Dufour and Soret Effects on Unsteady MHD Free Convection and Mass Transfer Fluid Flow Through a Porous Medium in a Rotating System

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Abstract

The numerical studies are performed to examine the unsteady MHD free convection and mass transfer flow through a porous medium with thermal diffusion and diffusion thermo past an infinite vertical porous plate in a rotating system. Method of superposition is used as a main tool for numerical solution. The study is mainly based on the similarity approach. Impulsively started plate moving in its own plane is considered. Similarity equations of the corresponding momentum, energy and concentration equations are derived by introducing a time dependent length scale which in fact plays the role of a similarity parameter. The velocity component is taken to be inversely proportional to this parameter. The effects on the velocity, temperature, concentration, local skin-friction coefficients, Nusselt number and the Sherwood number of the various important parameters entering into the problem separately are discussed with the help of graphs and tables.

Key words: Numerical studies, Magnetohydrodynamics, Dufour, Soret, Rotating system

Nomenclature

\( x, y, z \), Cartesian coordinates
\( t \) Time
\( u, v, w \) Fluid velocities
\( v_0 \) Velocity of suction
\( \mu \) Kinematics viscosity
\( \eta \) Similarity variables
\( \nu \) Coefficient of kinematics viscosity
\( \theta \) Dimensionless temperature
\( \varphi \) Dimensionless concentration
\( \rho \) Fluid density

\( B \) Magnetic field
\( \beta \) Coefficient of volume expansion
\( \beta^* \) Volumetric coefficient of expansion with concentration
\( g_0 \) Acceleration due to gravity
\( U_0 \) Uniform velocity
\( T \) Temperature
\( T_w \) Plate temperature
\( T_\infty \) Free stream temperature
\( C \) Concentration

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Introduction

The science of magnetohydrodynamics (MHD) was concerned with geophysical and astrophysical problems for a number of years. In recent years the possible use of MHD is to affect a flow stream of an electrically conducting fluid for the purpose of thermal protection, braking, propulsion and control. From the point of applications, model studies on the effect of magnetic field on free convection flows have been made by several investigators. Some of them are Georgantopoulos (1979), Nanousis et al. (1980) and Raptis and Singh (1983). Along with the effects of magnetic field, the effect of transpiration parameter, being an effective method of controlling the boundary layer has been considered by Singh (1982). On the other hand, along with the free convection currents, caused by the temperature difference, the flow is also effected by the difference in concentrations on material constitution. Gebhart and Pera (1971) made extensive studies of such a combined heat and mass transfer flow to highlight the insight of the flow.

In the above mentioned works, the level of concentration of foreign mass is assumed very low so that the Soret and Dufour effects are 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 (\( \text{H}_2, \text{He}\)) and of medium molecular weight (\( \text{N}_2, \text{air}\)). The Dufour effect was found to be of order of considerable magnitude such that it cannot be ignored (Eckert and Drake, 1972). In view of the importance of above mentioned effects, Kafoussias and Williams (1995) studied the Soret and Dufour effects on mixed free-forced convective and mass transfer boundary layer flow with temperature dependent viscosity. Anghel et al. (2000) investigated the Dufour and Soret effects on free convection boundary layer flow over a vertical surface embedded in a porous medium. Quite recently, Alam and Rahman (2006) investigated the Dufour and Soret effects on mixed convection flow past a vertical porous flat plate with variable suction.
In consequence of the above studies, several investigators disclosed that the Coriolis force is very significant as compared to viscous and inertia forces occurring in the basic fluid equations. It is generally admitted that the Coriolis force due to Earth's rotation has a strong effect on the hydromagnetic flow in the Earth's liquid core. The study of such fluid flow problem is important due to its applications in various branches of geophysics, astrophysics and fluid engineering. From the point of application in solar physics and cosmic fluid dynamics, it is important to consider the effects of the electromagnetic and rotation forces on the flow. Considering this aspect of the rotational flows, model studies were carried out on MHD free convection and mass transfer flows in a rotating system by many investigators of whom the names are Debnath (1975), Debnath et al. (1979) and Raptis and Perdikis (1982) are worth mentioning. Singh (1984), Raptis and Singh (1985) and Singh and Singh (1989) have made a few studies by taking various aspects of the flow phenomena. But no works of the simultaneous effects of the electromagnetic and rotation forces on the hydromagnetic free convection and mass transfer with Dufour and Soret effects have been reported in the literature.

