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Effect of free convection and mass transfer on MHD flow of a rotating elastico-viscous fluid past an infinite vertical porous plate through a porous medium with constant suction and heat flux

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Abstract: The steady free convective flow and mass transfer of a rotating elastico-viscous electrically conducting fluid through a porous medium occupying a semi infinite region of space bounded by an infinite vertical porous plate in presence of a transverse magnetic field with constant suction and heat flux is considered. A Cartesian co-ordinate system rotating uniformly with the fluid in a rigid state of rotation with a constant angular velocity Ω about z-axis is chosen. The temperature and the species concentration at the free stream are assumed to be constant. The expressions for velocity, temperature and concentration of the flow field are obtained analytically and the effects of the flow parameters on the flow field are discussed with the aid of graphs.

2000 Mathematics Subject Classification: 76W05

Keywords: MHD, free convection, mass transfer, rotating frame, elastico-viscous, porous medium

Nomenclature

C=Species concentration; C′=Dimensionless species concentration; C^n=Chemical reaction constant; C_p=Specific heat at constant pressure; D=Chemical molecular diffusivity; g =Acceleration due to gravity; G_m=Grashof number for mass transfer; G_r=Grashof number for heat transfer; k=Thermal conductivity; k*=Permeability of the medium; K_p= Permeability parameter; K_n=n^{th} order reaction rate constant; M=Magnetic parameter; P_r=Prandtl number, p'_{13}, p'_{23}=Stress tensor components; q=Constant heat flux per unit area; R=Rotation parameter; S_c=Schmidt number; T=Temperature; T′ =Dimensionless temperature; t=Time; U= Velocity in a rotating frame of reference; U′=Dimensionless velocity; u, v, w=Velocity components in x-, y- and z- direction respectively; w_0=Constant suction velocity at the plate; z=Normal direction of vertical porous plane surface;z′=Dimensionless normal distance.

Greek Symbols

α_1, α_2=Elastic parameters; β=Volumetric coefficient of thermal expansion; β^*=Volumetric coefficient of expansion with concentration; η_0=Coefficient of viscosity; ρ= Density; ν=Kinematic viscosity; Ω= Angular velocity of the rotating frame of reference; λ_1=Stress relaxation time; λ_2 =Rate of strain retardation time; λ_n=Reaction rate constant

Subscripts

w= Conditions on the porous plane surface; ∞=Conditions away from the plane surface

Superscripts

′ = Derivative with respect to z

Introduction

The study of free convective MHD flow of a rotating fluid with mass transfer is of general interest in view of its varied applications in the field of astrophysical and geophysical sciences. Such types of problems find their use in the atmospheric and oceanic circulations as well. Flow through porous media is helpful in the filtration process and also to maintain the temperature of a heated body.

Several researchers have analyzed a bewildering variety of flows connected to MHD free convection and mass transfer with/without rotation. Acharya *et al.* (2000) have analyzed the magnetic field effects on free convection and mass transfer flow through porous medium with constant suction and heat flux. Chaudhury and Sahoo (1995) studied the unsteady free convective flow and mass transfer of a visco-elastic fluid in a rotating porous medium. Das *et al*. (2004) have estimated the effect of free convection and mass transfer on the flow of an elastico-viscous fluid past an infinite vertical porous plate in a rotating porous medium. Dash and Das (1999) have investigated the effect of Hall current on MHD flow along an accelerated porous flat plate with mass transfer and internal heat generation. Israel-Cookey and Sigalo (2003) discussed the unsteady MHD free convection and mass transfer flow past an infinite heated porous vertical plate with time dependent suction. Jha (1998) has investigated the effects of applied magnetic field on the transient free convective flow in a vertical channel. Kim (2000) has reported the unsteady MHD convective heat transfer past a semi-infinite vertical porous moving plate with variable suction.

