysis is formulating a mathematical framework to describe the rate (and mechanisms) by which one chemical species are converted into another in the absence of any transport limitations (chemical kinetics). Once the intrinsic kinetics are available, the production rate and composition of the products can be related, in principle, to reactor volume, reactor configuration and mode of operation by solving mass, momentum and energy balances over the reactor. This is the central task of a reaction and reactor engineering activity. Analysis of the transport processes and their interaction with chemical reactions can be quite difficult and is intimately connected to the underlying fluid dynamics. Such a combined analysis of chemical and physical processes constitutes the core of chemical

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reaction engineering. Recent advances in understanding the physics of flows and computational flow modeling (CFM) can make tremendous contributions in chemical engineering.

Combined heat and mass transfer problems with chemical reaction are of importance in many processes and have, therefore, received a considerable amount of attention in recent years. In processes such as drying, evaporation at the surface of a water body, energy transfer in a wet cooling tower and the flow in a desert cooler, heat and mass transfer occur simultaneously. Natural convection processes involving the combined mechanisms are also encountered in many natural processes, such as evaporation, condensation and agricultural drying, and in many industrial applications, such as the curing of plastics, cleaning and chemical processing of materials relevant to the manufacture of printed circuitry, manufacture of pulp-insulated cables, etc. Diffusion rates can be altered tremendously by chemical reactions. The Effect of a chemical reaction depends whether the reaction is homogeneous or heterogeneous. This depends on whether they occur in an interface or as a single phase volume reaction. In a well-mixed system, the reaction is heterogeneous if the reactants are in multiple phase, and homogeneous if the reactants are in the same phase. In most cases of chemical reactions, the reaction rate depends on the concentration of the species itself. Cooling towers are the cheapest way to cool large quantities of water. For example, the formation of smog is a first-order homogeneous chemical reaction. Consider the emission of NO_2 from automobiles and other smoke stacks. This NO_2 reacts chemically in the atmosphere with unburned hydrocarbons (aided by sunlight) and produces peroxyacetylnitrate, which forms an envelope termed as the photochemical smog. Kandasamy et al. [6] studied thermophoresis and variable viscosity effects on MHD mixed convective heat and mass transfer past a porous wedge in the presence of chemical reaction. Kandasamy and Devi [7] studied the effects of chemical reaction, heat and mass transfer on non-linear laminar boundary-layer flow over a wedge with suction or injection.

Recently, considerable attention has also been focused on new applications of magneto-hydrodynamics (MHD) and heat transfer in for example metallurgical processing. Melt refining involves magnetic field application to control excessive heat transfer rates. Both laminar and turbulent flows are of interest. Many studies in MHD thermo-convection flows have been conducted. For e.g. Chamkha [8] studied the free convection boundary-layer flow over an isothermal plate in the presence of a non-uniform transverse magnetic field. Recently Asghar et. al. [9] investigated the MHD flow due to non-coaxial rotations of a porous disk, moving with uniform acceleration in its own plane and a second grade fluid at infinity.

Equally important is the study of heat generation or absorption in moving fluids for problems involving chemical reactions and those concerned with dissociating fluids. Specifically, the effects of heat generation may alter the temperature distribution, consequently affecting the particle deposition rate in nuclear reactors, electronic chips, and semiconductor wafers. In fact, the literature is replete with examples of heat transfer in the laminar flow of viscous fluids. Problem of radiative heat transfer with hydromagnetic flow and viscous dissipation over a stretching surface in the presence of variable heat flux is solved analytically by Kumar [10]. The problem of heat transfer in MHD boundary-layer flow through a porous medium, due to a non-isothermal stretching sheet, with suction, radiation, and heat annihilation is considered by Kumar [11]. The object of the paper is to study the steady mixed convection flow of a laminar, incompressible MHD micropolar fluid, thermal and mass diffusion in porous medium with the effects of radiation and ohmic heating in the presence of chemical reaction.

2. MATHEMATICAL ANALYSIS

Consider the mixed convection flow of an incompressible and electrically conducting viscous thermo-micropolar fluid past an infinite porous vertical plate. A magnetic field (B_0) of uniform strength is applied transversely to the direction of the flow that is y-axis and the induced magnetic field is neglected. Taking the x-axis along the vertical porous plate in upward direction and y axis normal to it. Since the length of the plate is large and fluid flow extends to infinity, therefore all physical variables are independent of x and hence the functions of y only, the governing equations of continuity, momentum, concentration, angular velocity and energy for the flow in the presence of radiation, chemical reaction and viscous dissipation are:

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

$$v^* = -V_0 \text{ (constant)} \tag{2}$$

$$\frac{dp^*}{\partial y^*} = 0 \Rightarrow p^* \text{ is independent of } y^* \tag{3}$$

