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THERMO DIFFUSION AND CHEMICAL EFFECTS WITH SIMULTANEOUS THERMAL AND MASS DIFFUSION IN MHD MIXED CONVECTION FLOW WITH OHMIC HEATING

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Abstract:

Thermo diffusion and chemical effects on heat transfer in MHD mixed convection flow and mass transfer past an infinite vertical plate with Ohmic heating and viscous dissipation have been studied. Approximate solutions have been derived for velocity, temperature, concentration profiles, skin friction, rate of heat transfer and rate of mass transfer using perturbation technique. The obtained results are discussed with the help of graphs to observe the effect of various parameters like Schmidt number (Sc), Prandtl number (Pr), Magnetic parameter (M),Soret number (So) and chemical parameter (K), taking two cases viz. Case I: when Gr > 0 (flow on cooled plate) and Case II: Gr < 0 (flow on heated plate). Thermal diffusion causes both the fluid velocity and temperature to fall due to the presence of the chemical effect. Velocity and temperature profiles are higher for mercury than electrolytic solution. Soret effect increased the concentration of the fluid while chemical effect decreased.

Keywords: Chemical effect, thermo diffusion, magnetic field and heat-mass transfer.

NOMENCLATURE

g	acceleration due to gravity
T^*	Temperature of the fluid
T_w	temperature near the plate
T_∞	temperature far away from the plate
Pr	Prandtl number
Re	Reynolds's number
C^*	concentration of the fluid
C_w	concentration near the plate
C_p	Specific heat of the fluid at constant pressure
Sc	Schmidt number
K	chemical reaction parameter
So	Soret number
D	Chemical molecular diffusivity
B_o	Magnetic field coefficient
D_1	Coefficient of thermal diffusivity
v_o	constant suction velocity
k	Thermal conductivity of the fluid
K_l	chemical reaction rate constant
Ec	Eckert number
Gr	Grashoff number for heat transfer
Gm	Grashoff number of mass transfer
Nu	Nusselt number
Sh	Sherwood number
u, v	velocity components in the x and y directions
C_∞	concentration far away from the plate
M	Hartmann number

Greek Symbols

θ	Dimensionless temperature
ϕ	Dimensionless concentration
υ	kinematic viscosity of the fluid
μ	viscosity of the fluid
β	Coefficient of thermal expansion
β^*	coefficient of mass expansion
σ	magnetic permeability of the fluid
ρ	Fluid density
τ	Skin-friction coefficient

Super script ' denotes differentiation with y

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1. Introduction

Convection flow driven by temperature and concentration differences has been the objective of extensive research because such processes exist in nature and have engineering applications. The processes occurring in nature include photo-synthetic mechanism, calm-day evaporation and vaporization of mist and fog, while the engineering application includes the chemical reaction in a reactor chamber consisting of rectangular ducts, chemical vapor deposition on surfaces and cooling of electronic equipment. Heat and mass transfer on flow past a vertical plate have been studied by several authors; viz. Somess (1956), Soundalgekar and Ganesan (1981) and Lin and Wu (1995) in numerous ways to include various physical aspects. Magnetohydrodynamic flows have applications in meteorology, solar physics, cosmic fluid dynamics, astrophysics, geophysics and in the motion of earth's core. In addition to the technological point of view, MHD free convection flows have significant applications in the field of stellar and planetary magnetospheres, aeronautics, chemical engineering and electronics. On account of their varied importance, this flow has been studied by Elbashbeshy (1997).

In the above mentioned studies the chemical effect is ignored. Chemical reaction can be codified as either heterogeneous or homogeneous processes. This depends on whether they occur at an interface or as a single phase volume reaction. In many chemical engineering processes, there does occur the chemical reaction between a foreign mass and the fluid in which the plate is moving. These processes take place in numerous industrial applications, e.g., polymer production, manufacturing of ceramics or glassware and food processing. Chamber and Young (1958) have analysed a first order chemical reaction in the neighborhood of a horizontal plate. Mass transfer effects on moving isothermal vertical plate in the presence of chemical reaction were studied by Das et al (1999). Muthucumaraswamy et al (2008) studied the effect of chemical reaction on unsteady MHD flow through an Impulsively started semi-infinite vertical plate. The effect of chemical reaction on an unsteady hydro magnetic free convection and mass transfer flow past an impulsively started infinite inclined porous plate in the presence of heat generation or absorption is studied numerically by Alam et al (2007). Muthucumaraswamya and Ganesan(2002) derived numerical solution of the transient natural convection flow of an incompressible viscous fluid past an impulsively started semi-infinite isothermal vertical plate with mass diffusion by taking into account a homogeneous chemical reaction of first order.

