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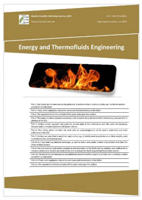

Rotating convective MHD flow over a vertical moving plate in the presence of heat source, radiation, chemical reaction and Hall effects

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Abstract: The steady MHD rotating flow and heat mass transfer over a semi-infinite vertical plate moving with a constant velocity in the presence of a heat source, thermal radiation, first-order chemical reaction and Hall effect are studied. The methodology proposed to predict the velocity, temperature and concentration evolutions is based on similarity transformation and finite difference method. The simulation has been carried out for different pertinent parameters of problem. The main results are that the velocity fields are considerably affected by the velocity ratio and coriolis parameters. Except the axial *w*-velocity that increases only near the plate with the velocity ratio parameter, all the velocities decrease as the velocity ratio and Coriolis parameters increase, whereas the temperature and the concentration profiles increase. Also, the fluid velocity and temperature increase when the heat source and radiation parameters increase but the concentration decreases.

1. Introduction

The study of heat and mass convection and magneto-hydrodynamic flows is one of the current concerns, which are the subject of much advanced work, in the context of the development of many technological areas like the MHD accelerators and generators, plasma physics, controlled thermo-nuclear reactors, drying process, space flight, industrial technical of the metallurgy, etc. (Chamkha 2004; Satya-Narayana et al. 2013; Ibrahim and Suneetha 2016).

Generally, in many of these flows where the density of the used fluid is low or the applied magnetic field is very strong, a very important Hall current is produced perpendicularly to both the electric and the magnetic field and which cannot be neglected. (Megahed et al. 2003; Satya-Narayana et al. 2013; Seth et al. 2014).

In recent years, many investigations on the electrically conducting fluid flow with heat and mass transfer during natural convection past a vertical plate submitted to a strong uniform magnetic field have been published but without considering the Hall effect. In this field, the unsteady flow and convection mechanisms past a fixed vertical plate have been investigated by Ghaly (2002) and Jordaín (2006) and the unsteady flow past a moving plate for various operating conditions has been investigated by Chamkha (2004), Ibrahim et al. (2008) and Sharma et al. (2010). However, other researchers have shown great interest in the steady flow from a fixed, moving or rotating vertical plate with heat source (Ziaul-Haque et al. 2012) and chemical reaction (Bakr 2011; Ibrahim and Suneetha 2016) and also with thermal radiation (Mohamed and Abo-Dahab 2009; Das 2011; Ahmed 2014; Raju et al. 2014). In addition, the effect of non-uniform magnetic field on MHD viscoelastic fluid flow from a porous vertical plate through

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a porous medium with chemical reaction and heat source/sink has presented by Rashidi et al. (2014). In the last few decades, nanofluids have become a very popular field with the increasing demand for industrial applications. For this reason, Arifuzzaman et al. (2018) used a non-similar approach in order to study the unsteady natural convective magneto-micropolar and chemically reactive fluid flow with nanoparticles, thermal radiation, radiation absorption and heat source past a vertical porous plate. In another paper, Kumar et al. (2018) decided to use three types of water-based nanofluids over a moving vertical plate through a medium of porous materials with Soret effect, second order chemical reaction and thermal radiation. Also, Swain et al. (2018) considered a steady viscoelastic nanofluid flow past a horizontal plate through a saturated porous medium subjected to thermal slip and temperature jump with chemical reaction.

The interest has also shifted to heat transfer with external uniform magnetic field and Hall current effects. Abo-Eldahab and El Aziz (2005) and Saha et al. (2007) give some ideas about steady fluid flow past a fixed vertical plate with different conditions. While, the systems in rotation have been admitted by various workers (Kinyanjui et al. 1998; Takhar et al. 2002; Anika et al. 2013). Further, the Hall current and moving magnetic field effects on unsteady magnetohydrodynamic flow through a porous medium bordered by two infinite porous plates have been investigated by Singh et al. (2016).