Panda *et al*. (2003) have investigated the unsteady free convective flow and mass transfer of a rotating elastico-viscous liquid through porous media past a vertical infinite porous plate. Raptis and Singh (1985) studied the effect of rotation on MHD free convection flow past an accelerated vertical plate. Sacheti and Singh (1992) have discussed the problem of free convection through a vertical channel in a rotating porous medium. Sattar (1994) analyzed the free convection and mass transfer flow through a porous medium past an infinite vertical porous plate with time dependent temperature and concentration. Singh (1984) has studied the MHD free convection flow of a fluid past an accelerated vertical

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porous plate in a rotating frame. In a separate paper he (1986) discussed the unsteady free convection flow through a rotating porous medium. Singh and Soundalgekar (1990) have estimated the transient free convection effect in cold water past an infinite vertical porous plate.

The present study considers the steady free convective flow and mass transfer of a rotating elastico-viscous electrically conducting fluid through a porous medium occupying a semi-infinite region of space bounded by an infinite vertical porous plate in presence of a transverse magnetic field with constant suction and heat flux assuming the temperature and species concentration at the free stream to be constant. The analytic expressions for velocity, temperature and concentration of the flow field are obtained and the effects of the flow parameters on the flow field are discussed with the help of graphs.

Mathematical formulation

Consider the steady free convective flow and mass transfer of a rotating elastico-viscous electrically conducting liquid (Oldroyd model) occupying a semi-infinite region of the space bounded by an infinite vertical porous plate with constant suction and heat flux subject to a transverse magnetic field through a porous medium. The temperature and species concentration at the free stream are assumed to be constant. We consider a Cartesian co-ordinate system rotating uniformly with the fluid in a rigid state of rotation with constant angular velocity Ω about z-axis. The vertical plate is assumed to coincide with the plane z = 0. Here, all the physical variables except the pressure are functions of z only. Thus the equation of continuity gives w = $-w_0$, where $w_0>0$ is the suction velocity normal to the plate. Taking into account the Boussinesq approximation and neglecting the effect of induced magnetic field, the equations which govern the flow are

$$-w_0\frac{du}{dz}-2\Omega v=\frac{1}{\rho}\frac{dp'_{13}}{dz}+g\beta(T-T_\infty)+g\beta^*(C-C_\infty)-\frac{\nu}{k^*}u-\frac{\sigma B_0^2 u}{\rho}, \quad (1)$$

$$-w_0\frac{dv}{dz}+2\Omega u=\frac{1}{\rho}\frac{dp'_{23}}{dz}-\frac{\nu}{k^*}v-\frac{\sigma B_0^2 v}{\rho}, \quad (2)$$

$$-w_0\frac{dT}{dz}=\frac{k}{\rho C_p}\frac{d^2T}{dz^2}, \quad (3)$$

$$-w_0\frac{dC}{dz}=D\frac{d^2C}{dz^2}-\lambda_n C^n, \quad (4)$$

The initial and boundary conditions are

$$u=0,\quad v=0,\quad \frac{dT}{dz}=-\frac{q}{k},\quad C=C_w \text{ at } z=0$$

$$u\to 0,\quad v\to 0,\quad T\to T_\infty,\quad C\to C_\infty \text{ as } z\to\infty \quad (5)$$

Following Mahato (1994), the components of stress tensor p'_{13} and p'_{23} are expressed by the implicit relations

$$\left(1-\lambda_1 w_0\frac{d}{dz}\right)p'_{13}=\eta_0\left[\frac{du}{dz}-\lambda_2 w_0\frac{d^2u}{dz^2}\right], \quad (6)$$

$$\left(1-\lambda_1 w_0\frac{d}{dz}\right)p'_{23}=\eta_0\left[\frac{dv}{dz}-\lambda_2 w_0\frac{d^2v}{dz^2}\right]. \quad (7)$$