In most of the works, the level of concentration of foreign mass is assumed very low so that the Soret effects can be neglected. However, exceptions are observed therein. The Soret effect, for instance, has been utilized for isotope separation, and in mixture between gases with very light molecular weight (H_2, He) and of medium molecular weight (N_2, air). In view of the importance of this effect, Gebhart and Pera (1971) and Georgantopoulos (1979) initiated a few studies on soret effects by taking various aspects of the flow phenomena. Kafoussias and Williams (1995) studied thermal-diffusion and diffusion-thermo effects on mixed free-forced convective and mass transfer boundary layer flow with temperature dependent. The soret effect on MHD free convective and mass transfer flow of an incompressible, viscous and electrically conducting fluid, past a moving vertical infinite plate is studied by Kafoussisas (1992). Islam and alam (2007) investigated the Dufour and Soret effects on steady MHD free convection and mass transfer flow through a porous medium past a semi-infinite vertical porous plate in a rotating system.

The propagation of thermal energy through mercury and electrolytic solution in the presence of magnetic field, thermo-diffusion and chemical effect has wide range of applications. Hence, our objective in the present paper is to study the combined effects of thermo-diffusion and chemical effect on heat and mass transfer in mercury and electrolytic solution past an infinite vertical porous plate in the presence of Ohmic heating and transverse magnetic field.

2. Mathematical Formulation

We consider the mixed convection flow of an incompressible and electrically conducting viscous fluid such that x^* -axis is taken along the plate in upward direction and y^* -axis is normal to it (See Fig. A). A transverse constant magnetic field is applied *i.e.* in the direction of y^* -axis. Since the motion is two dimensional and length of the plate is large therefore all the physical variables are independent of x^* . Let u^* and v^* be the components of velocity in x^* and y^* directions respectively, taken along and perpendicular to the plate.

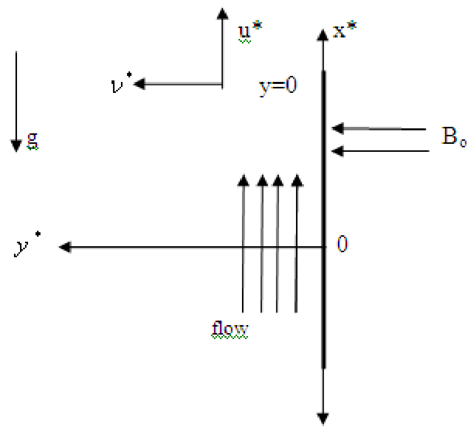

Fig. A: Physical model of the problem

The governing equations of continuity, momentum, energy and mass for a flow of an electrically conducting fluid are given by:

Equation of Continuity

$$\frac{\partial \nu^*}{\partial y^*} = 0 \Rightarrow \nu^* = -\nu_0 (\nu_0 > 0) \tag{1}$$

Equation of Motion

$$\nu^* \frac{du^*}{dy^*} = g\beta(T^* - T_\infty) + g\beta^*(C^* - C_\infty) + \upsilon \frac{d^2u^*}{dy^{*2}} - \frac{\sigma B_0^{\,2}}{\rho} u^* \tag{2}$$

Equation of Energy

$$\nu^* \frac{dT^*}{dy^*} = \frac{k}{\rho C_p} \frac{d^2T^*}{dy^{*2}} + \frac{\upsilon}{C_p}\left(\frac{du^*}{dy^*}\right)^2 + \frac{\sigma B_0^{\,2}}{\rho C_p} u^{*2} \tag{3}$$

Equation of Mass Transfer

$$\nu^* \frac{dC^*}{dy^*} = D\frac{d^2C^*}{dy^{*2}} + D_1 \frac{d^2T^*}{dy^{*2}} - K_1(C^* - C_\infty) \tag{4}$$

The boundary conditions are

$$\left.\begin{array}{l} y^* = 0: u^* = 0;\ T^* = T_W;\ C^* = C_W \\ y^* \to \infty: u^* \to 0;\ T^* \to T_\infty;\ C^* \to C_\infty \end{array}\right\} \tag{5}$$

