International Journal of Mathematical Archive-5(3), 2014, 160-167
Available online through www.ijma.info ISSN 2229 – 5046

UNSTEADY FREE CONVECTIVE MHD FLOW IN A ROTATING SYSTEM THROUGH POROUS MEDIUM WITH RADIATION

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(Received on: 28-02-14; Revised & Accepted on: 15-03-14)

ABSTRACT

The aim of this paper is to investigate the radiation effect on an unsteady MHD free convective heat and mass transfer flow of a viscous incompressible fluid through a porous medium, bounded by an infinite vertical porous surface, in a rotating system under the action of uniform magnetic field applied normal to the direction of flow in an optically thin environment. It is assumed that the porous surface is rotating with a constant angular velocity and the porous vertical surface is subjected to a uniform constant suction velocity. The temperature at this vertical surface is assumed to fluctuate in time about a non-zero constant mean. Analytical expressions for the velocity, temperature and concentration fields are obtained using the perturbation technique and influences of various thermo physical parameters are discussed and shown graphically. It is observed that the primary velocity component decreases with an increase in the radiation parameter R or rotation parameter E or permeability parameter Ko or Hartmann number M. It is also observed that the magnitude of the secondary velocity profiles increases when there is an increase in Radiation parameter R. It is also noted that the primary skin friction and the magnitude of the secondary skin friction component decreases due to an increase in radiation parameter R for the case of both water (Pr=7.0) or air (Pr=0.71).

Keywords*: Magneto hydrodynamics, heat and mass transfer, perturbation technique, free convection, porous medium, rotation, primary and secondary velocity components, radiation.*

1. INTRODUCTION

Radiation effects on free convection flow have become very important due to its applications in space technology, processes having high temperature, and design of pertinent equipments. Moreover, heat and mass transfer with thermal radiation on convective flows is very important due to its significant role in the surface heat transfer. Recent developments in gas cooled nuclear reactors, nuclear power plants, gas turbines, space vehicles, and hypersonic flights have attracted research in this field. Seddeek [12] explained the importance of thermal radiation and variable viscosity on unsteady forced convection with an align magnetic field. Muthucumaraswamy and Senthil [7] studied the effects of thermal radiation on heat and mass transfer over a moving vertical plate. Pal [8] investigated convective heat and mass transfer in a stagnation-point flow towards a stretching sheet with thermal radiation. Aydin and Kaya [2] justified the effects of thermal radiation on mixed convection flow over a permeable vertical plate with magnetic field. Chauhan and Rastogi [3] analyzed the effects of thermal radiation, porosity, and suction on unsteady convective hydromagnetic vertical rotating channel. Ibrahim and Makinde [5] investigated radiation effect on chemically reaction MHD boundary layer flow of heat and mass transfer past a porous vertical flat plate. Pal and Mondal [9] studied the effects of thermal radiation on MHD Darcy-Forchheimer convective flow past a stretching sheet in a porous medium. Satya narayana and sravanthi[11] studied the influence of thermal radiation on unsteady MHD convection flow past a semi-infinite inclined plate. Further due to increasing scientific and technical applications on the effect of radiation on flow characteristic has more importance in many engineering processes occurs at very high temperature and acknowledge radiative heat transfer such as nuclear power plant, gas turbine and various propulsion devices for aircraft, missile and space vehicles. Das et al.[4] discussed mass transfer effects on MHD flow and heat transfer past a vertical porous plate through a porous medium under oscillatory suction and heat source.

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On the other hand, the geophysical importance of the flows in the rotating frame of reference has attracted the attention of a number of scholars. Raptis [10] analyzed the steady free convective and mass transfer flow through porous medium in presence of a rotating fluid. Later Mahato and Maiti [6] investigated unsteady free convective flow and mass transfer in a rotating porous medium. Alam *et al*. [1] studied unsteady free convection and mass transfer flow in a rotating system with hall currents, viscous dissipation and joule heating. Recently Singh *et al*. [13] have studied free convective MHD flow of rotating viscous fluid in a porous medium past infinite vertical porous plate.