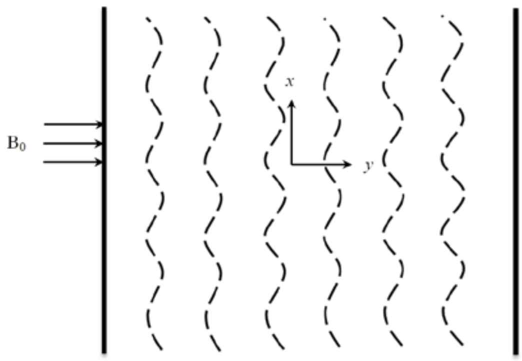

Fig. 1. Physical Model and Coordinate System.

$$\rho v^* \frac{\partial u^*}{\partial y^*} = (\kappa + \mu)\frac{\partial^2 u^*}{\partial y^{*2}} + \rho g \beta_T \left(T^* - T_\infty\right) + \rho g \beta_c \left(C^* - C_\infty\right) + \kappa \frac{\partial \omega^*}{\partial y^*} - \sigma B_0^2 u^* \tag{4}$$

$$\rho j \left(v^* \frac{\partial \omega^*}{\partial y^*} \right) = \gamma \frac{\partial^2 \omega^*}{\partial y^{*2}} - 2\kappa \omega^* \tag{5}$$

$$\rho c_p v^* \frac{\partial T^*}{\partial y^*} = k \frac{\partial^2 T^*}{\partial y^{*2}} + \mu \left(\frac{\partial u^*}{\partial y^*} \right)^2 + \frac{Q}{\rho c_p}\left(T_\infty - T^*\right) \tag{6}$$

$$v^* \frac{\partial C^*}{\partial y^*} = D \frac{\partial^2 C^*}{\partial y^{*2}} - k_l \left(C^* - C_\infty^*\right) \tag{7}$$

With the boundary conditions:

$$u^* = V_0,\ \frac{\partial\omega^*}{\partial y^*} = -\frac{\partial^2 u^*}{\partial y^{*2}},\ T^* = T_w,\ -D\frac{\partial C^*}{\partial y^*} = m_w \ at\ y = 0$$
$$u^* \to 0,\ \omega^* \to 0,\ T^* \to T_\infty,\ C^* \to C_\infty,\ as\ \ y \to \infty \tag{8}$$

here, $V_0 > 0$, $\gamma = \left(\mu + \frac{\kappa}{2}\right) j = \mu\left(1 + \frac{a}{2}\right) j$ and $j = \frac{\vartheta^2}{V_0^2}$

In order to write the governing equations and the boundary conditions in dimensionless form, the following non-dimensional quantities are introduced

$$y = \frac{V_0\, y^*}{\vartheta},\ u = \frac{u^*}{V_0},\ M = \frac{\sigma B_0^2 \vartheta}{\rho V_0^2},\ \Pr = \frac{\mu c_p}{k},\ \theta = \frac{T^* - T_\infty}{T_w - T_\infty},\ C = \frac{C^* - C_\infty}{m_w \vartheta / V_0 D},\ \beta = \frac{Q\vartheta}{\rho c_p V_0^2}$$

$$Ec = \frac{V_0^2}{c_p (T_w - T_\infty)},\ G_r = \frac{g\beta_T\ \vartheta (T_w - T_\infty)}{V_0^3},\ G_c = \frac{g\beta_c\ m_w \vartheta^2}{V_0^4 D},\ \omega = \frac{\vartheta\, \omega^*}{V_0^2},\ Sc = \frac{\vartheta}{D},$$

$$K_c = \frac{\vartheta K_l}{v_w^2},\ \ a = \frac{\kappa}{\mu}.$$

The equations (4)-(7) changes to

$$(1 + a)\frac{d^2u}{dy^2} + \frac{du}{dy} - M\,u + a\frac{d\omega}{dy} + G_r\,\theta + G_c\,C = 0 \tag{9}$$

$$\left(1 + \frac{a}{2}\right)\frac{d^2\omega}{dy^2} + \frac{d\omega}{dy} - 2a\omega = 0 \tag{10}$$

$$\frac{d^2\theta}{dy^2} + \Pr\frac{d\theta}{dy} - \beta\Pr\theta + \Pr Ec\left(\frac{du}{dy}\right)^2 = 0 \tag{11}$$

$$\frac{d^2C}{dy^2} + Sc\frac{dC}{dy} - K_c\ Sc\ C = 0 \tag{12}$$

Boundary conditions changes to:

$$at\ \ y = 0,\ \ u = 1,\ \ \theta = 1,\ \ \frac{d\omega}{dy} = -\frac{d^2u}{dy^2},\ \ \frac{dC}{dy} = -1$$

$$as\ \ y \to \infty,\ \ u \to 0,\ \ \theta \to 0,\ \ \omega \to 0,\ \ C \to 0 \tag{13}$$

Solution of the equation (12) is

$$C = b_1\, e^{-b_2 y} \tag{14}$$

In order to solve the equations (9) to (11), for boundary conditions (13) we expand u, ω and θ in powers of the Eckert number *Ec* which is very small (*Ec*<< 1) for incompressible fluids.