The Hall effect associated with heat and mass transfer is one of the most widely considered problems in MHD fluid dynamics areas. In this context, many researchers have shown great interest in the case of natural convection over a fixed semi-infinite vertical plate as Aboeldahab and Elbarbary (2001) and Megahed et al. (2003). Kinyanjui et al. (2001) presented the same problem but in the presence of radiation absorption of a heat generating fluid through a vertical infinite porous plate moving with an impulsively started velocity. Similarly, the radiation absorption effect on magneto-micropolar fluid with Hall currents in a rotating system has been investigated by Satya-Narayana et al. (2013) and also by Sreedevi et al. (2016) but for double-diffusive flow. Later, Seth et al. (2014) discussed the transient radiative MHD free convection flow with heat and mass transfer of an impulsively moving vertical plate and rotating system in a porous medium considering Hall effect. For a similar field, some researchers proposed the presence of chemical reaction to analyze the hydro-magnetic flow past a vertical plate with heat generation/ absorption (Salem and El-Aziz 2008) or past a horizontal plate with ion-slip effects and temperature dependent viscosity and thermal diffusivity in a porous medium (Elgazery 2009), while the combined rotating system and rotating fluid has been discussed by Singh et al. (2017).

Under this circumstance, it is of great importance to investigate heat and mass transfer and steady rotating fluid flow induced by Hall effect around a semi-infinite vertical plate moving with a constant velocity subjected to a strong uniform magnetic field in presence of heat source, thermal radiation, first-order chemical reaction and rotational effects where the Coriolis effect is present (Takhar et al. 2002; Seth et al. 2014) and which have a practical interest in engineering (Satya-Narayana et al. 2013; Seth et al. 2014; Sreedevi et al. 2016). Attention is also paid to examine the influence of several parameters such as velocity ratio, Coriolis, heat source and thermal radiation. In this case, the governing equations of our problem are simplified by applying the similarity transformations. Using a finite difference method, the obtained numerical results are presented graphically and are showed the importance of effects of the heat source, thermal radiation and especially the velocity ratio and Coriolis on the velocity, temperature and concentration profiles and which can produce remarkable deviations with the literature results.

2. Mathematical analysis

Fig.1 shows the physical model considered, with the important geometric parameters for a MHD free convection flow. It consists of a moving semi-infinite vertical plate, its leading edges coincide with the coordinate system (x, y, z) and its end at the origin while its wall maintained at a constant temperature T_w and species concentration C_w and which are different with those from the fluid, T_∞ and C_∞. This plate uniformly moving with a velocity V_1, in the z-direction, subjected to a strong magnetic field B_0 where the Hall currents are present. It should be noted that no external electric field is applied. The electrically conducting fluid used in the analysis, moves with a uniform velocity V_2 in the same direction of the plate and rotates uniformly about y-axis with an angular velocity Ω. A heat source, thermal radiation and homogenous chemical reaction of first-order are considered.

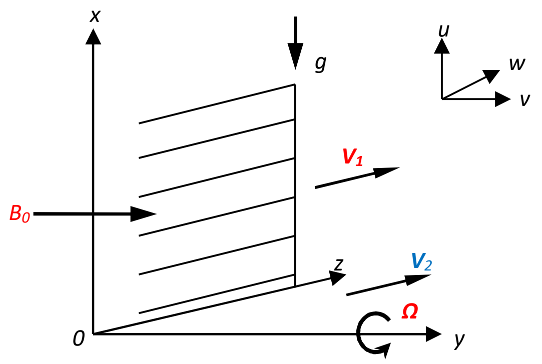

Fig. 1. Geometry of physical model.

The mathematical model for heat and mass transfer and MHD fluid flow was developed under some assumptions as steady state, viscous and incompressible fluid. Viscous and electrical dissipations, ion slip and thermoelectric pressure are neglected. The fluid flow, heat and mass transfer variations in the *z*-direction resulting from Coriolis rotating motions and (or) Hall current effects are also neglected (Takhar et al. 2002; Salem and Abd El-Aziz 2008; Elgazery 2009). It is thus assumed that the induced magnetic field is neglected in the industrial applications widely using the partially ionized fluids and liquid metals and which are characterized by a very small magnetic Reynolds number (Seth et al. 2014). It's noted that since plate is electrically non-conducting, the electric current density in *y*-direction given by the generalized Ohm's law is equal to zero (Aboeldahab and Elbarbary 2001; Salem and Abd El-Aziz 2008).