To the authors knowledge, in the studies mentioned above, the radiation effects on an unsteady free convective flow with heat and mass transfer effects in a rotating porous medium occupying a semi infinite region of space bounded by a vertical infinite porous surface in a rotating frame / system under the influence of a transverse magnetic field have not been discussed while such flows are very important in geophysical and astrophysical problems. Therefore, the objective of the present paper is to analyze the radiation effects on a viscous incompressible fluid past an infinite vertical porous surface in a rotating system, when the temperature of the surface varies with time about a non-zero constant mean and temperature at the free stream is constant.

2. FORMULATION OF THE PROBLEM

Consider an unsteady flow of an viscous, incompressible, electrically conducting fluid through a porous medium occupying a semi-infinite region of space bounded by a vertical infinite porous surface in a rotating system under the influence of transversely applied magnetic field. It is assumed that:

1) The fluid considered is an optically thin gray gas.
2) The transversely applied magnetic field and magnetic Reynolds number are assumed to be very small so that the induced magnetic field and hall effects are negligible.
3) The temperature of the surface varies with time about a non-zero constant mean and the temperature at the free stream is constant.
4) The concentration of the diffusing species in the binary mixture is assumed to be very small and hence, Soret and Dufour effects are negligible.
5) All the fluid properties except the density in the buoyancy force term are constant.
6) The effect of radiation on vertical surface which is subjected to uniform constant suction velocity in the direction perpendicular to surface.
7) The plate is maintained at constant temperature T_w^* and concentration C_w^* higher than the ambient temperature T_∞^* and concentration C_∞^* respectively.

A vertical infinite porous plate rotating in unison with a viscous fluid occupying the porous region with the constant angular velocity Ω about an axis which is perpendicular to the vertical plane surface is considered. Cartesian coordinate system is chosen such that x, y axes respectively are in the vertical upward and perpendicular directions on the plane of the vertical porous surface z = 0 while z-axis is normal to it. With the above frame of reference and assumptions, the physical variables, except the pressure p are functions of z and time t only. Consequently, the governing equations relevant to the problem are

$$\frac{\partial W^*}{\partial z^*} = 0 \tag{1}$$

$$\frac{\partial u^*}{\partial t^*} + \omega^* \frac{\partial u^*}{\partial z^*} - 2\Omega v^* = g\beta(T^* - T_\infty^*) + g\beta^*(C^* - C_\infty^*) + \mathcal{V}\frac{\partial^2 u^*}{\partial z^{*2}} - \frac{\mathcal{V}}{K^*}u^* - \frac{\sigma B_0^2 u^*}{\rho} \tag{2}$$

$$\frac{\partial v^*}{\partial t^*} + \omega^* \frac{\partial v^*}{\partial z^*} + 2\Omega u^* = \mathcal{V}\frac{\partial^2 v^*}{\partial z^{*2}} - \frac{\mathcal{V}}{K^*}u^* - \frac{\sigma B_0^2 v^*}{\rho} \tag{3}$$

$$0 = -\frac{1}{\rho}\frac{\partial p^*}{\partial z^*} - \frac{\mathcal{V}}{K^*}\omega^* \tag{4}$$

$$\frac{\partial T^*}{\partial t^*} + \omega^* \frac{\partial T^*}{\partial z^*} = \frac{k}{\rho C_p}\frac{\partial^2 T^*}{\partial z^{*2}} - \frac{1}{\rho c_p}\frac{\partial q_r^*}{\partial z^*} \tag{5}$$

$$\frac{\partial C^*}{\partial t^*} + \omega^* \frac{\partial C^*}{\partial z^*} = D\frac{\partial^2 C^*}{\partial z^{*2}} \tag{6}$$