$$\begin{aligned} u &= u_0 + Ec\, u_1 + 0\left(Ec^2\right), \\ \omega &= \omega_0 + Ec\, \omega_1 + 0\left(Ec^2\right), \\ \theta &= \theta_0 + Ec\, \theta_1 + 0\left(Ec^2\right). \end{aligned} \tag{15}$$

Thus on using the above series expansions in equations (9) to (11) and equating the coefficient of like powers of *Ec* to zero, the zeroth order and first order equations are solved to give

$$\omega_0 = b_3\, e^{-b_4 y} \tag{16}$$

$$\theta_0 = e^{-b_5 y} \tag{17}$$

$$u_0 = b_7\, e^{-b_6 y} + b_3\, b_8\, e^{-b_4 y} - b_9\, e^{-b_5 y} - b_{10}\, e^{-b_2 y} \tag{18}$$

$$\begin{aligned} \theta_1 &= d_2\, e^{-b_5 y} + d_3\, e^{-2b_6 y} + d_4\, e^{-2b_4 y} + d_5\, e^{-2b_5 y} + d_6\, e^{-2b_2 y} + d_7\, e^{-(b_4+b_6) y} \\ &+ d_8\, e^{-(b_5+b_6) y} + + d_{12}\, e^{-(b_2+b_5) y} d_9\, e^{-(b_2+b_6) y} + d_{10}\, e^{-(b_4+b_5) y} + d_{11}\, e^{-(b_2+b_4) y} \end{aligned} \tag{19}$$

$$\omega_1 = f_1\, e^{-b_4 y} \tag{20}$$

$$\begin{aligned} u_1 &= f_2\, e^{-b_6 y} + b_8\, f_1\, e^{-b_4 y} + f_3\, e^{-b_5 y}\; f_8\, e^{-(b_4+b_6) y} + f_4\, e^{-2b_6 y} + f_5\, e^{-2b_4 y} \\ &+ f_6\, e^{-2b_5 y} + f_7\, e^{-2b_2 y} + f_{12}\, e^{-(b_2+b_4) y} + f_9\, e^{-(b_5+b_6) y} + f_{10}\, e^{-(b_2+b_6) y} + f_{11}\, e^{-(b_4+b_5) y} \\ &+ f_{13}\, e^{-(b_2+b_5) y} \end{aligned} \tag{21}$$

Where the constants are given as follows:

$$b_1 = \frac{2}{Sc + \sqrt{Sc^2 + 4Kc\, Sc}},\; b_2 = \frac{1}{b_1},\; b_4 = \frac{1+\sqrt{1+8\,a+4\,a^2}}{2+a},\; b_5 = \frac{\Pr + \sqrt{\Pr^2 + 4\,\beta\,\Pr}}{2},$$

$$b_6 = \frac{1+\sqrt{1+4M(1+a)}}{2(1+a)},\; b_8 = \frac{a\, b_4}{(1+a)b_4^2 - b_4 - M},\; b_9 = \frac{G_r}{(1+a)b_5^2 - b_5 - M},$$

$$b_{10} = \frac{G_c\, b_1}{(1+a)b_2^2 - b_2 - M},\; b_3 = \frac{b_6^2(1+b_9+b_{10}) - b_9\, b_5^2 - b_{10}\, b_2^2}{b_4 + b_8(b_6^2 - b_4^2)},\; b_7 = 1 - b_3 b_8 + b_9 + b_{10},$$

$$d_3 = \frac{-\Pr b_7^2 b_6^2}{4b_6^2 - 2\Pr b_6 - \beta \Pr},\ d_4 = \frac{-\Pr b_3^2 b_8^2 b_4^2}{4b_4^2 - 2\Pr b_4 - \beta \Pr},\ d_5 = \frac{-\Pr b_9^2 b_5^2}{4b_5^2 - 2\Pr b_5 - \beta \Pr},$$

$$d_6 = \frac{-\Pr b_{10}^2 b_2^2}{4b_2^2 - 2\Pr b_2 - \beta \Pr},\ d_7 = \frac{-2\Pr b_3 b_7 b_8 b_4 b_6}{(b_4 + b_6)^2 - \Pr (b_4 + b_6) - \beta \Pr},$$

$$d_8 = \frac{2\Pr b_7 b_9 b_5 b_6}{(b_5 + b_6)^2 - \Pr (b_5 + b_6) - \beta \Pr},\ d_9 = \frac{2\Pr b_7 b_{10} b_2 b_6}{(b_2 + b_6)^2 - \Pr (b_2 + b_6) - \beta \Pr},$$

$$d_{10} = \frac{2\Pr b_3 b_8 b_9 b_4 b_5}{(b_4 + b_5)^2 - \Pr (b_4 + b_5) - \beta \Pr},\ d_{11} = \frac{2\Pr b_3 b_8 b_{10} b_2 b_4}{(b_2 + b_4)^2 - \Pr (b_2 + b_4) - \beta \Pr},$$