Eliminating p'_{13} and p'_{23} from equations (1) and (2) with the help of equations (6) and (7), putting U = u + iv and introducing the dimensionless quantities

$$U'=\frac{U}{w_0},\quad z'=\frac{w_0 z}{\nu},\quad \alpha_1=\frac{\lambda_1 w_0^2}{\nu},\quad \alpha_2=\frac{\lambda_2 w_0^2}{\nu},$$

$$T'=(T-T_\infty)\frac{kw_0}{q\nu},\quad C'=\frac{C-C_\infty}{C_w-C_\infty},\quad R=\frac{\Omega\nu}{w_0^2},$$

$$G_r=\frac{g\beta\nu^2 q}{kw_0^4},\quad G_m=\frac{\nu g\beta^*(C_w-C_\infty)}{w_0^3},$$

$$M=\sqrt{\frac{\sigma B_0^2\nu}{\rho w_0^2}},$$

$$P_r=\frac{\rho\nu C_p}{k},\quad S_c=\frac{\nu}{D},\quad K_p=\frac{w_0^2 k^*}{\nu^2},$$

$$K_n=\frac{\lambda_n C^n}{C_w-C_\infty}\frac{\nu}{w_0^2},$$

equations (1) - (4) become (dropping the primes)

$$\alpha_2\frac{d^3U}{dz^3}+(\alpha_1-1)\frac{d^2U}{dz^2}-\left(1+2i\alpha_1 R+\frac{\alpha_1}{K_p}+\alpha_1 M^2\right)\frac{dU}{dz}$$

$$+\left(2iR+\frac{1}{K_p}+M^2\right)U=G_rT+G_mC-\alpha_1 G_r\frac{dT}{dz}-G_m\frac{dC}{dz} \quad (8)$$

$$\frac{d^2T}{dz^2}+P_r\frac{dT}{dz}=0 \quad (9)$$

$$\frac{d^2C}{dz^2}+S_c\frac{dC}{dz}=K_n \quad (10)$$

subject to the boundary conditions

$$U=0,\quad \frac{dT}{dz}=-1,\quad C=1 \quad \text{at } z=0 \quad (11)$$

$$U\to 0,\quad T\to 0,\quad C\to 0 \text{ as } z\to\infty$$

Method of solution

The solutions of equations (9) and (10) under the boundary conditions (11) are

$$T=\frac{1}{P_r}e^{-P_r z}, \quad (12)$$

$$C=e^{-S_c Z}. \quad (13)$$

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Inserting equations (12) and (13) in equation (8), we obtain

$$\alpha_2 \frac{d^3U}{dz^3} + (\alpha_1 - 1)\frac{d^2U}{dz^2} - \left(1 + 2i\alpha_1 R + \frac{\alpha_1}{K_p} + \alpha_1 M^2\right)\frac{dU}{dz} \quad (14)$$

$$+\left(2iR + \frac{1}{K_p} + M^2\right)U = \frac{G_r}{P_r}e^{-P_r z} + \alpha_1 G_r e^{-P_r z} + G_m e^{-S_c z} + \alpha_1 G_m S_c e^{-S_c z}$$

If $\alpha_1 = 0$ and $\alpha_2 = 0$, equation (14) reduces to the steady free convection flow and mass transfer of an incompressible viscous fluid in a rotating system.

We note that the equation (14) is of order three. Hence an additional boundary condition will be required in order to get a unique solution. Since no additional boundary condition is physically plausible, we impose the requirement that the solution of the equation (14) reduces to the classical viscous case as $\alpha_1, \alpha_2 \to 0$. As it will be seen, this enables to determine all the arbitrary constants appearing in the solution of the equation (14) in the case of elastico-viscous liquid is

$$U = C_1 e^{m_1 z} + C_2 e^{m_2 z} + C_3 e^{m_3 z} + \frac{H_1}{M_{11}} e^{-P_r z} + \frac{G_1}{M_{12}} e^{-S_c z} \quad (15)$$