Introducing following non-dimensional quantities

$$\left.\begin{array}{l} y = \dfrac{y^*\nu_0}{\upsilon},\ u = \dfrac{u^*}{\nu_0},\ \Pr = \dfrac{\upsilon\rho C_p}{k},\ \theta = \dfrac{T^* - T_\infty}{T_w - T_\infty},\ \phi = \dfrac{C^* - C_\infty}{C_w - C_\infty}, \\ Gr = \dfrac{\upsilon g\beta(T_w - T_\infty)}{\nu_0^{\,3}},\ Gm = \dfrac{g\beta^*\upsilon(C_w - C_\infty)}{\nu_0^{\,3}},\ Ec = \dfrac{\nu_0^{\,2}}{C_p(T_w - T_\infty)}, \\ M^2 = \dfrac{\sigma B_0^{\,2}\upsilon}{\nu_0^{\,2}\rho},\ \upsilon = \dfrac{\mu}{\rho},\ Sc = \dfrac{\upsilon}{D},\ So = \dfrac{D_1(T_w - T_\infty)}{\upsilon(C_w - C_\infty)},\ K = \dfrac{K_1\upsilon}{\nu_0^{\,2}} \end{array}\right\} \tag{6}$$

into Equations (2), (3) and (4), we get

$$\frac{d^2u}{dy^2} + \frac{du}{dy} - M^2u = -Gr\theta - Gm\phi \tag{7}$$

$$\frac{d^2\theta}{dy^2} + \Pr\frac{d\theta}{dy} + \Pr Ec\left(\frac{du}{dy}\right)^2 + \Pr EcM^2u^2 = 0 \tag{8}$$

$$\frac{d^2\phi}{dy^2} + Sc\frac{d\phi}{dy} - ScK\phi + ScSo\frac{d^2\theta}{dy^2} = 0 \tag{9}$$

(after dropping the asterisks)

The corresponding boundary conditions in dimensionless form are reduced to

$$\left.\begin{array}{l} y = 0: \ u = 0;\ \theta = 1;\ \phi = 1 \\ y \to \infty: \ u \to 0;\ \theta \to 0;\ \phi \to 0 \end{array}\right\} \tag{10}$$

3. Method of solution

The physical variables u, θ and ϕ can be expanded in the power of Eckert number (Ec). This can be possible physically as Ec for the flow of an incompressible fluid is always less than unity. It can be interpreted physically as the flow due to the Joules dissipation is super imposed on the main flow. Hence we can assume

$$\left.\begin{array}{l} u(y) = u_0(y) + Ecu_1(y) + O(Ec^2) \\ \theta(y) = \theta_0(y) + Ec\theta_1(y) + O(Ec^2) \\ \phi(y) = \phi_0(y) + Ec\phi_1(y) + O(Ec^2) \end{array}\right\} \tag{11}$$

Using Eqn. (11) in Equations (7) to (9) and equating the coefficient of like powers of Ec, we have

$$\frac{d^2u_0}{dy^2} + \frac{du_0}{dy} - M^2u_0 = -Gr\theta_0 - Gm\phi_0 \tag{12}$$

$$\frac{d^2\theta_0}{dy^2} + \Pr\frac{d\theta_0}{dy} = 0 \tag{13}$$

$$\frac{d^2\phi_0}{dy^2} + Sc\frac{d\phi_0}{dy} - ScK\phi_0 = -ScSo\frac{d^2\theta_0}{dy^2} \tag{14}$$

$$\frac{d^2u_1}{dy^2} + \frac{du_1}{dy} - M^2u_1 = -Gr\theta_1 - Gm\phi_1 \tag{15}$$

$$\frac{d^2\theta_1}{dy^2} + \Pr\frac{d\theta_1}{dy} = -\Pr u_0'^2 - \Pr M^2u_0^2 \tag{16}$$

$$\frac{d^2\phi_1}{dy^2} + Sc\frac{d\phi_1}{dy} - ScK\phi_1 = -ScSo\frac{d^2\theta_1}{dy^2} \tag{17}$$

and the corresponding boundary conditions are

$$\left.\begin{array}{l} y = 0: \ u_0 = 0;\ u_1 = 0;\ \theta_0 = 1;\ \theta_1 = 0;\ \ \phi_0 = 1;\ \phi_1 = 0 \\ y \to \infty: \ u_0 \to 0;\ u_1 \to 0;\ \theta_0 \to 0;\ \theta_1 \to 0;\ \ \phi_0 \to 0;\ \phi_1 \to 0 \end{array}\right\} \tag{18}$$