The relevant boundary conditions are

$$u^* = 0, v^* = 0, T^* = T_\infty^* + \varepsilon(T_\omega^* - T_\infty^*)e^{i\omega t}, C^* = C_\infty^* \quad at \quad z^* = 0$$

$$u^*, v^* \to 0, T^* \to T_\infty^*, C^* \to C_\infty^* \quad as \; z^* \to \infty \tag{7}$$

where u^*, v^*, w^* are components of velocity, g is the acceleration due to gravity, β is the coefficient of thermal expansion, $\beta^*$is the concentration expansion coefficient,ω^* is the frequency of fluctuation, υ is the kinematic viscosity of the fluid, B_0 is the applied constant magnetic field, ρ is the density of the fluid, σ is the electrical conductivity, κ is thermal conductivity, c_p is the specific heat of the fluid at constant pressure, D is the chemical molecular diffusivity, P^* is the pressure, q_r^* is radiative heat flux and Ω angular velocity of the rotating frame of reference.

The plate temperature is assumed to vary harmonically with time. It varies from $T_\infty^* \pm \varepsilon(T_\omega^* - T_\infty^*)e^{i\omega t}$ as t varies from 0 to 2π/ω. Since ε is small, the plate temperature varies only slightly from the mean value T_∞^* .

For constant suction, we have from equation (1) in view of equation (7)

$$\omega^* = -\omega_0 \tag{8}$$

Considering $u^* + iv^* = U^*$ and taking into account equation (8), the equations (2) and (3) can be written as

$$\frac{\partial U^*}{\partial t^*} - \omega_0 \frac{\partial U^*}{\partial z^*} + 2\Omega i U^* = g\beta(T^* - T_\infty^*) + g\beta^*(C^* - C_\infty^*) + \mathcal{V}\frac{\partial^2 U^*}{\partial z^{*2}} - \frac{\mathcal{V}}{K^*}U^* - \frac{\sigma B_0^2 U^*}{\rho} \tag{9}$$

We introduce the following non-dimensional quantities

$$z = \frac{\omega_0 z^*}{\upsilon}, u = \frac{U^*}{\omega_0}, t = \frac{t^*\omega_0^2}{\mathcal{V}}, T = \frac{T^* - T_\infty^*}{T_w^* - T_\infty^*}, C = \frac{C^* - C_\infty^*}{C_w^* - C_\infty^*}, Sc = \frac{\mathcal{V}^*}{D}, R = \frac{16\sigma^* a^* T_\infty^* \mathcal{V}}{\rho c_p \omega_0^2},$$

$$Pr = \frac{\rho \upsilon c_p}{\kappa}, k_0 = \frac{k_r \omega_0^2}{\mathcal{V}^2},\ Gr = \frac{\upsilon g\beta\,(T_w^* - T_\infty^*)}{\omega_0^3}, Gm = \frac{\upsilon g\beta^*(C_w^* - C_\infty^*)}{\omega_0^3}, E = \frac{\Omega\upsilon}{\omega_0^2}, M^2 = \frac{\sigma B_0^2 \upsilon}{\rho\omega_0^2} \tag{10}$$

For the case of an optically thin gray gas, the radiative heat flux in energy equation (5) in the spirit of Vincenti and Krugger [14] is expressed as

$$\frac{\partial {q_r}^*}{\partial z^*} = -4a^*\sigma^*({T^*}_\infty^4 - {T^*}^4) \tag{11}$$

where a[*] is the mean absorption coefficient and σ^* is the Stefan-Boltzmann constant. It is assumed that the temperature differences within the flow are sufficiently small such that ${T^*}^4$may be expressed as linear function of the temperature T^*.This is accomplished by expanding ${T^*}^4$ in Taylor series about ${T^*}_\infty$ and neglecting higher order terms, thus

$${T^*}^4 \cong 4{T^*}_\infty^3 T - 3{{T^*}_\infty}^4 \tag{12}$$

Using the transformations (10) and with the help of (11) and (12), the non-dimensional forms of equations (9), (5) and (6) are

$$\frac{\partial U}{\partial t} - \frac{\partial U}{\partial z} + 2EiU = GrT + GmC + \frac{\partial^2 U}{\partial z^2} - \left(\frac{1}{k_0} + M^2\right)U \tag{13}$$

$$\frac{\partial T}{\partial t} - \frac{\partial T}{\partial z} = \frac{1}{Pr}\frac{\partial^2 T}{\partial z^2} - RT \tag{14}$$

$$\frac{\partial C}{\partial t} - \frac{\partial C}{\partial z} = \frac{1}{Sc}\frac{\partial^2 C}{\partial z^2} \tag{15}$$