where

$$M_{11} = -\alpha_2 P_r^3 + (\alpha_1 - 1)P_r^2 + \left(1 + 2iR\alpha_1 + \frac{\alpha_1}{K_p} + \alpha_1 M^2\right)P_r + 2iR + \frac{1}{K_p} + M^2,$$

$$M_{12} = -\alpha_2 S_c^3 + (\alpha_1 - 1)S_c^2 + \left(1 + 2iR\alpha_1 + \frac{\alpha_1}{K_p} + \alpha_1 M^2\right)S_c + 2iR + \frac{1}{K_p} + M^2,$$

$$H_1 = \left(\alpha_1 + \frac{1}{P_r}\right)G_r,$$

$$G_1 = G_m(1 + \alpha_1 S_c),$$

$$a_1 = \frac{\alpha_1 - 1}{\alpha_2},$$

$$a_2 = -\frac{1}{\alpha_2}\left(1 + \frac{\alpha_1}{K_p} + \alpha_1 M^2\right) + 2iR\frac{\alpha_1}{\alpha_2},$$

$$a_3 = \frac{1}{\alpha_2 K_p} + \frac{M^2}{\alpha_2} + \frac{2iR}{\alpha_2},$$

$$Q = -\frac{1}{9}\left[-a_1^2 - \frac{3}{\alpha_2}\left(1 + \frac{\alpha_1}{K_p} + \alpha_1 M^2\right) + 6R\frac{\alpha_1}{\alpha_2}i\right],$$

$$R_1 = -\left(\frac{a_1}{6\alpha_2} + \frac{\alpha_1 a_1}{6K_p\alpha_2} + \frac{\alpha_1 a_1 M^2}{6\alpha_2} + \frac{1}{2K_p\alpha_2} + \frac{M^2}{2\alpha_2} + \frac{a_1^3}{27}\right) + i\left(\frac{R\alpha_1}{3\alpha_2} - \frac{R}{\alpha_2}\right),$$

$$Q_1 = \sqrt{Q^3 + R_1^2},$$

$$S_1 = (R_1 + Q_1)^{\frac{1}{3}},$$

$$S_2 = (R_1 - Q_1)^{\frac{1}{3}},$$

$$m_1 = S_1 + S_2 - \frac{a_1}{3},$$

$$m_2 = -\frac{1}{2}(S_1 + S_2) + \frac{\sqrt{3}}{2}i\sqrt{S_1 - S_2} - \frac{a_1}{3},$$

$$m_3 = -\frac{1}{2}(S_1 + S_2) - \frac{\sqrt{3}}{2}i\sqrt{S_1 - S_2} - \frac{a_1}{3},$$

In the limit when $\alpha_1, \alpha_2 \to 0$, we have

$$m_1 \to \infty, \quad (16)$$

$$m_2 = -0.5 + 0.5\,(1 + 8iR + 4/K_p + 4M^2)^{\frac{1}{2}} \quad (17)$$

and

$$m_3 = -0.5 - 0.5\,(1 + 8iR + 4/K_p + 4M^2)^{\frac{1}{2}} \quad (18)$$

It can be seen from the above that the roots m_2 and m_3 reduce to the classical viscous case, while m_1 is the additional root. Hence we take the arbitrary constant $C_1 = 0$ in the complementary function. Using the boundary condition (11), the other two arbitrary constants are obtained and the final solution of equation (14) can be written as

$$U = \frac{u}{w_0} + i\frac{v}{w_0} = \frac{H_1}{M_{11}}\left(e^{-P_r z} - e^{m_3 z}\right) + \frac{G_1}{M_{12}}\left(e^{-S_c z} - e^{m_3 z}\right) \quad (19)$$