According to the above assumptions with usual Boussinesq approximations, the equations governing the problem are written in a dimensional form as:

$$\frac{\partial u}{\partial x}+\frac{\partial \upsilon}{\partial y}=0 \quad (1)$$

$$u\frac{\partial u}{\partial x}+\upsilon\frac{\partial u}{\partial y}+2\Omega w=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\frac{\partial^2 u}{\partial y^2}+g\beta(T-T_\infty)$$
$$+g\beta^*(C-C_\infty)-\left(\frac{\sigma B_0^2}{\rho(1+m^2)}\right)(u+mw) \quad (2)$$

$$u\frac{\partial w}{\partial x}+\upsilon\frac{\partial w}{\partial y}-2\Omega u=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\nu\frac{\partial^2 w}{\partial y^2}$$
$$-\left(\frac{\sigma B_0^2}{\rho(1+m^2)}\right)(w-mu) \quad (3)$$

$$u\frac{\partial T}{\partial x}+\upsilon\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2}-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial y}+\frac{Q}{\rho c_p}(T-T_\infty) \quad (4)$$

$$u\frac{\partial C}{\partial x}+\upsilon\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-K_r C \quad (5)$$

The term Q represents the additional heat source.

The radiative heat flux is determined by applying the Rosseland approximation as follow (Das 2011; Seth et al. 2014):

$$q_r=-\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y} \quad (6)$$

$$T^4\cong 4T_\infty^3 T-3T_\infty^4 \quad (7)$$

Using Eqs. 6 and 7, the energy Eq. 4 becomes

$$u\frac{\partial T}{\partial x}+\upsilon\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2}+\frac{1}{3\rho c_p}\frac{16\sigma^* T_\infty^3}{k^*}\frac{\partial^2 T}{\partial y^2}+\frac{Q}{\rho c_p}(T-T_\infty) \quad (8)$$

The studied phenomenon is subject to the boundary conditions listed below as

$$u=0, \upsilon=0, w=V_1, T=T_w, C=C_w \quad \text{at} \quad y=0,$$
$$u=0,\ w=V_2,\ T=T_\infty,\ C=C_\infty \quad \text{as } y\to\infty \quad (9)$$

Following Takhar et al. (2002), the gradients of pressure must balance the forces of Lorentz and Coriolis while moving away from the plate and are given by

$$-\frac{1}{\rho}\frac{\partial p}{\partial x}=2\Omega V_2+\left(\frac{\sigma B_0^2}{\rho(1+m^2)}\right)mV_2,$$
$$-\frac{1}{\rho}\frac{\partial p}{\partial z}=\left(\frac{\sigma B_0^2}{\rho(1+m^2)}\right)V_2 \quad (10)$$

The following dimensionless variables are used here as

$$\eta=\sqrt{\frac{\Omega}{\nu}}y,\ \ \psi=\sqrt{\Omega\nu}xF_1,\ \ w=\Omega xF_2,$$
$$F_3=(T-T_\infty)/(T_w-T_\infty),\ \ F_4=C/C_\infty,$$
$$\zeta=\Omega x/V,\ V=V_1+V_2,\ \lambda=V_1/V \quad (11)$$

where $\psi(x, y)$ is the stream function defined by $u=\partial\psi/\partial y$ and $\upsilon=-\partial\psi/\partial x$ (Aboeldahab and Elbarbary 2001).

Using the above-mentioned equations, local similarity equations can be written as follow

$$F_1'''-F_1^2+F_1F_1''-2F_2+GrF_3+GcF_4$$
$$-\frac{M}{(1+m^2)}\left[F_1'+m\left(F_2+\frac{(\lambda-1)}{\zeta}\right)\right]+\frac{2(1-\lambda)}{\zeta}=0 \quad (12)$$

$$F_2''+F_1F_2'-F_1'F_2+2F_1'$$
$$-\frac{M}{(1+m^2)}\left[F_2-mF_1'+\frac{(\lambda-1)}{\zeta}\right]=0 \quad (13)$$

$$F_3''+\left(\frac{3NPr}{3N+4}\right)F_1F_3'+\left(\frac{3NBP}{3N+4}\right)F_3=0 \quad (14)$$

$$F_4''+ScF_1F_4'-\gamma ScF_4=0 \quad (15)$$

The differentiation is with respect to η, the dimensionless quantities appearing in equations (12-15) are the magnetic, thermal Grashof, solutal Grashof, radiation, heat source, Prandtl, Schmidt and chemical reaction parameters respectively, defined as:

$$M = \sigma B_0^2/\rho\Omega, \quad Gr = g\beta(T_w - T_\infty)/\Omega^2 x,$$

$$Gc = g\beta^*(C_w - C_\infty)/\Omega^2 x, \quad N = KK^*/4\sigma^* T_\infty^3,$$

$$B = Q/\rho c_p \Omega, \ Pr = \rho v c_p/k, \ Sc = v/D, \ \gamma = K_r/\Omega.$$