Hence, our objective is to investigate the Dufour and Soret effects on unsteady MHD free convection and mass transfer flow through a porous medium past an infinite vertical porous plate in a rotating system.

### Governing Equation

Consider an unsteady MHD free convection and mass transfer flow of an electrically conducting viscous fluid through a porous medium along an infinite vertical porous plate \( y=0 \) in a rotating system. The flow is also assumed to be in the \( x \)-direction which is taken along the plate in the upward direction and \( y \)-axis is normal to it. Initially the fluid as well as the plate is at rest, after that the whole system is allowed to rotate with a constant angular velocity \( \Omega \) about the \( y \)-axis. The temperature and the species concentration at the plate are constantly raised from \( T_w \) and \( C_w \) to \( T_{\infty} \) and \( C_{\infty} \) respectively, which are thereafter maintained constant, where \( T_{\infty} \) and \( C_{\infty} \) are the temperature and species concentration of the uniform flow respectively. A uniform magnetic field \( \mathbf{B} \) is taken to be acting along the \( y \)-axis which is assumed to be electrically non-conducting. We assumed that the magnetic Reynolds number of the flow is taken to be small enough so that the induced magnetic field is negligible in comparison with applied one (Pai, 1962), so that \( \mathbf{B} =(0,B_0, 0) \) and the magnetic lines of force are fixed relative to the fluid. The equation of conservation of charge \( \nabla \cdot \mathbf{J}=0 \) gives \( J_z = \text{constant} \), where the current density \( \mathbf{J}=(J_x, J_y, J_z) \). Since the plate is electrically non-conducting, this constant is zero and hence \( J_z = 0 \) at the plate and hence zero everywhere.
The physical configuration considered here is shown in the following Fig. 1.

![Fig. 1. Physical configuration and coordinate system](image)

With in the frame of such assumptions, neglecting the Joule heating and viscous dissipation terms and under the usual Boussinesq’s approximation, the governing equations relevant to the problem are

The continuity equation:
\[ \frac{\partial v}{\partial y} = 0 \]  
\[ (1) \]

The momentum equations:
\[ \frac{\partial u}{\partial t} + v \frac{\partial u}{\partial y} = g_0 \beta (T - T_\infty) + g_0 \beta' (C - C_\infty) \]
\[ + \nu \frac{\partial^2 u}{\partial y^2} + 2 \Omega w \frac{v}{K} u - \frac{\sigma B_0^2 u}{\rho} \]
\[ (2) \]

\[ \frac{\partial w}{\partial t} + v \frac{\partial w}{\partial y} = \nu \frac{\partial^2 w}{\partial y^2} - 2 \Omega u - \frac{v}{K'} w - \frac{\sigma B_0^2 w}{\rho} \]
\[ (3) \]

The energy equation:
\[ \frac{\partial T}{\partial t} + v \frac{\partial T}{\partial y} = \frac{k}{\rho c_p} \frac{\partial^2 T}{\partial y^2} + \frac{D_m k_T}{c_p c_p} \frac{\partial^2 C}{\partial y^2} \]  
\[ (4) \]

The concentration equation:
\[ \frac{\partial C}{\partial t} + v \frac{\partial C}{\partial y} = \frac{D_m}{T_m} \frac{\partial^2 C}{\partial y^2} + \frac{D_m k_T}{T_m} \frac{\partial^2 T}{\partial y^2} \]  
\[ (5) \]

where all physical quantities are defined in the nomenclature.