Separating the real and imaginary parts in equation (15), we get

$$\frac{u}{w_0} = G_{11}\left[A_3\left(e^{-S_c z} - e^{A_1 z}\cos A_2 z\right) - A_4 e^{A_1 z}\operatorname{Sin} A_2 z\right]$$

$$+ H_{11}\left[\left(e^{-pz} - e^{A_1 z}\cos A_2 z\right)A_5 - A_6 e^{A_1 z}\operatorname{Sin} A_2 z\right] \quad (20)$$

$$\frac{v}{w_0} = G_{11}\left[-A_4\left(e^{-S_c z} - e^{A_1 z}\cos A_2 z\right) - A_3 e^{A_1 z}\operatorname{Sin} A_2 z\right]$$

$$+ H_{11}\left[-A_6\left(e^{-P_r z} - e^{A_1 z}\cos A_2 z\right) - A_5 e^{A_1 z}\operatorname{Sin} A_2 z\right]$$

where $M_1 = \left[\left(1 + \frac{4}{K_p} + 4M^2\right)^2\right] + 64R^2$,

$$A_1 = -\frac{1}{2} - \frac{1}{2}\left[0.5\left(1 + \frac{4}{K_p} + 4M^2 + M_1\right)\right]^{\frac{1}{2}},$$

$$A_2 = -\frac{1}{2}\left[0.5\left(M_1 - 1 - \frac{4}{K_p} - 4M^2\right)\right]^{\frac{1}{2}},$$

$$A_3 = -\alpha_2 S_c^{\,3} + (\alpha_1 - 1)S_c^{\,2} + \left(1 + \frac{\alpha_1}{K_p} + \alpha_1 M^2\right)S_c + \frac{1}{K_p} + M^2,$$

$$A_4 = 2R(1 + \alpha_1 S_c),$$

$$A_5 = -\alpha_2 P_r^{\,3} + (\alpha_1 - 1)P_r^{\,2} + \left(1 + \frac{\alpha_1}{K_p} + \alpha_1 M^2\right)P_r + \frac{1}{K_p} + M^2$$

$$A_6 = 2R(1 + \alpha_1 P_r),$$

$$G_{11} = \frac{G_1}{(A_3^2 + A_4^2)},$$

$$H_{11} = \frac{H_1}{(A_5^2 + A_6^2)}.$$

Results and discussions

The problem of steady free convective flow and mass transfer of a rotating elastico-viscous electrically conducting liquid through a porous medium bounded by an infinite vertical porous plate in presence of a transverse magnetic field with constant suction and heat flux has been analyzed both analytically and graphically and the results are discussed.

The primary and secondary velocity profiles are presented in figures (1) - (8) for different values of elastic parameters (α_1, α_2), magnetic parameter (M), Schmidt number (S_c), Prandtl number (P_r). In the present paper dilute water solution of non-Newtonian fluid flow through porous medium in rotating frame of reference has been considered. In numerical calculations, the values of the parameters are chosen from the realistic situations. In view of experimental findings, the value of α_1 is taken higher than that of α_2. In the following discussion, we have chosen $G_r > 0$ which corresponds to an externally cooled plate as the free convection current is carried away from the plate.

The effects of elastic parameters (α_1, α_2) and porosity parameter (K_p) on the primary and secondary velocity are shown in Fig.1 and 2 respectively. From the curves (2 -5) and (2, 3) of both the figures, it is observed that α_1 accelerates the magnitude of both the components of velocity and α_2 retards the velocity components of the flow field. But the effect of α_2 is more significant than the effect of α_1. The porosity parameter (K_p) enhances the magnitude of both the components of velocity (curves 2 and 4) of the flow field. Curve (6) with M = 0 coincides with the results of Das *et al.* (2004).