Further, one can also define a dimensionless quantity so called velocity ratio λ as the plate velocity V_1 to the composite velocity V. In addition, the dimensionless Coriolis force ζ is called Coriolis parameter.

The relevant transformed boundary conditions are given by

$$F_1'(0) = 0, F_1(0) = 0, F_2(0) = \frac{\lambda}{\zeta}, F_3(0) = 1, F_4(0) = 1,$$

$$F_1'(\infty) = 0, F_2(\infty) = \frac{1-\lambda}{\zeta}, F_3(\infty) = 0, F_4(\infty) = 0 \qquad (16)$$

3. Results and Discussions

The governing equations (12-15) along with the boundary conditions (16) are solved numerically using MATLAB® based on a finite difference method. The numerical results, presented in Figures 2-17, have been carried out for medium encountered parameters $Gr = Gc = 0.5$ and for air $Pr = 0.71$, $Sc = 0.22$ with different values of the velocity ratio parameter λ, Coriolis parameter ζ, heat source parameter B and the radiation parameter N. Velocity, temperature and concentration profiles are plotted as a function of variation of the dimensionless variable η.

Figs. 2-5 exhibit the influence of velocity ratio parameter λ on the fluid velocity, temperature and concentration profiles F_1', F_2, F_3 and F_4 for $M=m=\zeta= 1$, $N=0.5$, $B=0.3$, $\gamma=0.1$. In Fig. 2 the transverse u-velocity F_1' decreases as λ increases. In addition, large values of λ lead to negative values of the flow velocity that is explained by the competitive role between the velocities of the fluid and the plate.

The variation of the axial w-velocity F_2 and the velocity ratio parameter λ effects are plotted in Fig. 3. As observed, the increase of λ causes the decrease of the axial w-velocity F_2 for about $\eta \geq 0.5$. Also, for large values of λ, the flow velocity is reversed due to the acting of several forces in different directions. It is important to note that more the plate velocity becomes great the fluid axial velocity near the plate becomes more important and contrary away from the plate.

Further, as λ increases, both temperature F_3 and concentration F_4 distributions increase as shown in Figs. 4 and 5. Thus, one can say that as the plate and fluid move rapidly or in opposite directions, the heat and mass convection currents are greater.

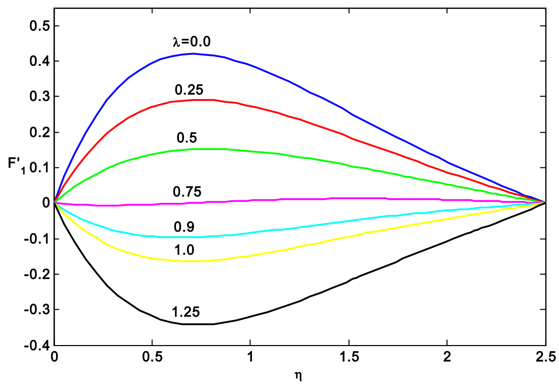

Fig. 2. Variation of λ on u-velocity profile for $M=m=1$, $\zeta=1$, $N=0.5$, $B=0.3$, $\gamma=0.1$.

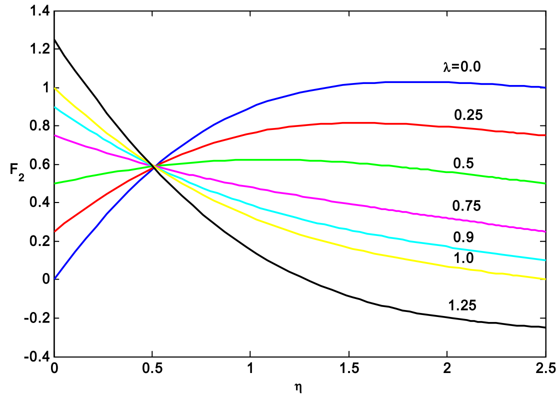

Fig. 3. Variation of λ on w-velocity profile for $M=m=1$, $\zeta=1$, $N=0.5$, $B=0.3$, $\gamma=0.1$.