Solving Eqns. (12) to (17) with the help of Eqn. (18), we get

$$u_0 = k_3e^{-P_ry} + k_4e^{-t_1y} + k_5e^{-t_2y},$$

$$\theta_0 = e^{-P_ry},$$

$$\phi_0 = k_1e^{-P_ry} + k_2e^{-t_1y},$$

$$u_1 = k_{21}e^{-2P_r y} + k_{22}e^{-2t_1 y} + k_{23}e^{-2t_2 y} + k_{24}e^{-t_3 y} + k_{25}e^{-t_4 y} + k_{26}e^{-t_5 y} + k_{27}e^{-P_r y} + k_{28}e^{-t_1 y} + k_{29}e^{-t_2 y} ,$$

$$\theta_1 = k_6 e^{-2P_r y} + k_7 e^{-2t_1 y} + k_8 e^{-2t_2 y} + k_9 e^{-t_3 y} + k_{10}e^{-t_4 y} + k_{11}e^{-t_5 y} + k_{12}e^{-P_r y} ,$$

$$\phi_1 = k_{13}e^{-2P_r y} + k_{14}e^{-2t_1 y} + k_{15}e^{-2t_2 y} + k_{16}e^{-t_3 y} + k_{17}e^{-t_4 y} + k_{18}e^{-t_5 y} + k_{19}e^{-P_r y} + k_{20}e^{-t_1 y} .$$

Where $k_1, k_2, k_3 .... k_{28}, k_{29}, t_1 .... t_5$ are the constants which are not mentioned because of brevity.

Skin-friction

The skin-friction coefficient at the plate is given by

$$\tau = \left(\frac{\partial u}{\partial y}\right)_{y=0}$$

$$= (-P_r k_3 - t_1 k_4 - k_5 t_2) - Ec\left[2P_r k_{21} + 2t_1 k_{22} + 2t_2 k_{23} + k_{24}t_3 + k_{25}t_4 + k_{26}t_5 + k_{27}P_r + k_{28}t_1 + k_{29}t_2\right]$$

Rate of heat transfer

Rate of heat transfer in terms of Nusselt number at the plate is given by

$$Nu = \left(\frac{\partial \theta}{\partial y}\right)_{y=0}$$

$$= (-P_r) - Ec\left[2k_6 P_r + 2k_7 t_1 + 2k_8 t_2 + k_9 t_3 + k_{10}t_4 + k_{11}t_5 + k_{12}P_r\right]$$

Rate of mass transfer

Rate of mass transfer in terms of Sherwood number at the plate is given by

$$Sh = \left(\frac{\partial \phi}{\partial y}\right)_{y=0}$$

$$= (-k_1 P_r - k_2 t_1) - Ec\left[2k_{13}P_r + 2k_{14}t_1 + 2k_{15}t_2 + k_{16}t_3 + k_{17}t_4 + k_{18}t_5 + k_{19}P_r + k_{20}t_1\right]$$

4. Results and Discussion

A study of velocity field, temperature field, concentration field, skin friction, heat transfer and mass transfer of the MHD mixed convection flow of a viscous incompressible electrically conducting fluid over an infinite vertical porous plate in the presence of magnetic field has been carried out in the preceding sections, taking soret and chemical effects into account. We have computed the numerical values of velocity, temperature, concentration, skin friction, heat and mass transfer for two cases viz. (i) for cooling of the plate (Gr > 0) and (ii) for heating of the plate (Gr < 0). The values of Prandtl number (Pr) are taken as 1 and 0.025, which represent electrolytic friction, heat and mass transfer for two cases viz. (i) cooled plate (Gr > 0) and (ii) heated plate solution and mercury at 20°C temperature and 1 atmosphere pressure. The value of Eckert number (Ec) is taken as 0.01. The values of Sc considered are Hydrogen (Sc = 0.22), Helium (Sc = 0.30), Water-vapour (Sc = 0.60) and Ammonia (Sc = 0.78). The obtained results are illustrated in Figs. 1 to 8.