$$d_{12} = \frac{2\Pr b_9 b_{10} b_2 b_5}{(b_2 + b_5)^2 - \Pr (b_2 + b_5) - \beta \Pr},\ d_2 = -d_3 - d_4 - d_5 - d_6 - d_7 - d_8 - d_9 - d_{10} - d_{11} - d_{12},$$

$$f_3 = \frac{-G_r d_2}{(1+a)\, d_1^2 - d_1 - M},\ f_4 = \frac{-G_r d_3}{4(1+a)\, b_6^2 - 2b_6 - M},\ f_5 = \frac{-G_r d_4}{4(1+a)\, b_4^2 - 2b_4 - M}$$

$$f_6 = \frac{-G_r d_5}{4(1+a)\, b_5^2 - 2b_5 - M},\ f_7 = \frac{-G_r d_6}{4(1+a)\, b_2^2 - 2b_2 - M},\ f_8 = \frac{-G_r d_7}{(1+a)\,(b_4 + b_6)^2 - b_4 - b_6 - M},$$

$$f_9 = \frac{-G_r d_8}{(1+a)\,(b_5 + b_6)^2 - b_5 - b_6 - M},\ f_{10} = \frac{-G_r d_9}{(1+a)\,(b_2 + b_6)^2 - b_2 - b_6 - M},$$

$$f_{11} = \frac{-G_r d_{10}}{(1+a)\,(b_4 + b_5)^2 - b_4 - b_5 - M},\ f_{12} = \frac{-G_r d_{11}}{(1+a)\,(b_2 + b_4)^2 - b_2 - b_4 - M},$$

$$f_{13} = \frac{-G_r d_{12}}{(1+a)\,(b_2 + b_5)^2 - b_2 - b_5 - M},$$

$$f_1 = \frac{\left[\begin{array}{l} f_3\left(b_5^2 - b_6^2\right) + 3 f_4 b_6^2 + f_5\left(4b_4^2 - b_6^2\right) \\ + f_6\left(4b_5^2 - b_6^2\right) + f_7\left(4b_2^2 - b_6^2\right) + f_8\left(b_4 + 2b_4 b_6\right) \\ + f_9\left(b_5^2 + 2b_5 b_6\right) + f_{10}\left(b_2^2 + 2b_2 b_6\right) \\ + f_{11}\left(b_4^2 + b_5^2 - b_6^2 + 2b_4 b_5\right) \\ + f_{12}\left(b_2^2 + b_4^2 - b_6^2 + 2b_2 b_4\right) \\ + f_{13}\left(b_2^2 + b_5^2 - b_6^2 + 2b_2 b_5\right) \end{array}\right]}{\left(b_4 + b_8 b_6^2 - b_8 b_4^2\right)}$$

3. NUMERICAL DISCUSSIONS

In order to understand the physical solution, the numerical values of concentration, transverse velocity, angular velocity and temperature are presented in figs 2-11.

Different variations in chemical reaction parameter are plotted for transverse velocity in Fig.2. It is seen that an increase in K_c leads to decrease u. It is considered here, to be a homogeneous first-order chemical reaction.

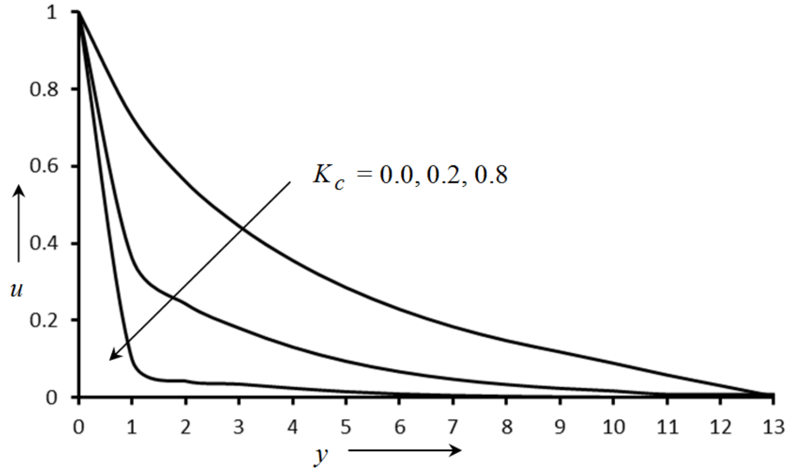

Fig. 2. The dimensionless velocity verses various values of K_c when *Sc*=0.22, *a*=0.3, Pr=2.0, β =3.0, *M*=2.5, G_r =1.0, G_c =0.5 and *Ec*=0.01.

The diffusing species either can be destroyed or generated in the homogeneous reaction. The chemical reaction parameter can be adjusted to meet these circumstances if one takes $K_c > 0$ for a destructive reaction, $K_c < 0$ for a generative reaction and $K_c = 0$ for no reaction. The destructive chemical reaction is taken into account here. In mixed convection regime, the velocity of the fluid decrease with increase of destructive reaction.

Fig. 3 represent the effect of material parameter on transverse velocity. An increase in the material parameter leads to decrease u.