Fig.2. Effect of elastic parameters on secondary velocity profiles with P_r =7, S_c=900, G_m=2, G_r=2, R=0.4

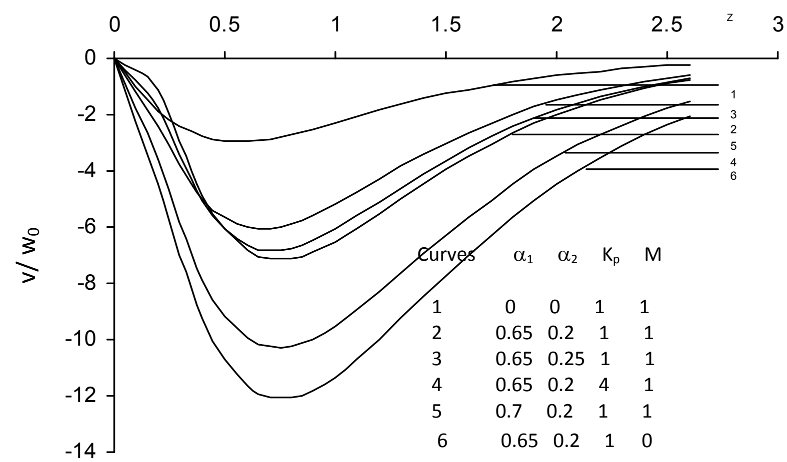
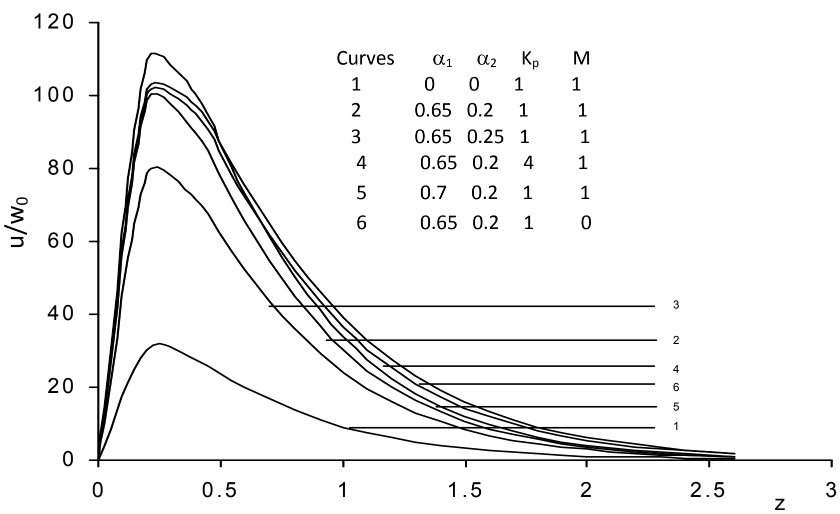


Fig. 3 and 4 depict the effect of magnetic parameter (M) on the primary and secondary velocity of the flow field respectively. Comparing the curves of both the figures, it is noticed that the magnetic parameter (M) retards both the components of velocity of the flow field as a result of the magnetic pull imposed by the Lorentz force of the applied magnetic field. Curve (6) with M=0 is due to Das *et al.* (2004).

The variation of velocity components in the presence of foreign species (S_c) is shown in Fig.5 and 6. Curve (1) of both the figures represents the work of Das *et al.* (2004). Comparing curves (2, 4 and 5) of Fig.5 and 6, it is observed that in presence of higher diffusing species (S_c), the velocity

Fig.1. Effect of elastic parameters on primary velocity profiles with P_r=7, S_c=900 G_m=2, G_r=2, R=0.4



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components retard in magnitude. Further, it is observed that under similar physical situations of S_c and M, the porosity parameter enhances both the components of velocity (curves 2 and 3).

Fig.7 and 8 show the nature of velocity profiles (both the components) with the variation of Prandtl number (P_r), porosity parameter (K_p) and magnetic parameter (M). The Prandtl number (P_r) is found to retard the absolute value of both the components of velocity (curve 4 and 5). Under identical physical conditions of P_r and K_p both the components of velocity are higher in magnitude in case of non-MHD flow (M=0) than its counter part in MHD flow (curves 1 and 3). Further, the porosity parameter (K_p) enhances both the components of velocity under similar conditions of P_r and M (curves 1 and 2).