And the boundary conditions (7) becomes

$$U = 0, T = 1 + \varepsilon e^{i\omega t}, C = 1 \quad at \quad z = 0$$

$$U \to 0, T \to 0, C \to 0 \qquad as \quad z \to \infty \tag{16}$$

3. METHOD OF SOLUTION

In order to reduce the system of partial differential, equations(13)-(15) under their boundary conditions (16), to a system of ordinary differential equations in the non dimensional form, we assume the following as the solutions for velocity, temperature and concentration of the flow field as the amplitude ε (<< 1) of the permeability variations is very small.

$$U(z,t) = U_0(z) + \varepsilon e^{i\omega t}U_1(z)$$

$$T(z,t) = T_0(z) + \varepsilon e^{i\omega t}T_1(z)$$

$$C(z,t) = C_0(z) + \varepsilon e^{i\omega t}C_1(z) \tag{17}$$

Substituting (17) into the system (13)-(15) and equating harmonic and non-harmonic terms we get

$$U_0'' + U_0' - \left(2iE + \frac{1}{k_0} + M^2\right) U_0 = -(GrT_0 + GmC_0) \tag{18}$$

$$U_1'' + U_1' - \left(\frac{1}{k_0} + M^2 + i(2E + \omega)\right) U_1 = -(GrT_1 + GmC_1) \tag{19}$$

$$T_0'' + PrT_0' - PrRT_0 = 0 \tag{20}$$

$$T_1'' + PrT_1' - (i\omega + R)PrT_1 = 0 \tag{21}$$

$$C_0'' + ScC_0' = 0 \tag{22}$$

$$C_1'' + ScC_1' - Sci\omega C_1 = 0 \tag{23}$$

The appropriate boundary conditions reduce to

$$U_0(0) = 0, T_0(0) = 1, C_0(0) = 1$$

$$U_1(0) = 0, T_1(0) = 1, T_1(0) = 0$$

$$U_0(\infty) \to 0, T_0(\infty) \to 0, C_0(\infty) \to 0$$

$$U_1(\infty) \to 0, T_1(\infty) \to 0, C_1(\infty) \to 0 \tag{24}$$

Thus, the solution of the problem is

$$U(z,t) = L_1 e^{-M_1 z} + L_2 e^{-Scz} + L_3 e^{M_4 z} + \varepsilon e^{i\omega t} L_4 (e^{-M_2 z} - e^{M_6 z}) \tag{25}$$

$$T(z,t) = e^{-M_1 z} + \varepsilon e^{i\omega t} e^{-M_2 z} \tag{26}$$

$$C(z,t) = e^{-Scz} \tag{27}$$

Now, it is convenient to write the primary and secondary velocity fields, in terms of the fluctuating parts, separating the real and imaginary parts from equations (25) and (26) and taking only the real parts as they have physical significance, the velocity and temperature distribution of the flow field can be expressed in fluctuating parts as given below.

$$\frac{u}{w_0} = u_0 + \varepsilon(N_r cos\omega t - N_i sin\omega t) \tag{28}$$

$$\frac{v}{w_0} = v_0 + \varepsilon(N_r sin\omega t + N_i cos\omega t) \tag{29}$$

where $u_0 + iv_0 = U_0$ and $N_0 + iN_i = U_i$

Hence, the expressions for the transient velocity profiles for $\omega t = \frac{\pi}{2}$ are given by

$$\frac{u}{w_0}\left(z, \frac{\pi}{2\omega}\right) = u_0(z) - \varepsilon N_i(z)$$

$$\frac{v}{w_0}\left(z, \frac{\pi}{2\omega}\right) = v_0(z) + \varepsilon N_r(z)$$

The skin-friction, Nusselt numbr and Sherwood number are important physical parameters for this type of boundary layer flow.