The boundary conditions for the present problem are
\[ t \leq 0, u = 0, v = 0, w = 0, T = T_\infty, C = C_\infty \]  
for all values of \( y \)
\[ t > 0, u = U_0, v = v(t), w = 0, T = T_v, C = C_v, \text{ at } y = 0 \]
\[ t > 0, u = 0, v = 0, w = 0, T \to T_v, C \to C_v, \text{ at } y \to \infty \]
\[ (6) \]

In order to obtain similar solutions we introduce a similarity parameter \( \sigma \) as
\[ \sigma = \sigma (t) \]  
\[ (7) \]

such that \( \sigma \) is the time dependent length scale. In terms of this length scale, a convenient solution of equation (1) is considered to be
\[ v = -\frac{v_0}{\sigma} u . \]  
\[ (8) \]

Here the constant \( v_0 \) represents a dimensionless normal velocity at the plate which is positive for suction and negative for blowing.
We now introduce the following dimensionless variables to attain a similarity solution

\[
\begin{align*}
\eta &= \frac{y}{\sigma} \\
f(\eta) &= \frac{u}{U_0} \\
g(\eta) &= \frac{w}{U_0} \\
\theta(\eta) &= \frac{T-T_m}{T_w-T_m} \\
\phi(\eta) &= \frac{C-C_m}{C_w-C_m}
\end{align*}
\]  

(9)

Then introducing equations (8)-(9) into equations (2)-(5), we obtain

\[
\begin{align*}
-\frac{\sigma}{v} \frac{\partial \sigma}{\partial t} \eta f' - v_0 f' &= f'' + G_r \theta + \\
G_m \phi - Kf - Mf - 2Rg &= 0 \\
-\frac{\sigma}{v} \frac{\partial \sigma}{\partial t} \eta g' - v_0 g' &= g'' - Kg - Mg + 2Rf \\
-\frac{\sigma}{v} \frac{\partial \sigma}{\partial t} \eta \theta' - v_0 \theta' &= \frac{1}{P_r} \theta'' + D_r \phi'' \\
-\frac{\sigma}{v} \frac{\partial \sigma}{\partial t} \eta \phi' - v_0 \phi' &= \frac{1}{S_c} \phi'' + S_r \theta''
\end{align*}
\]  

(10)-(13)

The equations (10)-(13) are similar except for the term \(\frac{\sigma}{v} \frac{\partial \sigma}{\partial t}\) where time t appears explicitly. Thus the similarity condition requires that \(\frac{\sigma}{v} \frac{\partial \sigma}{\partial t}\) in the equations (10)-(13) must be a constant quantity. Hence following the works of Sattar and Alam (1994) one can try a class of solutions of the equations (10)-(13) by assuming that

\[
\frac{\sigma}{v} \frac{\partial \sigma}{\partial t} = c (a \text{ constant})
\]  

(14)

Now integrating (14) one obtains

\[
\sigma = \sqrt{2c v t}
\]  

(15)

where the constant of integration is determined through the condition that \(\sigma = 0\) when \(t=0\). It thus appears from (15) that, by making a realistic choice of \(c\) to be equal to 2 in (14) the length scale \(\sigma\) becomes equal to \(\sigma = 2\sqrt{v t}\) which exactly corresponds to the usual scaling factor considered for various
unsteady boundary layer flows (Schlichting, 1968). Since $\sigma$ is a scaling factor as well as a similarity parameter, any other value of $c$ in (14) would not change the nature of the solution except that the scale would be different. Finally, introducing (14) with $c = 2$ in equations (10)-(13), we respectively have the following dimensionless ordinary differential equations

\begin{align*}
 f'' + 2\xi f' + G\theta + G_m\phi - K f' - M f' - 2R g = 0 \\
 g'' + 2\xi g' - Kg - Mg + 2Rf' = 0 \\
 \theta'' + 2\xi P, \theta' + P, D, \phi'' = 0 \\
 \phi'' + 2\xi S, \phi' + S, S, \theta'' = 0
\end{align*}

where $\xi = \eta + \frac{v_0}{2}$.