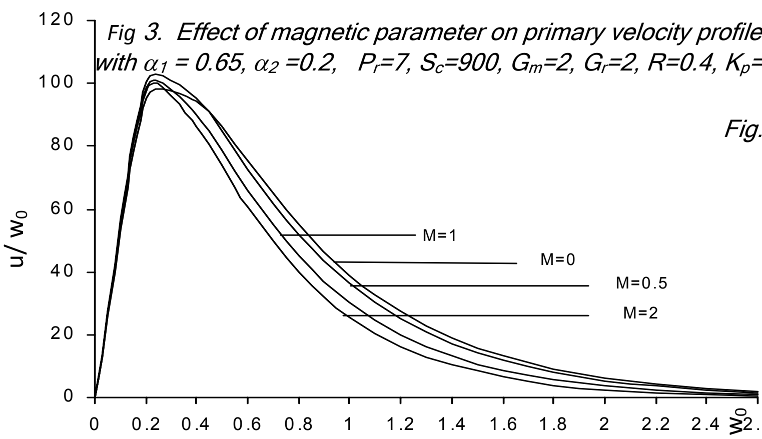

Fig 3. Effect of magnetic parameter on primary velocity profiles with α_1 = 0.65, α_2 =0.2, P_r=7, S_c=900, G_m=2, G_r=2, R=0.4, K_p=1

Conclusions

The following conclusions are drawn on the velocity components from the above discussion:

- The presence of elastic parameter (α_1) in the flow field enhances the magnitude of both the components of velocity while the other elastic parameter α_2 shows reverse effect. The effect of α_2 is more significant than that of α_1.
- The porosity/permeability parameter (K_p) accelerates both the components of velocity at all points of the flow field.
- The magnetic parameter (M) retards the velocity components (primary and secondary) at all points of the flow field as a result of the magnetic pull (Lorentz force) of the applied magnetic field. The effect is more significant in case of secondary velocity components.
- In presence of heavier diffusing species (S_c), the velocity components suffer a decrease in magnitude at all points of the flow field.
- The Prandtl number (P_r) has a retarding effect on both the components of velocity of the flow field.

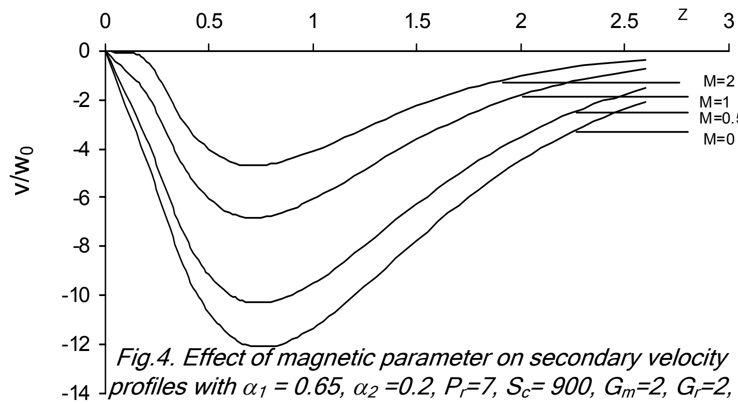

Fig.4. Effect of magnetic parameter on secondary velocity profiles with α_1 = 0.65, α_2 =0.2, P_r=7, S_c= 900, G_m=2, G_r=2, R=0.4. K_p=1

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Fig. 5. Primary velocity profiles for different values of S_c with α_1 = 0.65, α_2 =0.2, P_r=7, G_m=2, G_r=2, R=0.4

