Influence of Chemical Reaction, Magnetic Field, Radiation on Heat And Mass Transfer Over A Rotating Disk Embedded in A Porous Medium Considering Soret And Dufour Effects

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ABSTRACT

Heat and mass transfer characteristics of steady flow over a rotating disc embedded in a porous medium subjected to a chemical reaction, magnetic field, radiation are investigated numerically by taking into account the Soret and Dufour effects. The temperature and concentration profiles are drawn for various values of radiation parameter, magnetic field parameter, chemical reaction parameter, Prandtl number, Schmidt number, Darcy number, Soret and Dufour numbers. Numerical results of rate of heat and mass transfer for different parameters are presented in tabular form and the results are depicted graphically.

Keywords- Heat and mass transfer, chemical reaction, magnetic field, radiation, Soret and Dufour effects.

1. INTRODUCTION

Convective flow through porous media has attracted considerable attention in last several decades due to its many important engineering, environmental and geophysical applications. The combined heat and mass transfer problems with chemical reactions are investigated by many researchers in recent years. Researchers such as Nield and Bejan[1], Ingham and Pop [2] have made comprehensive reviews in free convection heat and mass transfer through porous media. Von Karman [3] introduced the flow due to an infinite rotating disk which is one of the classical problems in fluid mechanics. He formulated the problem in the steady state and then introduced similarity transformations to reduce the governing partial differential equations to ordinary differential equations. Cochran [4] obtained asymptotic solutions for the steady hydrodynamic problem formulated by von Karman. Millsaps and Pohlhausen [5] considered the problem of heat transfer from a rotating disk at a constant temperature for a variety of Prandtl numbers in the steady state. Sparrow and Gregg [6] studied the steady state heat transfer from a rotating disk maintained at a constant temperature to fluids at any Prandtl number. El-Mistikawy et al. [7] studied the effects of the magnetic field on the steady flow due to the rotation of a disk. Kumar et al. [8] and Turkyilmazoglu [9] covered the effects of a uniform
external magnetic field on the steady flow over a rotating disk. Hossain et.al. [10] and Maleque and Sattar [11] investigated the influence of variable properties on the physical quantities of the rotating disk problem by obtaining a self-similar solution of the Navier–Stokes equations along with the energy equation. Attia [12-14] investigated the effects of uniform suction or injection through a rotating porous disk on the steady hydrodynamic or hydromagnetic flow induced by the disk. Hossain and Takhar [15] studied the effects of radiation on mixed convection flow of an optically dense viscous incompressible fluid past a heated vertical plate with uniform free stream velocity and surface temperature. Damesh et al. [16] studied the similarity analysis of magnetic field and thermal radiation effects on forced convection flow. Sharma and Aich [17] studied the influence of chemical reaction, magnetic field and radiation on Heat and Mass Transfer by free convection flow near the lower stagnation point of an isothermal horizontal circular cylinder in a porous medium considering Soret and Dufour Effects. Anjalidevi and Uma-devi [18] studied the hydromagnetic flow due to a rotating disc with radiation effects. Attia [19] investigated numerically the steady flow and heat transfer of an incompressible viscous fluid in a porous medium due to a rotating disk neglecting Soret and Dufour effects. Sharma and Borgohain [20] investigated the influence of chemical reaction, Soret and Dufour effects on heat and mass transfer of a binary fluid mixture in porous medium over a rotating disk.

The objective of this paper is to study the effect of chemical reaction, radiation, thermal-diffusion and diffusion-thermal effects on MHD heat and mass transfer over a rotating disc embedded in a porous medium.

2. MATHEMATICAL FORMULATION

We consider steady, laminar, three dimensional MHD heat and mass transfer of a viscous incompressible electrically conducting fluid over a rotating disk embedded in a porous medium in the presence of radiation. It is assumed that the fluid is infinite in extent in the positive z-direction. Let \((r, \phi, z)\) be the set of cylindrical polar coordinates and let the disk rotate with constant angular velocity \(\omega\) and be placed at \(z = 0\) as indicated in Fig. 1.