Knowing the velocity field, the skin-friction at the plate can be obtained, which in non-dimensional form is given by

$$\left.\frac{dU}{dz}\right|_{z=0} = \left.\frac{dU_0}{dz}\right|_{z=0} + \varepsilon e^{i\omega t} \left.\frac{dU_1}{dz}\right|_{z=0}$$

$$= (L_3 M_4 - L_1 M_1 - ScL_2) + \varepsilon e^{i\omega t} L_4(-M_2 - M_6) \tag{30}$$

Knowing the temperature field, the rate of heat transfer coefficient can be obtained, which in non-dimensional form, in terms of the Nusselt number, is given by

$$\left.\frac{dT}{dz}\right|_{z=0} = \left.\frac{dT_0}{dz}\right|_{z=0} + \varepsilon e^{i\omega t} \left.\frac{dT_1}{dz}\right|_{z=0}$$

$$= -M_1 + \varepsilon e^{i\omega t}(-M_2) \tag{31}$$

Knowing the concentration field, the rate of mass transfer coefficient can be obtained, which in non-dimensional form, in terms of Sherwood number, is given by

$$\left.\frac{dC}{dz}\right|_{z=0} = \left.\frac{dC_0}{dz}\right|_{z=0} + \varepsilon e^{i\omega t} \left.\frac{dC_1}{dz}\right|_{z=0} = -Sc \tag{32}$$

where, the mathematical expressions for the constants involved in equations (25) to (27) are not given here to save space.

4. RESULTS AND DISCUSSIONS

We have analyzed radiation effects on unsteady MHD free convective flow with heat and mass transfer in a rotating porous medium in the presence of magnetic field in an optically thin environment. The effects of flow parameters such as the magnetic parameter *M*, Grashof numbers for heat and mass transfer *Gr* and *Gm*, porosity parameter *Ko*, Prandtl number *Pr*, radiation parameter *R* and the rotation parameter *E* on the velocity, temperature and concentration fields have been studied analytically and shown graphically with the help of Figures 1 to 6, while the values of some of the physical parameters are taken as constants such as *Sc=0.6(*water vapor at approximately 25^{0}C and 1atm), *Pr=0.71*(air),*ω=5.0, M=1.0, ko=1.0, Gm=1.0, ε=0.002, R=1.0, t=1,E=2.0* ,$\omega t = \frac{\pi}{2}$ *and Gr= 1.0* in all the figures.