The corresponding boundary conditions are

\begin{align*}
 f = 1, g = 0, \theta = 1, \phi = 1 \text{ at } \eta = 0 \\
 f = 0, g = 0, \theta = 0, \phi = 0 \text{ as } \eta \to \infty
\end{align*}

In all the above equations primes denote the differentiation with respect to $\eta$.

**Solutions**

The solutions of equations (16)-(19) are now obtained by the method of superposition (Na, 1979). The essence of this method is to reduce the boundary value problem to an initial value problem which can easily be integrated out, without any iteration, by any initial value solver.

For the purpose of numerical integration, the well known Runge-Kutta Merson Integration Scheme has been used as an initial value problem solver to integrate the above mentioned equations and to obtain converged solutions. If now $\tau_x$, $\tau_z$, $N_u$ and $S_h$ respectively denote the local values of the $x$ and $z$ components of the skin-friction, the Nusselt number and the Sherwood number they are respectively proportional to $\frac{\partial f(0)}{\partial \eta}$, $\frac{\partial g(0)}{\partial \eta}$, $\frac{\partial \theta(0)}{\partial \eta}$ and $\frac{\partial \phi(0)}{\partial \eta}$.

The numerical values of local skin-friction coefficients, the Nusselt number and the Sherwood number are sorted in Tables I-III.

**Results and Discussion**

The velocity profiles for $x$ and $z$ components of velocity, commonly known as non-dimensional primary ($f$) and secondary ($g$) velocities, are shown in Figs. 2 - 17 for different values of suction parameter ($v_0$), the magnetic parameter ($M$), the rotation parameter ($R$), the Prandtl number ($P_r$), the Soret number ($S_r$), the Schmidt number ($S_c$), the Dufour number ($D_f$) and the permeability parameter ($K$) and for fixed values of Grashof number ($G_r$) and modified Grashof number ($G_m$). The values of Grashof number ($G_r$) and modified Grashof number ($G_m$) are taken to be large, since these value correspond to a cooling problem that is generally encountered in nuclear engineering in connection with the cooling of reactors. For Prandtl number ($P_r$), three values 0.71, 1.0 and 7.0 are considered (0.71 represents air at
20° C, 1.0 corresponds to electrolyte solutions such as salt water and 7.0 correspond to water). The values 0.22, 0.60 and 0.75 of the Schmidt number ($S_c$) are also considered for they represent specific conditions of the flow. In particular, 0.22 corresponds to hydrogen while 0.60 corresponds to water vapor that represents a diffusivity chemical species of most common interest in air and the value 0.75, represent oxygen. The values of $v_0$, $M$, $R$, $S_r$, $D_f$, $K$ and $G_m$ are however chosen arbitrary.

| $v_0$ | $M$ | $\tau_x$ | $\tau_z$ | $N_u$ | $S_h$ |
|-------|-----|-----------|-----------|------|------|
| 0.5   | 0.5 | 2.7611793 | -1.2612417| 1.3540955| 0.7810146|
| 1.0   | 0.5 | 2.3337250 | -1.1613957| 1.5962112| 0.8407938|
| 1.5   | 0.5 | 1.8513867 | -1.0594143| 1.8520351| 0.9010674|
| 0.5   | 1.0 | 2.4824549 | -1.1592220| 1.3540893| 0.7810245|
| 0.5   | 1.5 | 2.2226458 | -1.0718636| 1.3540834| 0.7810350|

| $R$ | $S_r$ | $\tau_x$ | $\tau_z$ | $N_u$ | $S_h$ |
|-----|------|----------|----------|------|------|
| 0.2 | 1.0  | 2.9867173| -0.2631226| 1.3539250| 0.7808163|
| 0.4 | 1.0  | 2.9565132| -0.5232471| 1.3540188| 0.7809357|
| 0.6 | 1.0  | 2.9080943| -0.7778524| 1.3540590| 0.7809765|
| 0.2 | 2.0  | 3.0757815| -1.4052470| 1.3790387| 0.5116685|
| 0.2 | 3.0  | 3.2797583| -1.4241212| 1.4983555| -0.4302568|