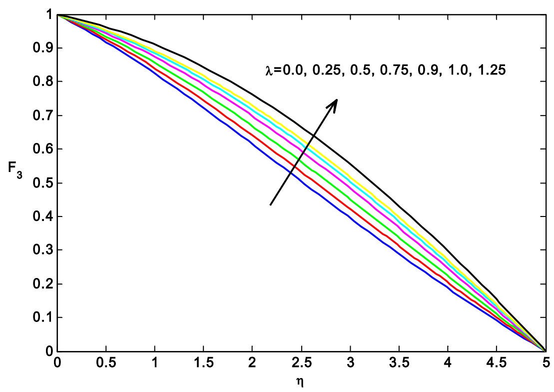

Fig. 4. Variation of λ on temperature profile for $M=m=1$, $\zeta=1$, $N=0.5$, $B=0.3$, $\gamma=0.1$.

In Figs. 6-9, other interesting results are given by the study of the effect of the Coriolis parameter ζ on the behavior of F_1', F_2, F_3 and F_4 for M=m=1, λ =0.25, N=0.5, B=0.3 and γ=0.1. There is a clear high decrease in the both transverse u-velocity F_1' and axial w-velocity F_2, as shown in Figs. 6 and 7. For a large value of ζ, a slight reverse of the flow velocity is observed. This is due to the dominate role of the Coriolis force resulting to effects of fluid rotation.

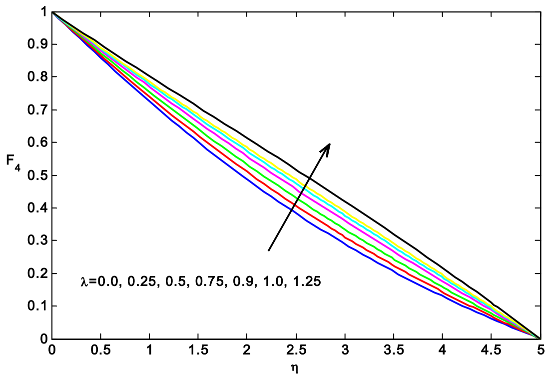

Fig. 5. Variation of λ on concentration profile for M=m=1, ζ=1, N=0.5, B=0.3, γ=0.1.

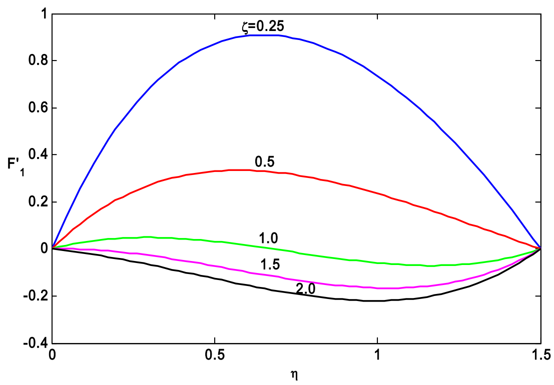

Fig. 6. Variation of ζ on u-velocity profile for M=m=1, λ=0.25, N=0.5, B=0.3, γ=0.1.

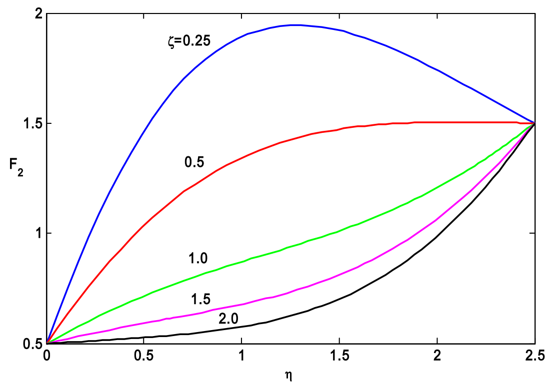

Fig. 7. Variation of ζ on w-velocity profile for M=m=1, λ=0.25, N=0.5, B=0.3, γ=0.1.