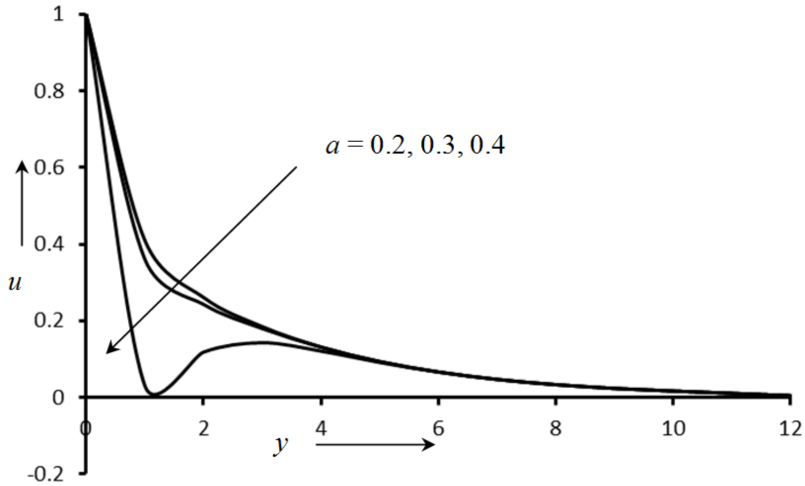

Fig. 3. The dimensionless velocity verses various values of *a* when *Sc*=0.22, K_c =0.2, Pr=2.0, β =3.0, *M*=2.5, G_r =1.0, G_c =0.5 and *Ec*=0.01.

Increase in a implies that spin gradient viscosity supersedes the vortex viscosity in value, as a increase it enhances the micro-rotation and the spin gradient viscosity is boosted and micro elements rotates faster hence the velocity rises.

Figs. 4 and 5 are drawn for the effects of G_r on transverse velocity and angular velocity.

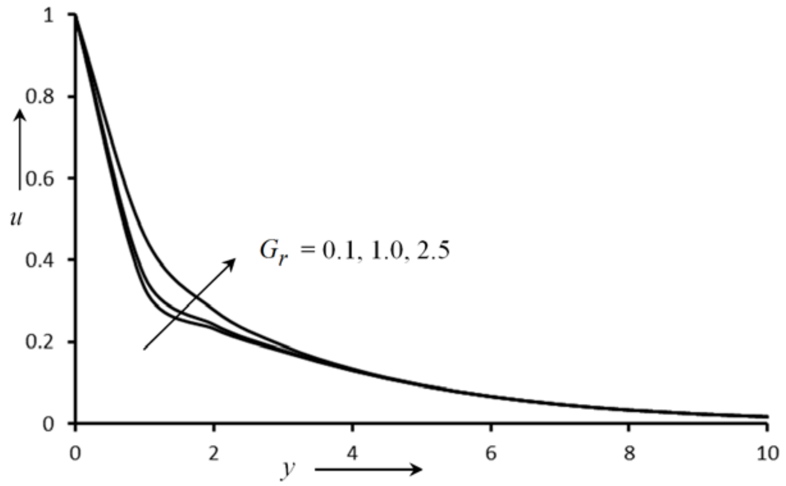

Fig. 4. The dimensionless velocity verses various values of G_r when *Sc*=0.22, K_C=0.2, *a*=0.3, Pr=2.0, β=3.0, *M*=2.5, G_C=0.5 and *Ec*=0.01.

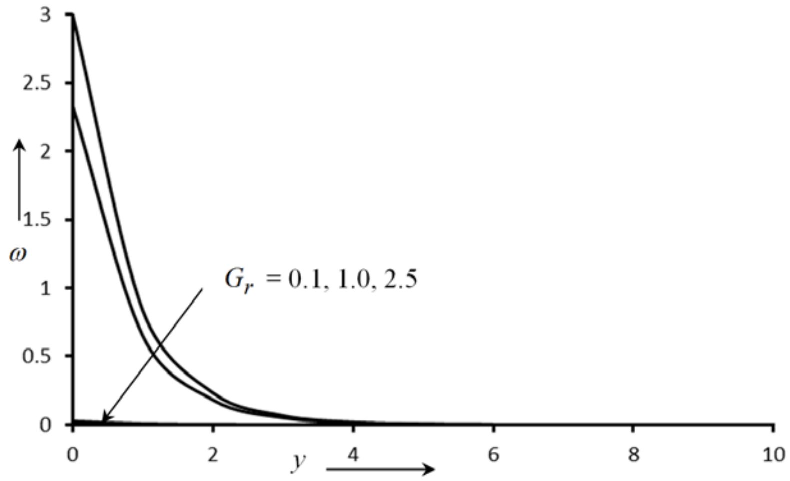

Fig. 5. The dimensionless angular velocity verses various values of G_r when *Sc*=0.22, K_C=0.2, *a*=0.3, Pr=2.0, β=3.0, *M*=2.5, G_C=0.5 and *Ec*=0.01.