Fig. 1: Physical model and coordinate system
The motion of the fluid is due to its rotation about an axis perpendicular to its plane. The ambient temperature far away from the surface of the disk is $T_\infty$ and the surface of the disk is maintained at constant temperature $T_W$ such that $T_W > T_\infty$. The concentration of the fluid at the surface is $C_W$ and far away from the disk is $C_\infty$ such that $C_W > C_\infty$. The fluid properties are assumed to be constant. The effects of thermal-diffusion, diffusion-thermal, a first order homogenous chemical reaction, radiation and uniform magnetic field on heat and mass transfer are taken into account. The external weak uniform magnetic field $B_0$ is imposed in the direction normal to the surface of the disk by considering small magnetic Reynolds number ($Re < 1$). It is assumed that the induced magnetic field due to the motion of the electrically conducting fluid is negligible. The fluid is considered to be gray absorbing-emitting radiations but non scattering medium and the Rosseland approximation is used to describe the radiative heat flux in $z$-direction.

Under these assumptions, the basic boundary layer equations describing the conservation of mass, momentum, energy and concentration can be written as follows:

\[
\frac{\partial u}{\partial r} + \frac{u}{r} + \frac{\partial w}{\partial z} = 0 , \quad \ldots (1)
\]

\[
\rho \left( \frac{\partial u}{\partial r} + w \frac{\partial u}{\partial z} - \frac{v^2}{r} \right) + \frac{\partial p}{\partial r} = \mu \left( \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} - \frac{u}{r^2} + \frac{\partial^2 u}{\partial z^2} \right) - \frac{\mu u}{K'} - \sigma B_0^2 u , \quad \ldots (2)
\]

\[
\rho \left( \frac{\partial v}{\partial r} + w \frac{\partial v}{\partial z} + \frac{uv}{r} \right) = \mu \left( \frac{\partial^2 v}{\partial r^2} + \frac{1}{r} \frac{\partial v}{\partial r} - \frac{v}{r^2} + \frac{\partial^2 v}{\partial z^2} \right) - \frac{\mu v}{K'} - \sigma B_0^2 v , \quad \ldots (3)
\]

\[
\rho \left( \frac{\partial w}{\partial r} + w \frac{\partial w}{\partial z} \right) + \frac{\partial p}{\partial z} = \mu \left( \frac{\partial^2 w}{\partial r^2} + \frac{1}{r} \frac{\partial w}{\partial r} + \frac{\partial^2 w}{\partial z^2} \right) - \frac{\mu w}{K'} , \quad \ldots (4)
\]

\[
\rho C_p \left( \frac{\partial T}{\partial r} + w \frac{\partial T}{\partial z} \right) = \frac{k}{C_p} \left( \frac{\partial^2 T}{\partial z^2} + \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) + \frac{\rho D_m k_T}{C_p} \left( \frac{\partial^2 C}{\partial z^2} + \frac{\partial^2 C}{\partial r^2} + \frac{1}{r} \frac{\partial C}{\partial r} \right) - \frac{\partial r}{\partial z} , \quad \ldots (5)
\]

\[
u \frac{\partial C}{\partial r} + w \frac{\partial C}{\partial z} = D_m \left( \frac{\partial^2 C}{\partial z^2} + \frac{\partial^2 C}{\partial r^2} + \frac{1}{r} \frac{\partial C}{\partial r} \right) + \frac{D_m k_T}{T_m} \left( \frac{\partial^2 T}{\partial z^2} + \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) - K_1 (C - C_\infty) , \quad \ldots (6)
\]

where $u, v, w$ are velocity components in the directions of increasing $r, \phi, z$ respectively, $p$ is the pressure, $\mu$ is the coefficient of viscosity, $\rho$ is the density of the fluid, $B_0$ is the strength of the magnetic field, $K'$ is permeability of porous medium, $\sigma$ is the electrical conductivity, $k$ is the thermal conductivity, $k_T$ is the thermal diffusion ratio, $D_m$ is the mass diffusivity, $T$ is temperature, $C$ is concentration, $C_p$ is the specific heat capacity, $C_s$ is the concentration susceptibility, $q_r$ is the radiative heat flux, $T_m$ is the mean fluid temperature and $K_1$ is the dimensional chemical reaction parameter.

The radiative heat flux $q_r$ under Rosseland approximation is given by the expression

\[
q_r = \frac{4 \sigma^* \partial T^4}{3 k^* \partial z} \quad \ldots (7)
\]

where $\sigma^*$ is Stefan-Boltzmann constant and $k^*$ is the mean absorption coefficient.