Figs. 1 and 2 depict the velocity profiles for fluid flow on cooled and heated plates respectively. From Fig. 1 it is observed that an increase in M, K and Sc lead to a fall in the velocity. Reverse phenomenon is observed in the case of heated plate as exhibited in Fig. 2. The effect of M is more dominant compared to the other parameters. Figs. 3 and 4 demonstrate the effects of So, Pr and Gm on fluid velocity on cooled and heated plates respectively. From Fig. 3 it is observed that for cooling of the plate, the velocity decreases with increasing

Prandtl number. Physically, this is true because the increase in the Prandtl number is due to the increase in the viscosity of the fluid which makes the fluid thick and hence the velocity decreases. Usually So accelerates the fluid velocity but here So is decelerating the fluid velocity due to the presence of the chemical effect. Also increase in Gm lead to fall in velocity. Fig. 4 demonstrates the same phenomenon as observed in the case of flow on cooled plate. The velocity profiles are positive for Gr > 0 and negative for Gr < 0. In the vicinity of the plate, velocity increases and takes the maximum value and as we move far away from the plate, it goes on decreasing.

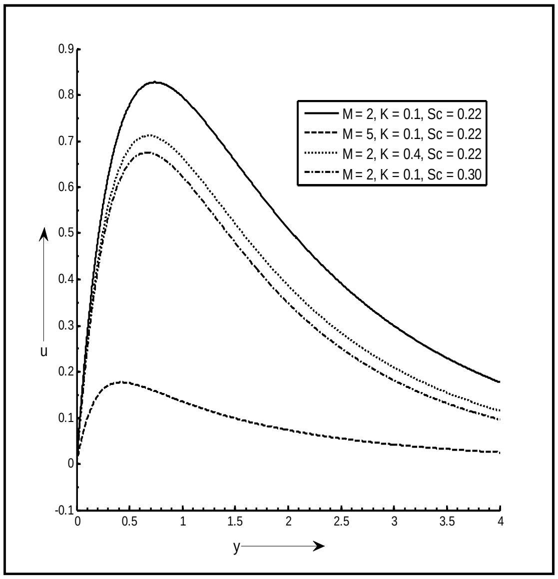

Fig. 1: Variation of velocity component for Gr = 5.0 (Pr = 1.0, Gm = 2 and So = 2)

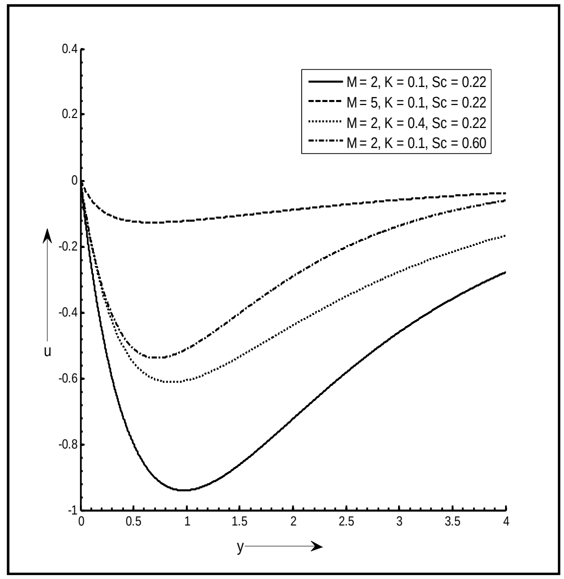

Fig. 2: Variation of velocity component for Gr = - 5.0 (Pr = 1.0, Gm = 2 and So = 2)

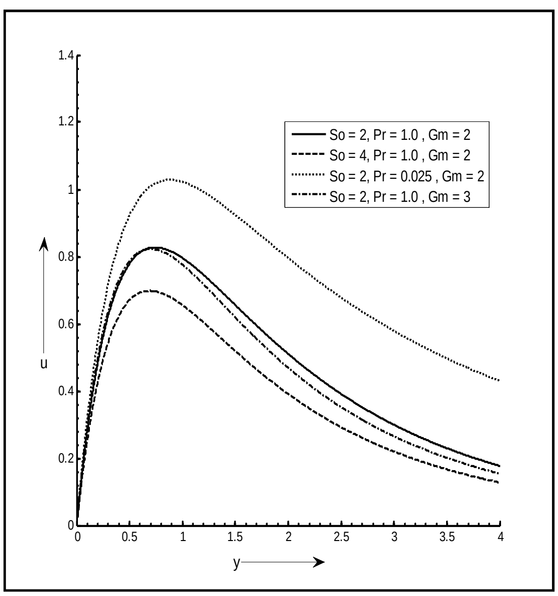

Fig. 3: Variation of velocity component for Gr = 5.0 (M = 2, K = 0.1 and Sc = 0.22)