The thermal Grashof number signifies the relative effect of the thermal buoyancy force to the viscous hydrodynamic force in the boundary layer. As expected, it is observed that there is a rise in the velocity due to the enhancement of thermal buoyancy force. Also, it is observed that with an increase of G_r, ω decreases, which show that excessive buoyancy, decrease the spin and that reduces the angular velocity.

Effects of G_c on the transverse and angular velocity are shown in the Figs. 6 and 7.

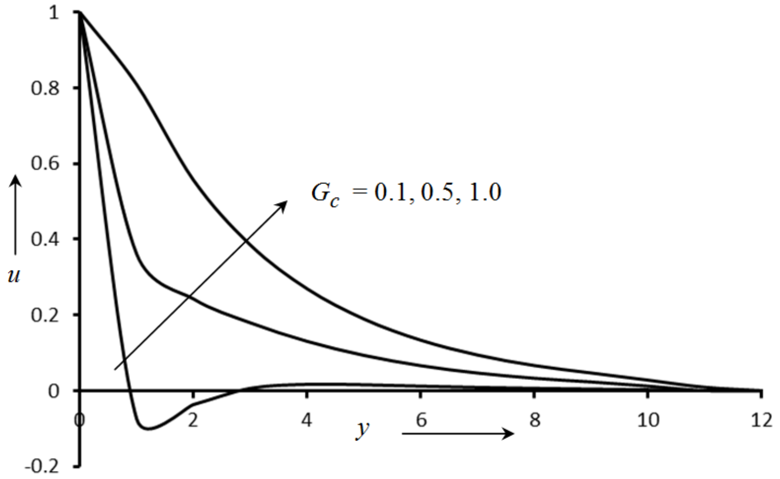

Fig. 6. The dimensionless velocity verses various values of G_c when *Sc*=0.22, K_c =0.2, *a*=0.3, Pr=2.0, β =3.0, *M*=2.5, G_r =1.0 and *Ec*=0.01.

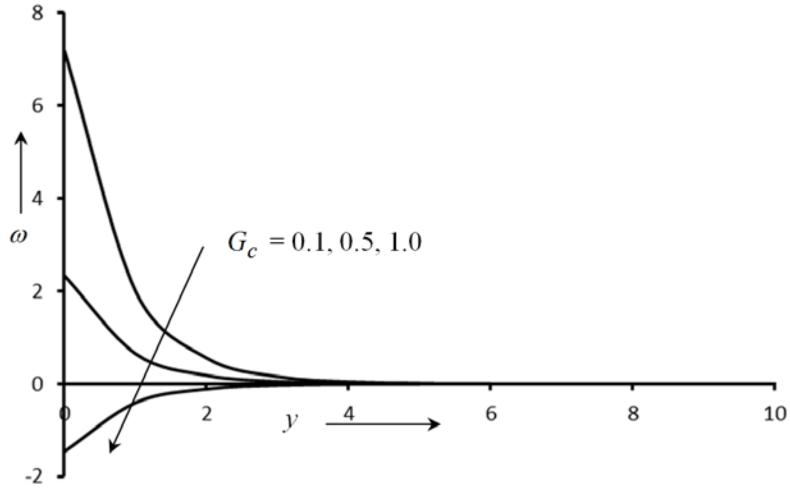

Fig. 7. The dimensionless angular velocity verses various values of G_c when *Sc*=0.22, K_c =0.2, *a*=0.3, Pr=2.0, β =3.0, *M*=2.5, G_r =1.0 and *Ec*=0.01.

The solutal Grashof number G_c defines the ratio of the species buoyancy force to the viscous hydrodynamic force. It is noticed that the velocity increases with increasing values of the solutal Grashof number, and the peak value is more distinctive due to increase in the species buoyancy force. The velocity distribution attains a distinctive maximum value in the vicinity of the plate and then decreases to approach the free stream value. The angular velocity decreases as G_c increases, also profile of ω depicting that for larger values of G_c the micro-rotation is negative, which implies that higher species buoyancy force promotes reverse spin near the wall.

Figs. 8 and 9 are drawn for the effects of Ec on transverse velocity and angular velocity. Increase in Ec reduces u, whereas Ec increases with ω. Increasing rotational velocity, the shear stress due to viscosity of the fluid creates more and more dissipation, hence the transverse velocity decreased.