It is assumed that temperature differences within the flow are sufficiently small such that $T^4$ can be expanded in a Taylor’s series about $T_\infty$ and after rejecting higher order terms, we have

\[
T^4 = 4T_\infty^3 T - 3T_\infty^4 \quad \ldots (8)
\]

The boundary conditions for this problem are given by

\[
u = 0, \quad w = 0, \quad T = T_W, \quad C = C_W \quad \ldots \text{at} \ z = 0 \quad (9)
\]
We now introduce the following von-Karman transformations:

\[ u = \tau \omega F, \quad v = \tau \omega G, \quad w = \sqrt{\omega \nu} H, \quad \eta = z \sqrt{\frac{\omega}{\nu}}, \quad \theta = \frac{T - T_\infty}{T_w - T_\infty}, \quad \phi = \frac{C - C_\infty}{C_w - C_\infty}, \quad \rho = \rho_\infty + \rho \nu \nu \]

...(10)

where \( \eta \) is the non-dimensional distance measured along the axis of rotation. \( F, G, H, P, \theta \) and \( \phi \) are the non-dimensional functions of \( \eta \), \( \nu = \frac{\mu}{\rho} \) is the kinematic viscosity of the fluid.

Introducing the relation (10) into the equations (1) - (6), we obtain the following system of ordinary coupled differential equations:

\[ 2F + H' = 0 \]

...(11)

\[ F'' - HF' - F^2 + G^2 - (Da + M)F = 0 \]

...(12)

\[ G'' - HG' - 2FG - (Da + M)G = 0 \]

...(13)

\[ H'' - HH' - P' - DaH = 0 \]

...(14)

\[ \frac{\theta''}{Pr} \left( 1 + \frac{4}{3Rd} \right) - H \theta' + Df \phi'' = 0 \]

...(15)

\[ \frac{1}{Sc} \phi'' - H \phi' + S_r \theta'' - \gamma \phi = 0 \]

...(16)

where \( Da = \frac{\nu}{\omega K} \) is the porosity parameter, \( M = \frac{\sigma B_0^2}{\rho \omega} \) is the magnetic parameter, \( Pr = \frac{\mu C_p}{k} \) is the Prandtl number, \( Rd = \frac{k \kappa^*}{4 \sigma^* T_0^2} \) is the radiation parameter, \( Df = \frac{D_m k_T(C_w - C_\infty)}{C_e C_p V(T_w - T_\infty)} \) is the Dufour number, \( Sc = \frac{\nu}{D_m} \) is the Schmidt number, \( S_r = \frac{D_m k_T(T_w - T_\infty)}{T_m V(C_w - C_\infty)} \) is the Soret number and \( \gamma = \frac{K_1}{\omega} \) is the chemical reaction parameter.

The boundary conditions (9) are now transformed to

\[ F = 0, G = 1, H = 0, \theta = 1, \phi = 1 \] at \( \eta = 0 \)

\[ F \to 0, G \to 0, \theta \to 0, \phi \to 0 \] as \( \eta \to \infty \)

...(17)

3. RESULTS AND DISCUSSIONS

The ordinary differential equations (11) , (12), (13), (15) and (16) with the corresponding boundary conditions (17) have been solved numerically by using bvp4c solver of MATLAB. Equation (14) can be used to solve the pressure distribution if required. From the process of numerical computation , the local Nusselt number and the local Sherwood number which are proportional to \( \theta'(0) \) and \( \phi'(0) \) respectively are worked out and their numerical values are presented in tabular form. Numerical calculations for \( \theta' \) and \( \phi' \) have been carried out by taking various values of parameters \( Da, M, Pr, Rd, Df, Sc, S_r \) and \( \gamma \). Several cases are considered:

Case I: \( M = 1.0, Pr = 7.0, Rd = 2.0, Df = 0.15, Sc = 1.6, S_r = 0.1, \gamma = 0.2, Da = (0.2, 0.5, 0.8) \).

Case II: \( Da = 0.5, Pr = 7.0, Rd = 2.0, Df = 0.15, Sc = 1.6, S_r = 0.1, \gamma = 0.2, M = (0.5, 1.0, 1.5) \).
Case III: $Da = 0.5, M = 1.0, Rd = 2.0, D_f = 0.15, Sc = 1.6, S_r = 0.1, \gamma = 0.2, Pr = (5.0,7.0,9.0)$.