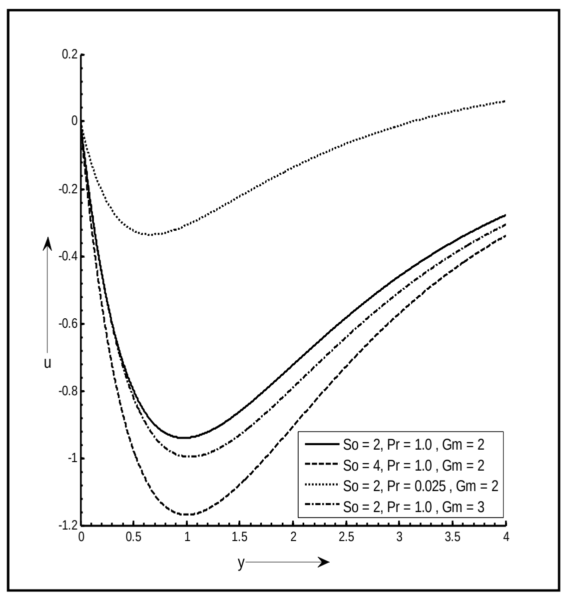

Fig. 4: Variation of velocity component for Gr = - 5.0 (M = 2, K = 0.1 and Sc = 0.22)

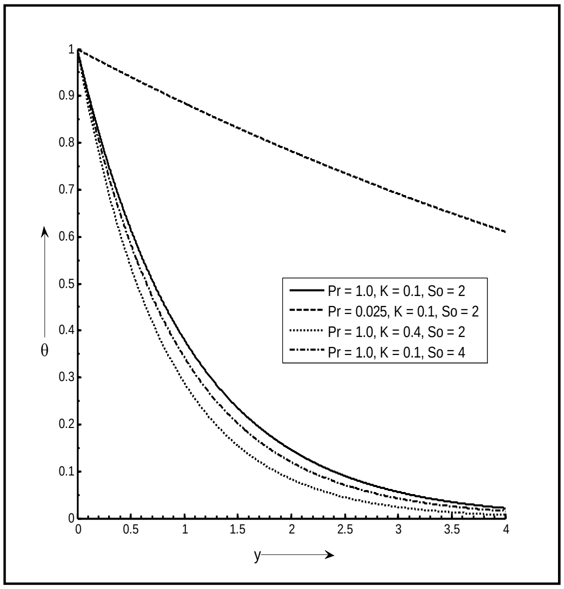

Fig. 5: Variation of temperature component for Gr = 5 (Gm = 2, M = 2 and Sc = 0.22)

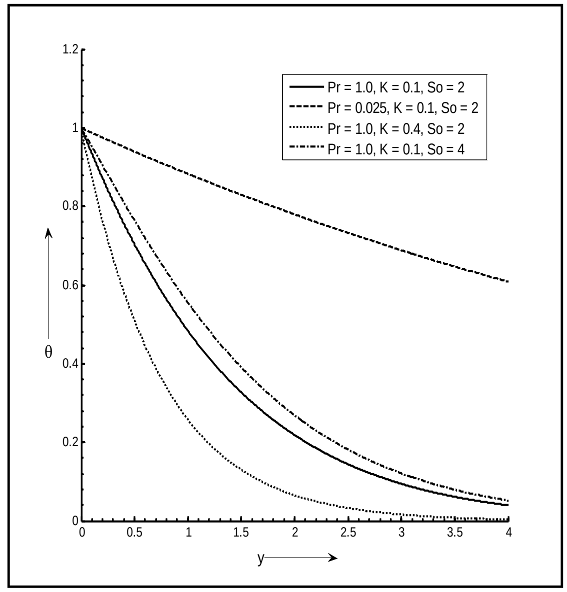

Fig. 6: Variation of temperature component for Gr = - 5 (Gm = 2, M = 2 and Sc = 0.22)

The temperature profiles for Gr = 5 and Gr = – 5 are represented in Figs. 5 and 6 respectively. The effects of Pr, K and So on temperature profiles are drawn. It is observed that for both the plates, an increase in Prandtl number results in the decrease of temperature distribution. This is due to the fact that there would be a decrease of thermal boundary layer thickness with the increase of Prandtl number. The same effect is witnessed in the case of K. But the temperature of the fluid decreases in the case of cooled plate whereas increases in the case of heated plate for an increase in So. It is also concluded that for electrolytic solution, temperature falls exponentially and for mercury it falls slowly and steadily.