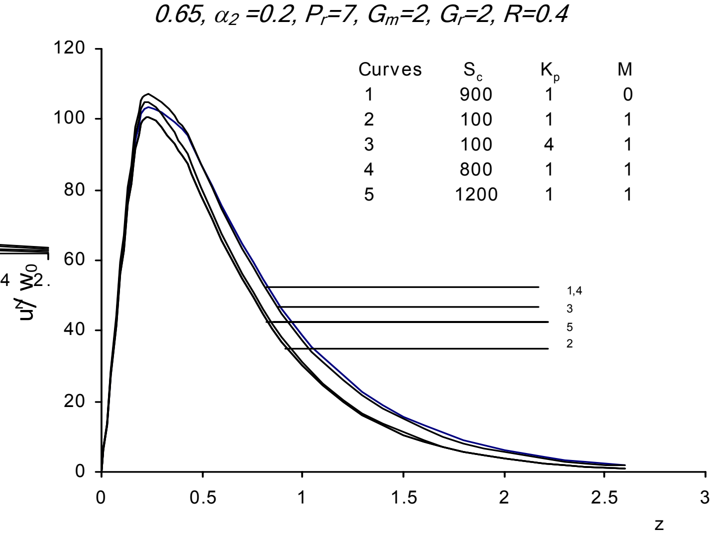

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Fig. 6. Secondary velocity of profiles for different values of S_c with α_1 = 0.65, α_2 =0.2, P_r=7, G_m=2, G_r=2, R=0.4

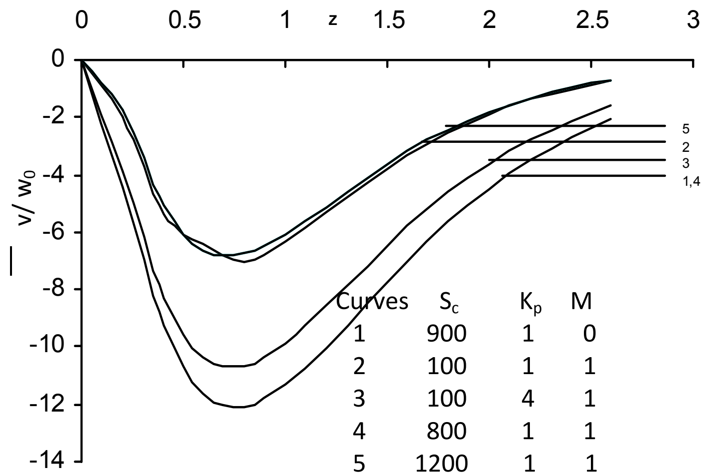

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Fig. 8. Secondary velocity profiles for different values of P_r when α_1 =0.65, α_2 =0.25, S_c=900, G_m=2, G_r=2, R=0.4

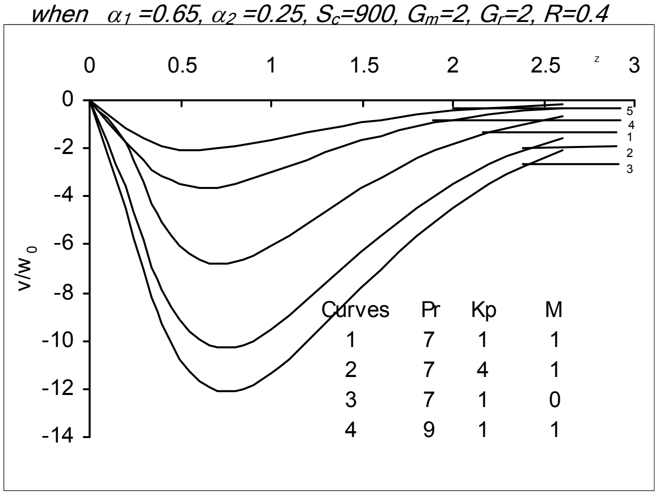

Fig.7. Primary velocity profiles for different values of P_r when α_1 = 0.65, α_2=0.25, S_c=900, G_m=2, G_r=2, R=0.4