Physically, the Coriolis force acting as a constraint in the fluid flow causes reduction in the fluid velocity and motion and consequently the heat and mass transfer between the plate and fluid decrease. This appears in the increasing of the temperature F_3 and the concentration F_4 profiles, as are shown in Figs. 8 and 9 respectively.

Figs. 10-13 display the effects of the heat source parameter B for M=m=ζ=1, λ=0.25, N=0.5 and γ=0.1.

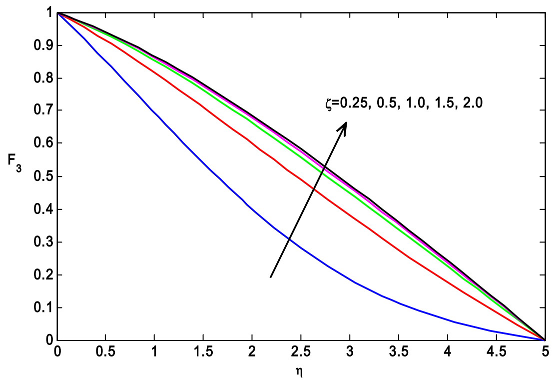

Fig. 8. Variation of ζ on temperature profile for M=m=1, λ=0.25, N=0.5, B=0.3, γ=0.1.

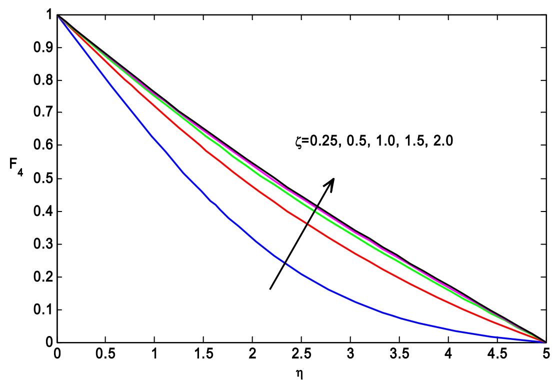

Fig. 9. Variation of ζ on concentration profile for M=m=1, λ=0.25, N=0.5, B=0.3, γ=0.1.

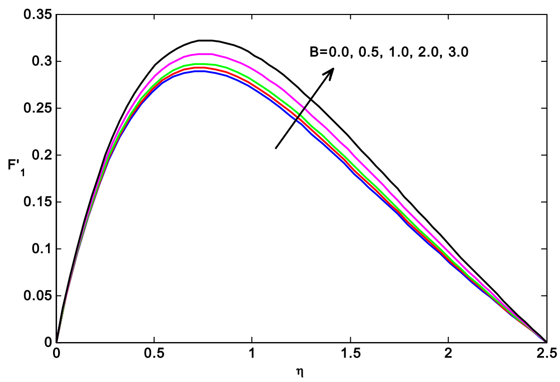

Fig. 10. Variation of B on u-velocity profile for M=m=1, λ=0.25, ζ=1, N=0.5, γ=0.1.

According to these profiles we can see that the transverse u-velocity F_1', axial w-velocity F_2 and temperature F_3 are increased as the heat source parameter B increases but the concentration F_4 decreases. As it is known that the intensified heat source increases the temperature, as shown in Fig. 12, and consequently increases the temperature gradients in the fluid regions that lead to increase the convection intensity resulting in a more heat and mass transfer, which mainly appears in the increasing of the velocities F_1' and F_2 of the fluid and the decreasing of the concentration, as shown in Figs. 10, 11 and 13 respectively.

According to Figs. 14-17, the effect of thermal radiation parameter N on F_1', F_2, F_3 and F_4 profiles is observed for M=m=ζ=1, λ=0.25, B=0.3, γ=0.1. As can be seen, the transverse u-velocity F_1', axial w-velocity F_2 and

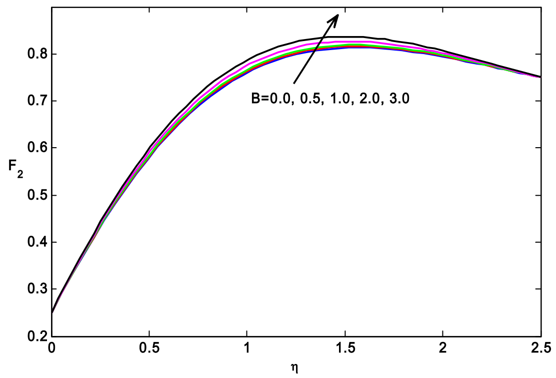

Fig. 11. Variation of B on w-velocity profile for M=m=1, λ=0.25, ζ=1, N=0.5, γ=0.1.