| $D_f$ | $K$ | $\tau_x$ | $\tau_z$ | $N_u$ | $S_h$ |
|------|-----|----------|----------|------|------|
| 0.2  | 0.5 | 2.7611793| -1.2612417| 1.3540955| 0.7810146|
| 0.5  | 0.5 | 2.9102812| -1.3154989| 1.275978| 0.8169440|
| 0.8  | 0.5 | 3.0681069| -1.3706838| 1.1795134| 0.8630274|
| 0.2  | 1.0 | 2.4824549| -1.1592220| 1.3540893| 0.7810245|
| 0.2  | 1.5 | 2.2226458| -1.0718636| 1.3540834| 0.7810350|
Fig. 2. Primary velocity profiles for different values of $v_o$ with $G_r=10.0$, $G_m=4.0$, $M=0.5$, $R=0.2$, $P_r=0.71$, $S_r=1.0$, $S_c=0.6$, $D_f=0.2$, $K=0.5$.

Fig. 3. Secondary velocity profiles for different values of $v_o$ with $G_r=10.0$, $G_m=4.0$, $M=0.5$, $R=0.2$, $P_r=0.71$, $S_r=1.0$, $S_c=0.6$, $D_f=0.2$, $K=0.5$.

Fig. 4. Primary velocity profiles for different values of $R$ with $v_o=0.5$, $G_r=10.0$, $G_m=4.0$, $M=0.5$, $P_r=0.71$, $S_r=1.0$, $S_c=0.6$, $D_f=0.2$, $K=0.5$.

Fig. 5. Secondary velocity profiles for different values of $R$ with $v_o=0.5$, $G_r=10.0$, $G_m=4.0$, $M=0.5$, $P_r=0.71$, $S_r=1.0$, $S_c=0.6$, $D_f=0.2$, $K=0.5$.

Fig. 6. Primary velocity profiles for different values of $S_r$ with $v_o=0.5$, $G_r=10.0$, $G_m=4.0$, $M=0.5$, $R=0.2$, $P_r=0.71$, $S_c=0.6$, $D_f=0.2$, $K=0.5$.

Fig. 7. Secondary velocity profiles for different values of $S_r$ with $v_o=0.5$, $G_r=10.0$, $G_m=4.0$, $M=0.5$, $R=0.2$, $P_r=0.71$, $S_c=0.6$, $D_f=0.2$, $K=0.5$. 

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Fig. 8. Primary velocity profiles for different values of $D_f$ with $v_o=0.5$, $G_r=10.0$, $G_m=4.0$, $M=0.5$, $R=0.2$, $P_r=0.71$, $S_r=1.0$, $S_c=0.6$, $K=0.5$.

Fig. 9. Secondary velocity profiles for different values of $D_f$ with $v_o=0.5$, $G_r=10.0$, $G_m=4.0$, $M=0.5$, $P_r=0.71$, $S_r=1.0$, $S_c=0.6$, $D_f=0.2$, $K=0.5$.

Fig. 10. Primary velocity profiles for different values of $M$ with $v_o=0.5$, $G_r=10.0$, $G_m=4.0$, $R=0.2$, $P_r=0.71$, $S_r=1.0$, $S_c=0.6$, $D_f=0.2$, $K=0.5$.

Fig. 11. Secondary velocity profiles for different values of $M$ with $v_o=0.5$, $G_r=10.0$, $G_m=4.0$, $R=0.2$, $P_r=0.71$, $S_r=1.0$, $S_c=0.6$, $D_f=0.2$, $K=0.5$.

Fig. 12. Primary velocity profiles for different values of $S_c$ with $v_o=0.5$, $G_r=10.0$, $G_m=4.0$, $M=0.5$, $R=0.2$, $P_r=0.71$, $S_r=1.0$, $D_f=0.2$, $K=0.5$.

Fig. 13. Secondary velocity profiles for different values of $S_c$ with $v_o=0.5$, $G_r=10.0$, $G_m=4.0$, $M=0.5$, $R=0.2$, $P_r=0.71$, $S_r=1.0$, $D_f=0.2$, $K=0.5$. 