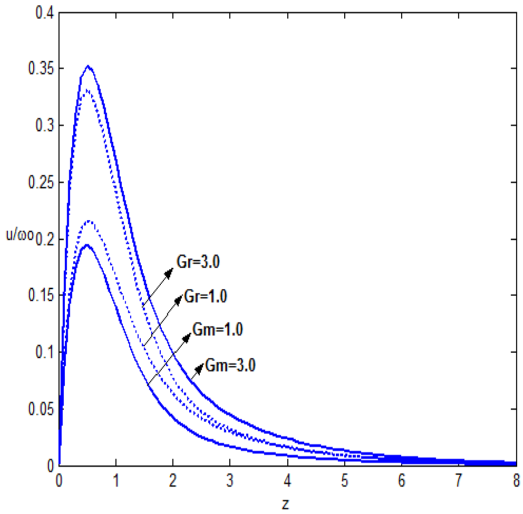

Figure 1: Effect of *Gr* and *Gm* on the Primary velocity

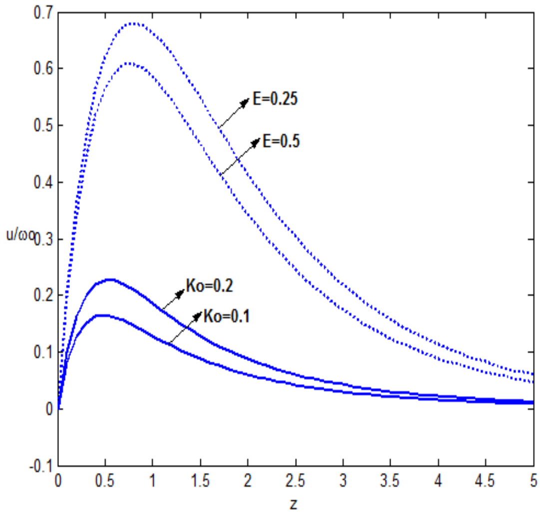

Figure 2: Effect of *Ko* and *E* on the primary velocity

For the case of different values of thermal Grashof number *Gr* and solutal Grashof number *Gm*, the primary velocity profiles in the boundary layer are shown in Figure 1. It is observed that an increase in either of *Gr* or *Gm* leads to a rise in the velocity due to the enhancement in buoyancy force which supports the motion of the fluid. Here, the positive values of *Gr* correspond to cooling of the surface. Figure 2 depicts the effect of permeability of the porous medium *(Ko)* and the rotation parameter *E* on the primary fluid velocity and it is observed that the fluid velocity decreases as porosity parameter *Ko* increases. Physically speaking, increasing permeability *Ko* means reduce the drag force and hence cause the flow velocity to increase. It is obvious that the effect of increasing the values of the parameter *E* results in a decreasing the velocity distribution across the boundary layer.