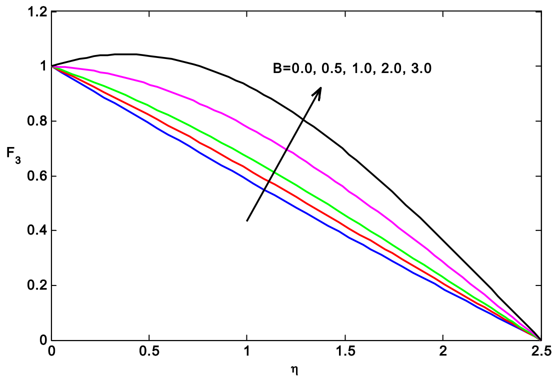

Fig. 12. Variation of B on temperature profile for M=m=1, λ=0.25, ζ=1, N=0.5, γ=0.1.

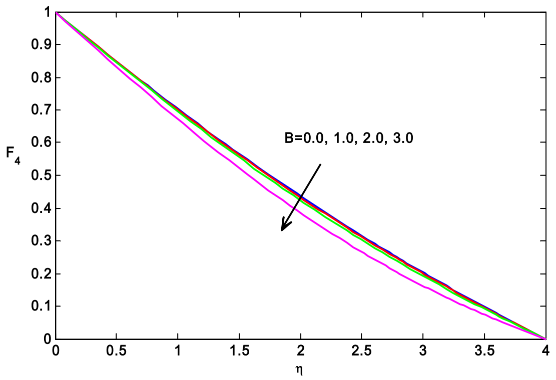

Fig. 13. Variation of B on concentration profile for M=m=1, λ=0.25, ζ=1, N=0.5, γ=0.1.

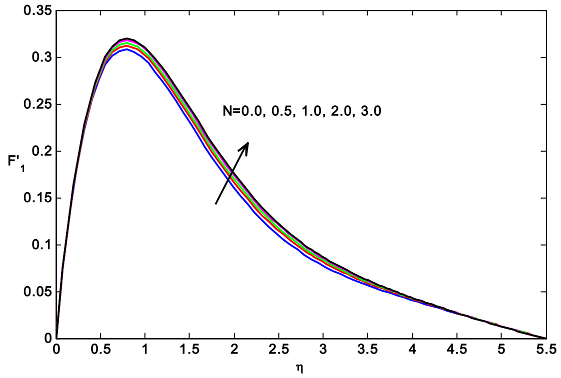

Fig. 14. Variation of N on u-velocity profile for M=m=1, λ=0.25, ζ=1, B=0.3, γ=0.1.

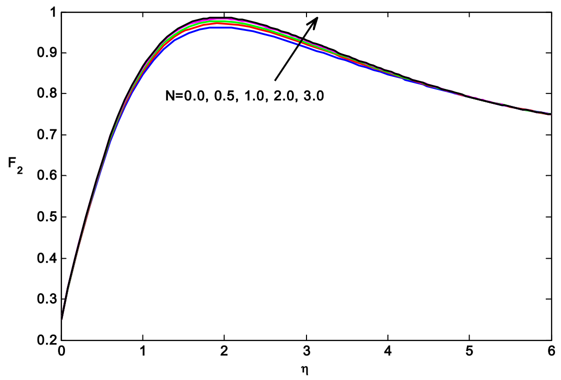

Fig. 15. Variation of N on w-velocity profile for M=m=1, λ=0.25, ζ=1, B=0.3, γ=0.1.