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With the above mentioned parameters, the velocity profiles for the primary and the secondary velocities are presented in Figs. 2 - 17, the temperature profiles are presented in Figs. 18 - 20 and the concentration profiles are presented in Figs. 21 - 24.

The effects of the suction parameter \( (v_o) \) on the primary and secondary velocities are shown in Figs. 2 and 3. It is observed from these figures that an increase in the suction parameter \( (v_o) \) leads, respectively, to a decrease in the primary velocity and to an increase in the secondary velocity. The usual stabilizing effect of the suction parameter on the boundary layer growth is also evident from these figures.

In Figs. 4 and 5, the effects of rotation parameter \( (R) \) on the primary and secondary velocities are shown respectively. It is observed from these figures that the rotation parameter has minor decreasing effect on the primary velocity while the same has quite larger decreasing effect on the secondary velocity. In Figs. 6 and 7 and 8 and 9, the effects of Soret number \( (S_r) \) and Dufour number \( (D_f) \) on the primary and secondary velocities are shown respectively. It is observed from these figures that the primary velocity increases while the secondary velocity decreases with the increase of Soret number \( (S_r) \). The same effect is observed from these figures in case of Dufour number \( (D_f) \). The effects of magnetic parameter \( (M) \), Schmidt number \( (S_c) \), permeability parameter \( (K) \) and Prandtl number \( (P_r) \) on the primary and secondary velocities are shown respectively in Figs. 10 and 11, 12 and 13, 14 and 15, and 16 and 17. From Figs. 10 and 11, it is observed that the primary velocity decreases while the secondary velocity increases with the increase of magnetic parameter \( (M) \). The same effects are observed from Figs. 12 and 13 and 14 and 15 in case of Schmidt number \( (S_c) \) and permeability parameter \( (K) \) respectively. From Figs. 16 and 17, it is seen that the Prandtl number \( (P_r) \) has quite a larger decreasing effect on the primary velocity while it has a similar increasing effect on the secondary velocity.

The effects of suction parameter \( (v_o) \) on the temperature field is shown in Fig. 18. It is observed from this figure that the temperature decreases as the suction parameter \( (v_o) \) increase. In Fig. 19, the effects of Dufour number \( (D_f) \) on the temperature field is shown. It is observed from this figure that the temperature increases as the Dufour number \( (D_f) \) increase.

In Fig. 20, the effects of Prandtl number \( (P_r) \) on the temperature field is shown. It is observed from this figure that as the Prandtl number increases the temperature decrease at a particular position of the boundary layer. This decrease is very large in case of water \( (P_r=7.0) \). We also observe that for \( P_r=7.0 \) the field temperature remains less than the uniform flow temperature for most part of the boundary layer.

The effects of suction parameter \( (v_o) \) on the concentration field are displayed in Fig. 21, which shows that the concentration decreases as the suction parameter \( (v_o) \) increase. In Fig. 22, the effect of Soret number \( (S_r) \) on the concentration field is displayed. It is
Fig. 14. Primary velocity profiles for different values of $K$ with $v_o=0.5, G_r=10.0, G_m=4.0, M=0.5, R=0.2, P_r=0.71, S_r=1.0, S_c=0.6, D_f=0.2$.

Fig. 15. Secondary velocity profiles for different values of $K$ with $v_o=0.5, G_r=10.0, G_m=4.0, M=0.5, R=0.2, S_r=1.0, S_c=0.6, D_f=0.2, K=0.5$.

Fig. 16. Primary velocity profiles for different values of $P_r$ with $v_o=0.5, G_r=10.0, G_m=4.0, M=0.5, R=0.2, S_r=1.0, S_c=0.6, D_f=0.2, K=0.5$.

Fig. 17. Secondary velocity profiles for different values of $P_r$ with $v_o=0.5, G_r=10.0, G_m=4.0, M=0.5, R=0.2, S_r=1.0, S_c=0.6, D_f=0.2, K=0.5$.