Case IV: $Da = 0.5, M = 1.0, Pr = 7.0, D_f = 0.15, Sc = 1.6, S_r = 0.1, \gamma = 0.2, Rd = (1.0,2.0,3.0)$.

Case V: $Da = 0.5, M = 1.0, Pr = 7.0, Rd = 2.0, D_f = 0.15, Sc = 1.6, S_r = 0.1, \gamma = 0.2, D_f = (0.1,0.15,0.2)$.

Case VI: $Da = 0.5, M = 1.0, Pr = 7.0, Rd = 2.0, D_f = 0.15, Sc = 1.6, S_r = 0.1, \gamma = 0.2, Sc = (1.0,1.6,2.0)$.

Case VII: $- Da = 0.5, M = 1.0, Pr = 7.0, Rd = 2.0, D_f = 0.15, Sc = 1.6, S_r = 0.1, \gamma = (0.1,0.2,0.3)$.

Case VIII: $- Da = 0.5, M = 1.0, Pr = 7.0, Rd = 2.0, D_f = 0.15, Sc = 1.6, S_r = 0.1, \gamma = (0.1,0.2,0.3)$.

**Case I:** Fig. 2(a)-(b) exhibit temperature and concentration profile for various values of Darcy parameter $Da$. It is observed that the temperature and concentration decrease exponentially from their maximum values at the surface to their minimum values at the end of the boundary layer. Fig. 2(a) exhibits that with the increase in the values of $Da$, temperature of the fluid increases in the boundary layer region $0 < \eta < 9$ and no effect is observed from $\eta = 9$ onwards. Fig. 2(b) exhibits that with the increase in the value of $Da$, concentration of the fluid increases slightly in the boundary layer region $0 < \eta < 8.5$ and no effect is observed from $\eta = 8.5$ onwards.

![Fig. 2: Effect of Darcy parameter $Da$ on (a) the temperature profile and (b) the concentration profiles](image)

**Case II:** Fig. 3(a)-(b) exhibit temperature and concentration profile for various values of Magnetic field parameter $M$. It is observed that the temperature and concentration decrease exponentially from their maximum values at the surface to their minimum values at the end of the boundary layer. Fig. 3(a) exhibits that with the increase in the values of $M$, temperature of the fluid increases in the boundary layer region $0 < \eta < 10$. Fig. 3(b) exhibits that with the increase in the value of $M$, concentration of the fluid increases slightly in the boundary layer region $0 < \eta < 8.5$ and no effect is observed from $\eta = 8.5$ onwards.
Fig. 3: Effect of Magnetic field parameter $M$ on (a) the temperature profile and (b) the concentration profiles

**Case III:** Fig. 4(a)-(b) exhibit temperature and concentration profile for various values of Prandtl number $Pr$. It is observed that the temperature and concentration decrease exponentially from their maximum values at the surface to their minimum values at the end of the boundary layer. Fig. 4(a) exhibits that with the increase in the values of $Pr$, temperature of the fluid decreases in the boundary layer region $0 < \eta < 10$. Fig. 4(b) exhibits that with the increase in the value of $Pr$, concentration of the fluid decreases slightly in the boundary layer region $0 < \eta < 0.2$ but reverse effect is observed from $0.2 < \eta < 10$.

Fig. 4: Effect of Prandtl number $Pr$ on (a) the temperature profile and (b) the concentration profiles

**Case IV:** Fig. 5(a)-(b) exhibit temperature and concentration profile for various values of Radiation parameter $Rd$. It is observed that the temperature and concentration decrease exponentially from their maximum values at the surface to their minimum values at the end of the boundary layer. Fig. 5(a) exhibits
that with the increase in the values of $Rd$, temperature of the fluid decreases in the boundary layer region $0 < \eta < 10$. Fig. 5(b) exhibits that with the increase in the value of $Rd$, concentration of the fluid decreases slightly in the boundary layer region $0 < \eta < 0.2$ but reverse effect is observed from $0.2 < \eta < 10$.