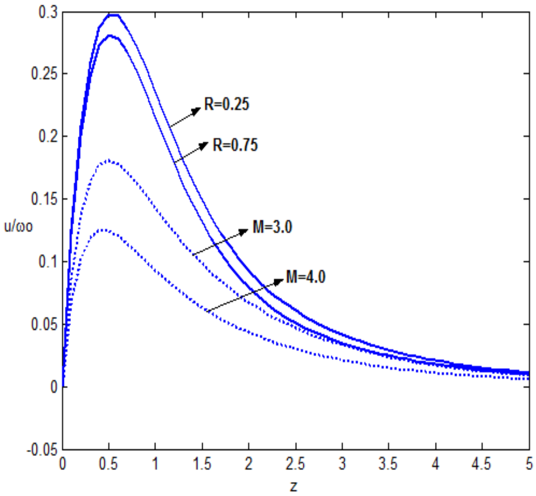

Figure 3: Effect of *R* and *M* on the primary velocity

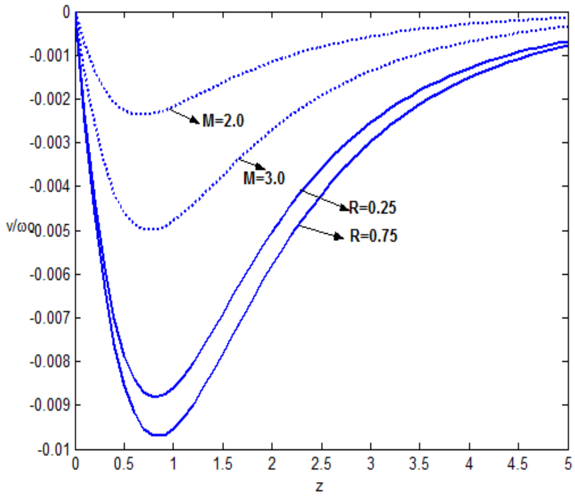

Figure 4: Effect of *R* and *M* on the secondary velocity

The effect of radiation parameter *R* and Hartmann number *M* on the primary velocity field has been illustrated in Figure 3. It is seen that as the radiation parameter increases the velocity field decreases. This may be attributed to the fact that an increase in *R* implies less interaction of radiation with the momentum boundary layer. It is interesting to note that the effect of Magnetic field is to decrease the value of the velocity through out the boundary layer. The peak value drastically decreases with increase in the value of the magnetic field, because, the presence of magnetic field in an electrically conducting fluid introduces a force called the Lorentz force, which acts against the flow if the magnetic field is applied in the normal direction. This type of resisting force slow downs the fluid velocity as shown in the graph. The effect of radiation parameter *R* and Hartmann number *M* on the secondary velocity profiles is shown in Figure 4. It is observed that as either *R* or *M* increases, the secondary velocity decreases. By comparing primary and secondary velocity profiles from Figures 3 and 4, it is noted that the secondary velocity profiles show a reverse flow.

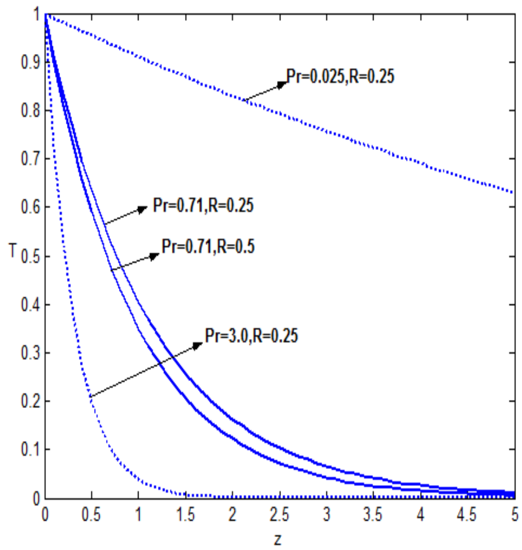

Figure 5: Effect of *Pr* and *R* on the temperature

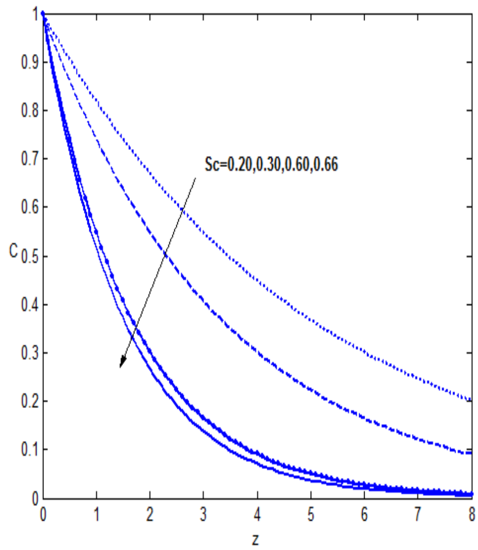

Figure 6: Effect of *Sc* on the concentration

Figure 5 shows the effect of radiation parameter *R and* Prandtl number *Pr* on the temperature. A rise in *R* causes a significant fall in the temperature values from the highest value at the wall (z=0) across the boundary layer to the free stream. Thus, a greater value of *R* corresponds to smaller radiation flux and the minimum temperature is observed. Radiation thereby reduces the rate of energy transport to the fluid. The Prandtl number *Pr* is taken to be equal to 0.025 which represents mercury (liquid metal i.e. very high thermal conductivity), 0.71 which represents air. The results show that an increase of the Prandtl number results in a decrease in the thermal boundary layer thickness and a more uniform temperature distribution across the boundary layer. The reason is that the smaller values of *Pr* are equivalent to increasing the thermal conductivities and therefore, heat is able to diffuse away from the heated surface more rapidly than for the larger values of *Pr*. For different values of the Schmidt number *Sc*, the concentration profiles are plotted in Figure 6. To be realistic, the values of the Schmidt number (*Sc*), so chosen to represent the presence of various species like Hydrogen (*Sc*=0.20), Helium (*Sc*=0.30), Steam (*Sc*=0.60), Oxygen (*Sc*=0.66). It is obvious that the effect of increasing values of *Sc* results in a decreasing concentration distribution.