Fig. 18. Temperature profiles for different values of $v_o$ with $G_r=10.0, G_m=4.0, M=0.5, R=0.2, P_r=0.71, S_r=1.0, S_c=0.6, D_f=0.2, K=0.5$.

Fig. 19. Temperature profiles for different values of $D_f$ with $v_o=0.5, G_r=10.0, G_m=4.0, M=0.5, R=0.2, P_r=0.71, S_r=1.0, S_c=0.6, K=0.5$. 
Fig. 20. Temperature profiles for different values of $P_r$ with $v_o=0.5$, $G_r=10.0$, $G_m=4.0$, $M=0.5$, $R=0.2$, $S_r=1.0$, $S_c=0.6$, $D_f=0.2$, $K=0.5$.

Fig. 21. Concentration profiles for different values of $v_o$ with $G_r=10.0$, $G_m=4.0$, $M=0.5$, $R=0.2$, $P_r=0.71$, $S_r=1.0$, $S_c=0.6$, $D_f=0.2$, $K=0.5$.

Fig. 22. Concentration profiles for different values of $S_r$ with $v_o=0.5$, $G_r=10.0$, $G_m=4.0$, $M=0.5$, $R=0.2$, $P_r=0.71$, $S_c=0.6$, $D_f=0.2$, $K=0.5$.

Fig. 23. Concentration velocity profiles for different values of $P_r$ with $v_o=0.5$, $G_r=10.0$, $G_m=4.0$, $M=0.5$, $R=0.2$, $S_r=1.0$, $S_c=0.6$, $D_f=0.2$, $K=0.5$.

Fig. 24. Concentration profiles for different values of $S_c$ with $v_o=0.5$, $G_r=10.0$, $G_m=4.0$, $M=0.5$, $R=0.2$, $P_r=0.71$, $S_r=0.71$, $D_f=0.2$, $K=0.5$. 
observed from this figure that the Soret number ($S_r$) has a large increasing effect on concentration. In Fig. 23 and 24, the effects of Prandtl number ($P_r$) and Schmidt number ($S_c$) on the concentration field are shown respectively. It is observed from these figures that the concentration increases as the Prandtl number ($P_r$) increase. It is also seen from these figures that the Schmidt number ($S_c$) has a major decreasing effect on the concentration field.

Finally, the effects of various parameters on the components of skin-friction ($\tau_x$ and $\tau_z$), the Nusselt number ($N_u$) and the Sherwood number ($S_h$) are shown in Tables I-III.

From Table I, we observe that the skin-friction component ($\tau_x$) decreases while the skin-friction component ($\tau_z$), the Nusselt number ($N_u$) and the Sherwood number ($S_h$) increase with the increase of the suction parameter ($v_0$). It is also seen from this table that the skin-friction component ($\tau_x$) and the Nusselt number ($N_u$) increase with the increase of magnetic parameter ($M$).

Again, from Table II, we see that the skin-friction components ($\tau_x$ and $\tau_z$) decrease with the increase of rotation parameter ($R$), but the Nusselt number ($N_u$) and the Sherwood number ($S_h$) increase with the increase of rotation parameter ($R$). It is also seen from this table that the skin-friction component ($\tau_x$) and the Nusselt number ($N_u$) increase with the increase of Soret number ($S_r$), but the skin-friction component ($\tau_z$) and the Sherwood number ($S_h$) decrease owing to the increase of Soret number ($S_r$). Also, from Table III, we observe that the skin-friction component ($\tau_x$) and the Sherwood number ($S_h$) increase with the increase of Dufour number ($D_f$), but the skin-friction component ($\tau_z$) and the Nusselt number ($N_u$) decrease with the increase of Dufour number ($D_f$). It is also seen from this table that the skin-friction component ($\tau_x$) and the Nusselt number ($N_u$) decrease while the skin-friction component ($\tau_z$) and the Sherwood number ($S_h$) increase with the increase of permeability parameter ($K$).

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