**Fig. 5:** Effect of Radiation parameter $Rd$ on (a) the temperature profile and (b) the concentration profiles.

**Case V:**- Fig. 6(a)-(b) exhibit temperature and concentration profile for various values of Dufour number $D_f$. It is observed that the temperature and concentration decrease exponentially from their maximum values at the surface to their minimum values at the end of the boundary layer. Fig. 6(a) exhibits that with the increase in the values of $D_f$, temperature of the fluid increases in the boundary layer region $0 < \eta < 9.5$ and no significant effect is observed from $\eta = 9.5$ onwards. Fig. 6(b) exhibits that with the increase in the value of $D_f$, concentration of the fluid decreases slightly in the boundary layer region $0 < \eta < 9$ and no effect is observed from $\eta = 9$ onwards.

**Fig. 6:** Effect of Dufour number $D_f$ on (a) the temperature profile and (b) the concentration profiles

**Case VI:**- Fig. 7(a)-(b) exhibit temperature and concentration profile for various values of Schmidt number $Sc$. It is observed that the temperature and concentration decrease exponentially from their maximum values
at the surface to their minimum values at the end of the boundary layer. Fig. 7(a) exhibits that with the increase in the values of $Sc$, temperature of the fluid increases in the boundary layer region $0 < \eta < 3.5$ but reverse effect is observed from $3.5 < \eta < 10$. Fig. 7(b) exhibits that with the increase in the value of $Sc$, concentration of the fluid decreases in the boundary layer region $0 < \eta < 9$ and no effect is observed from $\eta = 9$ onwards.

![Fig. 7: Effect of Schmidt number $Sc$ on (a) the temperature profile and (b) the concentration profiles](image)

**Case VII:**- Fig. 8(a)-(b) exhibit temperature and concentration profile for various values of Soret number $Sr$. It is observed that the temperature and concentration decrease exponentially from their maximum values at the surface to their minimum values at the end of the boundary layer. Fig. 8(a) exhibits that with the increase in the values of $Sr$, temperature of the fluid increases slightly in the boundary layer region $0 < \eta < 0.4$ but reverse effect is observed from $0.4 < \eta < 10$. Fig. 8(b) exhibits that with the increase in the value of $Sr$, concentration of the fluid decreases slightly in the boundary layer region $0 < \eta < 0.4$ but reverse effect is observed from $0.4 < \eta < 10$.

![Fig. 8: Effect of Soret number $Sr$ on (a) the temperature profile and (b) the concentration profiles](image)
Case VIII: - Fig. 9(a)-(b) exhibit temperature and concentration profile for various values of chemical reaction parameter $\gamma$. It is observed that the temperature and concentration decrease exponentially from their maximum values at the surface to their minimum values at the end of the boundary layer. Fig. 9(a) exhibits that with the increase in the values of $\gamma$, temperature of the fluid increases in the boundary layer region $0 < \eta < 3.5$ but reverse effect is observed from $3.5 < \eta < 10$. Fig. 9(b) exhibits that with the increase in the value of $\gamma$, concentration of the fluid decreases in the boundary layer region $0 < \eta < 9.5$ and no effect is observed from $\eta = 9.5$ onwards.

Fig. 9: Effect of chemical reaction parameter $\gamma$ on (a) the temperature profile and (b) the concentration profiles

Table 1: The values of rate of heat and mass transfer in terms of local Nusselt number $-\theta'(0)$ and local Sherwood number $-\phi'(0)$ for selected values of $Da, M, Pr, Rd, Df, Sc, Sr$ and $\gamma$.

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4. CONCLUSIONS

In this work, chemical reaction, radiation thermal-diffusion and diffusion-thermal effects on MHD heat and mass transfer on a rotating disc embedded in a porous medium has been investigated. From our investigation as obvious from table 1, we can conclude that the rate of heat transfer decreases in magnitude with increase in Darcy number, magnetic field parameter, Dufour number, Schmidt number, Soret number and chemical reaction parameter but increases in magnitude with increase in Prandtl number and Radiation parameter. We can also conclude from table 1 that the rate of mass transfer decreases in magnitude with increase in Darcy number and magnetic field parameter but increases in magnitude with increase in Prandtl number, Radiation parameter, Dufour number, Schmidt number, Soret number and chemical reaction parameter. So, further investigation of the problem can be done by considering viscous dissipation term in the energy equation.

5. REFERENCES