Table 1: Variation of the skin friction (primary and magnitude of secondary) for various values of the radiation parameter *R* when *Sc=0.6, ω=5.0, M=3.0, ko=1.0, Gm=4.0, ε=0.002, t=1, E=0.6,* $\omega t = \frac{\pi}{2}$ *and Gr= 4.0.*

R	Primary skin friction $\frac{d}{dz}\left(\frac{u}{w_0}\right)$	Secondary skin friction $\frac{d}{dz}\left(\frac{v}{w_0}\right)$	Magnitude of secondary skin friction
		Pr = 0.71	
1	1.1050	-0.0571	0.0571
2	1.0668	-0.0536	0.0536
3	1.0406	-0.0514	0.0514
		Pr = 7.0	
1	1.7216	-0.0372	0.0372
2	1.6903	-0.0367	0.0367
3	1.6662	-0.0364	0.0364

Table 2: Variation of the heat transfer for various values of the radiation parameter *R* when *Sc=0.6,ω=5.0, M=3.0, ko=1.0, Gm=4.0, ε=0.002, t=1, E=0.6* ,$\omega t = \frac{\pi}{2}$ *and Gr= 4.0.*

R	Rate of heat transfer (*Pr* = 0.71)	Rate of heat transfer (*Pr* = 7.0)
1	-1.2653	-7.8686
2	-1.5942	-8.6046
3	-1.8528	-9.2475

Table 1 represents variation of skin friction (primary and magnitude of secondary) for various values of radiation parameter *R*. It is noted from Table 1 that the primary skin friction and magnitude of the secondary skin friction component decreases due to an increase in radiation parameter *R* in the case of both air (*Pr*=0.71)and water (*Pr*=7.0). The rate of heat transfer for various values of radiation parameter *R* is given in Table 2. The rate of heat transfer decreases whenever there is an increase in radiation parameter R. Table 3 represents a comparison of the numerical values of primary skin friction obtained in the present case with that of Das et al. [9] for different values of *Gm, Gr, Ko, E, M*. The effects of all parameters closely agree with the results of Das et al [9].

Table 3: Comparison of the primary skin friction of present case with that of Das et al. [9] for different values of *Gm, Gr, Ko, E, M* when *Sc=0.6,ω=5.0 and Pr=0.71(air)*

Gm	*Gr*	*Ko*	*E*	*M*	*Present work*	*Das et al.[9]*
2	2	1	0.6	1	2.2342	2.7087
2	2	1	1	1	2.0108	2.2342
2	2	3	1	1	2.1105	2.2006
4	2	1	0.6	1	3.7308	4.1182
4	5	1	0.6	1	5.5211	6.0669
4	5	1	0.6	3	2.7503	2.1285

5. CONCLUSION

An analysis of the radiation effect on an unsteady MHD free convective heat and mass transfer of a viscous incompressible fluid in a rotating porous medium is presented under the action of transverse applied magnetic field. The transformed system of non-linear, coupled, ordinary differential equations was solved analytically by using perturbation technique. A comprehensive set of graphical results for velocity (Primary and secondary), temperature and concentration is presented and their dependence on some physical parameters is discussed. The observations are:

1) The Grashof number or modified Grashof number for mass transfer have the effect of accelerating the primary velocity profiles, the magnitude of the secondary velocity profiles whereas the Hartmann number or radiation parameter has the effect of decreasing the flow field at all the points due to the magnetic pull of the Lorentz force acting on the flow field.
2) The concentration profiles and the velocity profiles decrease with an increase in Schmidt number irrespective of the presence or absence of radiation parameter.
3) The dimensionless skin friction coefficient is found to increase with increasing values of Grashof number , modified Grashof number for mass transfer or porosity parameter whereas it decrease with increasing values of Hartmann number.
4) An increase in radiation parameter decreases the rate of heat transfer as well as skin friction.

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Source of support: Nil, Conflict of interest: None Declared