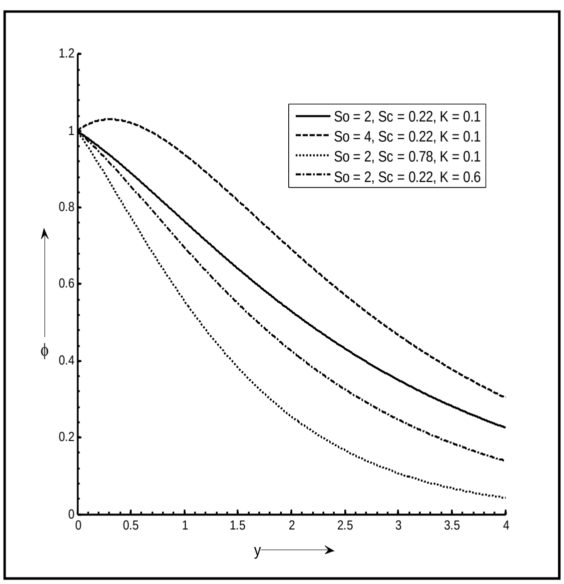

Fig. 7: Variation of concentration component for Gr = 5 (Gm = 2, M = 2 and Pr = 1.0)

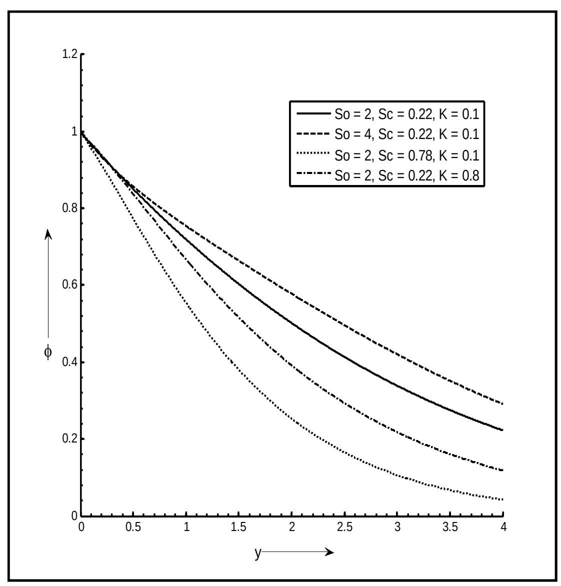

Fig. 8: Variation of concentration component for Gr = - 5 (Gm = 2, M = 2 and Pr = 1.0)

Figs. 7 and 8 gives the species concentration for different values of Sc, So and K. It is observed that the concentration at all points in the flow field decreases steadily with y and tends to zero as $y \rightarrow \infty$. A comparison of curves in Figs. 7 and 8 show a decrease in concentration with an increase in Schmidt number. Physically, theincrease of Sc means decrease of molecular diffusivity (D). That results in decrease of concentration boundary layer. Hence the concentration of the species is higher for small values of Sc and lower for larger values of Sc and this is analogous to the effect of increasing the Prandtl number on the thickness of a thermal boundary layer. The concentration falls due to the increasing values of chemical reaction parameter, but rises due to So for both cooled and heated plates.

Table 1: Variations in Skin friction

M	So	K	Sc	Skin Friction τ (Gr = 5)		Skin Friction τ (Gr = - 5)	
				Pr=0.025 Mercury	Pr=1.0 Electrolytic solution	Pr=0.025 Mercury	Pr=1.0 Electrolytic solution
2	2	0.1	0.22	3.6651	3.3005	-1.4210	-2.8648
5	2	0.1	0.22	1.4287	1.3308	-0.5833	-0.7287
2	4	0.1	0.22	3.6385	2.9593	-1.4473	-3.3985
2	2	0.3	0.22	3.6092	3.0311	-1.3397	-2.0762
2	2	0.1	0.30	3.5369	2.9372	-1.3028	-2.2806