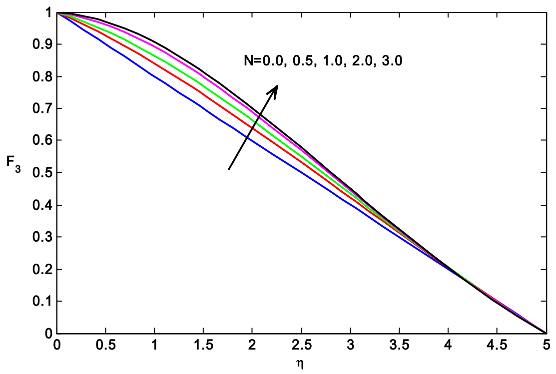

Fig. 16. Variation of N on temperature profile for M=m=1, λ=0.25, ζ=1, B=0.3, γ=0.1.

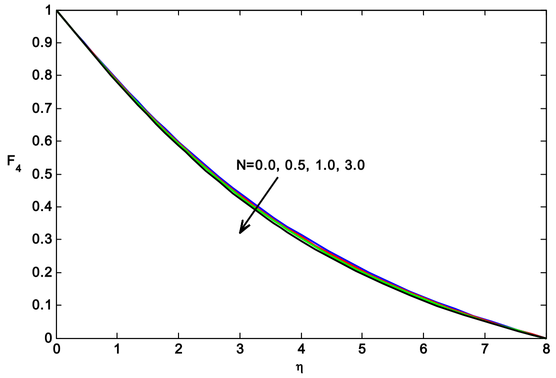

Fig. 17. Variation of *N* on concentration profile for *M*=*m*=1, *λ*=0.25, *ζ*=1, *B*=0.3, *γ*=0.1.

temperature F_3 increase with an increase of *N*, but the concentration slightly decreases. We note that these results are similar to those obtained with heat source parameter *B*.

4. Conclusions

The problem of steady magnetohydrodynamic free convection heat and mass transfer flow past a moving semi-infinite vertical plate in a rotating and moving fluid in the presence of Hall current, heat source, thermal radiation and first-order chemical reaction has been analyzed. Numerical analysis is made by using a finite difference method. Graphical numerical results are presented and discussed the effect of different physical parameters on the velocity, temperature and concentration profiles.

It was found that the characteristics of the flow are highly influenced by the velocity ratio and Coriolis parameters. The increasing of the velocity ratio parameter decreases the transverse velocity and the axial velocity but for $\eta \geq 0.5$, while the temperature and concentration of the fluid increase. Also, the Coriolis parameter decreases the flow velocities, which increases the temperature and concentration. The increasing of the heat source and thermal radiation parameters increases the fluid velocities and temperature but decreases the concentration.

Disclosures

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Nomenclature

B	Heat source parameter
B_0	Imposed magnetic field, T
C	Concentration, kg.m^{-3}
c_p	Specific heat, J. kg^{-1}. K^{-1}
D	Diffusion coefficient, m^2. s^{-1}
F_1 ... F_4	Similarity functions for (*u*, *w*, *T*, *C*)
Gc	Thermal Grashof number
Gr	Solutal Grashof number
g	Gravitational acceleration, m.s^{-2}
J	Electric current density, A. m^{-2}
K	Dimensionless permeability
K_r	Chemical reaction rate, J
k	Thermal conductivity, W.m^{-1}. K^{-1}
*k**	Absorption coefficient, m^{-1}
k_p	Permeability of porous medium, m^2
M	Magnetic parameter
m	Hall parameter
N	Thermal radiation parameter
p	Pressure, N. m^{-2}
Pr	Prandtl number
Q	Heat source, W m^{-3} K^{-1}
q_r	Radiative heat flux, W m^{-2}
Sc	Schmidt number
T	Temperature, K
V	Composite velocity, m. s^{-1}
V_1	Plate velocity, m. s^{-1}
V_2	Fluid velocity, m. s^{-1}
(*u, υ ,w*)	Velocity components along (*x*, *y*, *z*)-axes, m. s^{-1}

Greek symbols

α	Thermal diffusivity, m^2. s^{-1}
β	Thermal expansion coefficient, K^{-1}
*β**	Concentration expansion, Kg^{-1}. m^3
η	Similarity variable
λ	Wall velocity
ν	Kinematic viscosity, m^2. s^{-1}
ζ	Dimensionless Coriolis force
ρ	Fluid density, Kg. m^{-3}
ψ	Stream function, m^2. s-1
Ω	Angular velocity, Rad. s^{-1}
γ	Chemical reaction parameter

Subscripts

w	Wall condition
∞	Free stream condition

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