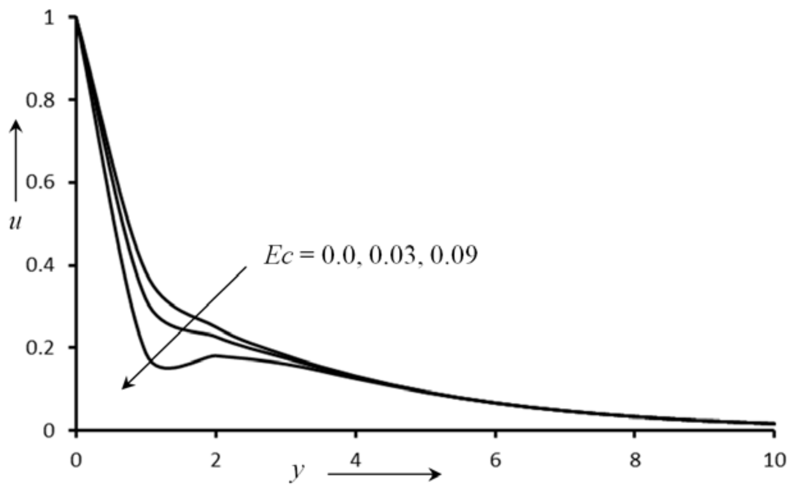

Fig. 8. The dimensionless velocity verses various values of *Ec* when *Sc*=0.22, K_C =0.2, *a*=0. 3, Pr=2.0, β =3.0, *M*=2.5, G_r =1.0 and G_C =0.5.

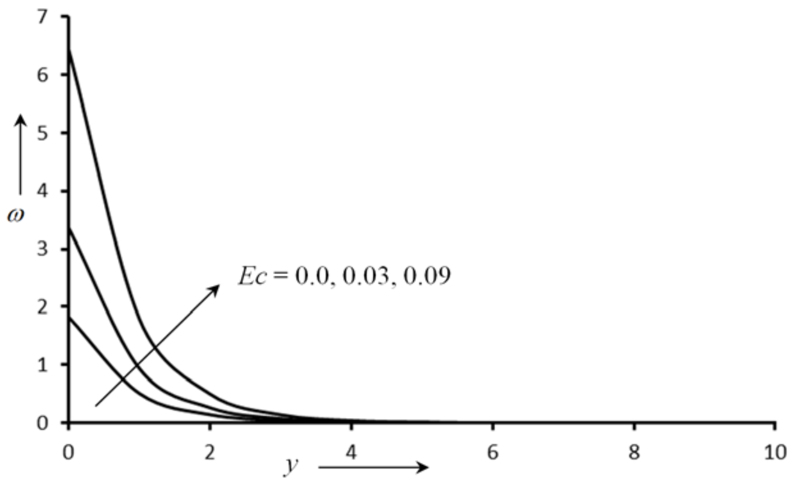

Fig. 9. The dimensionless angular velocity verses various values of *Ec* when *Sc*=0.22, K_C =0.2, *a*=0.3, Pr=2.0, β =3.0, *M*=2.5, G_r =1.0 and G_C =0.5.

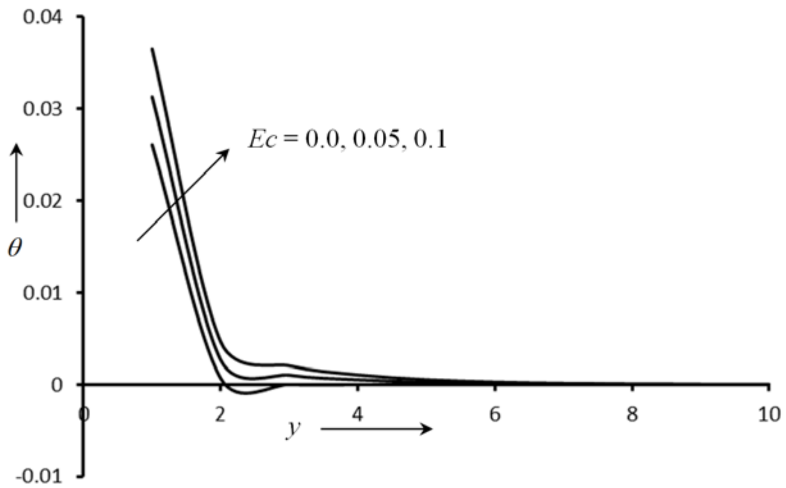

Fig. 10. The dimensionless temperature verses various values of *Ec* (Starting from *y* = 0.1 to present clear effects of Ec) when *Sc*=0.22, K_C =0.2, *a*=0.3, Pr=2.0, β =3.0, *M*=2.5, G_r =1.0 and G_C =0.5.

Fig.10 is drawn for the temperature for different values of Ec. It is noted that θ increases as Ec increases. Also, as the Eckert number designates the ratio of the kinetic energy of the flow to the boundary layer enthalpy difference. It embodies the conversion of kinetic energy into internal energy by work done against the viscous fluid stresses. The positive Eckert number implies cooling of the plate i.e., loss of heat from the plate to the fluid. Hence, greater viscous dissipative heat causes a rise in the temperature.