Table 2: Variations in Rate of heat transfer

M	So	K	Sc	Nusselt Number Nu (Gr = 5)		Nusselt Number Nu (Gr = - 5)	
				Pr=0.025 Mercury	Pr=1.0 Electrolytic solution	Pr=0.025 Mercury	Pr=1.0 Electrolytic solution
2	2	0.1	0.22	-0.1218	-0.9276	-0.1241	-0.6726
5	2	0.1	0.22	-0.1238	-1.1724	-0.1243	-1.1337
2	4	0.1	0.22	-0.1219	-1.0791	-0.1241	-0.4648
2	2	0.3	0.22	-0.1219	-1.3159	-0.1242	-1.5217
2	2	0.1	0.30	-0.1222	-1.2167	-0.1242	-1.3057

Table 3: Variations in Rate of mass transfer

M	So	K	Sc	Sherwood Number Sh (Gr = 5)		Sherwood Number Sh (Gr = - 5)	
				Pr=0.025 Mercury	Pr=1.0 Electrolytic solution	Pr=0.025 Mercury	Pr=1.0 Electrolytic solution
2	2	0.1	0.22	-0.4044	-0.1810	-0.4044	-0.3219
5	2	0.1	0.22	-0.4035	-0.0873	-0.4035	-0.1055
2	4	0.1	0.22	-0.3348	-0.2113	-0.3346	-0.3056
2	2	0.3	0.22	-0.4948	-0.0935	-0.4946	0.0010
2	2	0.1	0.30	-0.4946	-0.0486	-0.4945	0.0087

Tables 1 to 3 demonstrates the effects of M, So, K and Sc on skin friction, rate of heat transfer and rate of mass transfer respectively. From Table.1, it is evident that an increase in M, So, K and Sc decreased the skin-friction for both mercury and electrolytic solution for cooled plate. But in the case of heated plated, for both mercury and electrolytic solutions, an increase in M, K and Sc increased the skin-friction whereas increase in So decreased the skin friction. Effect of M is more dominant. Rate of heat transfer variations are shown in Table.2. Rate of heat transfer of both the fluids decrease with increase in M, So, K and Sc for cooled plate. But in the case of the fluid flow on heated plate, Nu decreases with increase in M, So, K and Sc for mercury and decreases with M, K, Sc but increases with So for electrolytic solution.

Variations in rate of mass transfer are shown in Table.3. Rate of mass transfer decreases with increase in K and Sc but increases for M and So for mercury. But in the case of electrolytic solution Sh decreases with increase in So but increases with increase in M, K and Sc for both the plates. τ and Nu are more for mercury than electrolytic solution whereas Sh is less for mercury than electrolytic solution which is in agreement with the existing literature.

5. Conclusion

MHD mixed convection flow and heat-mass transfer past an infinite vertical plate with Ohmic heating and viscous dissipation in the presence of thermal diffusion and chemical reaction have been discussed. The equations governing such flow are transformed to dimensionless form. The ultimate resulting equations obtained are solved using perturbation method. The results are shown graphically for different values of the parameters considered in the analysis. The present investigation can be concluded as follows:

- The velocity of the fluid decreases with M, Sc and K on cooled plate but increases on heated plate.
- Velocity field is considerably affected even for small values of K.
- Magnetic field retards the motion of the fluid.
- **So** retards the velocity of the fluid flow both on cooled and heated plates due to the presence of chemical effect.
- Soret and chemical effects lowered the temperature of the fluid.
- Velocity and temperature profiles are higher for mercury than electrolytic solution.
- Soret effect increased the concentration of the fluid while chemical effect decreased.

6. Application

The results of this study can be applied in many chemical engineering processes such as drying, evaporation, condensation, sublimation and crystal growth as well as deposition of thin films. These processes take place in numerous industrial applications, e.g., polymer production, manufacturing of ceramics or glassware and food processing.

In nature, the presence of pure air or water is rather impossible. It is always possible that some other foreign mass is either present naturally in air, water or foreign masses are mixed with air or water. Simple example is the naturally available water-vapour in nature which causes the flow of air. The flow is also caused by the differences in concentration or material constitution. The presence of foreign mass in air or water causes, many times, some kind of soret and chemical effects combined, For e.g., ammonia, benzene, ethyl alcohol etc., react with air when they come in contact under certain conditions.

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