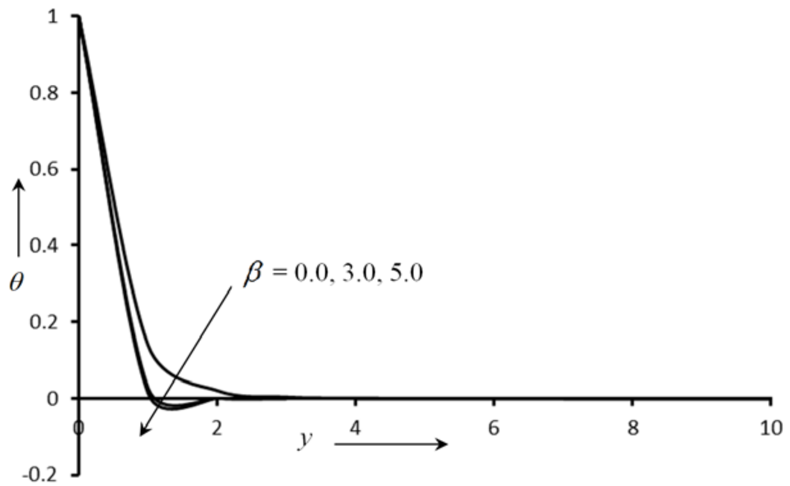

Fig. 11. The dimensionless temperature verses various values of β when *Sc*=0.22, K_c =0.2, *a*=0.3, Pr=2.0, *M*=2.5, G_r =1.0, G_c =0.5 and *Ec*=0.01.

Fig. 11 shows that dimensionless temperature θ decreases as heat sink parameter β increases, since β is the annihilation parameter, so its increase reduces heat content and subsequently temperature. Also here $T_w > T_\infty$ implies that there will be a supply of heat to the flow region from the wall.

4. CONCLUSIONS

In the present research, the effects of heat sink, viscous dissipation, material parameters and chemical reaction when $T_w > T_\infty$ over various field functions are obtained in Equations (16) to (21). One can conclude from the study that viscous dissipation increase the temperature; a stronger heat sink results in a thinner thermal boundary layer and more heat transfer from the surface to the fluid; transverse velocity increases with thermal or species buoyancy, whereas it decreases with an increase in chemical reaction or material parameter or viscous dissipation. Angular velocity increases with viscous dissipation and decreases as thermal or species buoyancy increases as increasing buoyancy the micro-rotation become negative.

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REFERENCES

[1] Ghebhart, B., Pera, L., *Int J Heat Mass Transfer*, **14**, 2025, 1971.
[2] Sparrow, E. M., Minkowycz, W. J., Eckert, E. R. G., *ASME Journal of Heat Transfer*, **86C**, 508, 1964.
[3] Soundalgekar, V. M., *Proc Indian Acad Sci*, **84**, 194, 1976.
[4] Acharya, M., Dash, G. C., Singh, L. P., *Indian J Pure Appl Math*, **31**, 1, 2000.
[5] Singh, K. D., Chand, K., *Proc Nat Acad Sci*, **70**, 49, 2000.
[6] Kandasamy, R., Muhaimin, I., Khamis, A. B., *Heat Mass Transfer*, **45**, 703, 2009.
[7] Kandasamy, R., Devi, S. P. A., *Journal of Computational and Applied Mechanics*, **5**, 21, 2004.
[8] Chamkha, A. J., *International Journal of Engineering Science*, **35**, 975, 1997.
[9] Asghar, S., Hanif, K., Hayat, T., Khalique, C. M., *Communications in Nonlinear Science and Numerical Simulation*, **12**, 465, 2007.
[10] Kumar, H., *Thermal Science*, **13**, 163, 2009.
[11] Kumar, H., *Chem Eng Comm*, **200**, 1, 2013.

Nomenclature

y^* horizontal coordinate (m)
u^* axial velocity (m/s)
v^* transverse velocity (m/s)
ω^* angular velocity vector normal to the xy – plane (rad/s)
p^* pressure (Pa)
T^* temperature of the fluid (K)
T_∞ far field temperature (K)
C^* species concentration (mol/m^3)
C_∞ far field concentration (mol/m^3)
ϑ kinematic viscosity (m^2/s)
ρ density (kg/m^3)
κ vortex viscosity (Pa.s)
μ dynamic coefficient of viscosity (Pa.s)
g acceleration due to gravity (m/s^2)
β_T coefficient of thermal expansion (K^{-1})
β_c coefficient of concentration expansion (m^3/mol)
K^* permeability of porous medium (m^2)
σ electrical conductivity (S/m)
B_0 magnetic field coefficient (T)
j micro inertia density (m^2)
γ spin gradient viscosity (kg.m/s)
c_p specific heat (J kg^{-1} K^{-1})
k thermal conductivity (W/m K)
q_r^* radiative heat flux in y- direction (W/m^2)
D mass diffusion coefficient (m^2 s^{-1})
k_l rate of chemical reaction (s^{-1})
m_w wall mass flux (mol/m^{2}s)
T_w wall temperature (K)
V_0 suction velocity (m/s)
Q heat sink coefficient (W m^{-3} K^{-1})
a material parameter
y dimensionless horizontal coordinate
u dimensionless axial velocity
M magnetic field parameter
β heat sink parameter
$\Pr$ Prandtl number
θ dimensionless temperature
C dimensionless species concentration
Ec Eckert number
G_r thermal Grashof number
G_c solutal Grashof number
ω dimensionless angular velocity
Sc Schmidt number
F radiation parameter
K_c chemical reaction parameter
K dimensionless permeability parameter