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Research Article

MHD EFFECT ON UNSTEADY FLOW PAST AN ACCELERATED VERTICAL PLATE

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ABSTRACT
An exact solution to the problem of a viscous incompressible electrically conducting fluid past an accelerated vertical plate with uniform mass diffusion is obtained. A uniform magnetic field is assumed to be applied normal to the plate directed into the fluid region. The Rosseland approximation is used to describe the radiative heat flux in the energy equation. The equations governing the flow are solved analytically by adopting Laplace transform technique in closed form. The profiles for the velocity, temperature, concentration fields, and skin-friction, Nusselt number and Sherwood number at the plate are demonstrated graphically for various values of the parameters involved in the problem and the results are physically interpreted.

Keywords: *MHD, Rotation, Thermal Radiation, Mass Transfer*

INTRODUCTION
Many natural phenomena and technological problems are susceptible to MHD analysis. Geophysics encounters MHD characteristics in the interactions of conducting fluids and magnetic fields. Engineers employ MHD principle, in the design of heat exchangers pumps and flow meters, in space vehicle propulsion, thermal protection, braking, control and re-entry, in creating novel power generating systems etc. From technological point of view, MHD convection flow problems are also very significant in the fields of stellar and planetary magnetospheres, aeronautics, chemical engineering and electronics. Model studies of the above phenomena of MHD convection have been made by many. Some of them are Sanyal and Bhattacharya (1992), Ferraro and Plumpton (1966) and Cramer and Pai (1973). On the other hand, along with free convection currents, caused by the temperature difference, the flow is also affected by the difference in concentrations on material constitutions. Many investigators have studied the phenomena of MHD free convection and mass transfer flow of who the names of Acharya *et al.*, (2000), Raptis and Kafousias (1982), Singh and Singh (2000) and Singh *et al.,* (2007) are worth mentioning. Radiation is a process of heat transfer through electromagnetic waves. Radiative convective flows are encountered in countless industrial and environment process. Radiative heat and mass transfer play an important role in manufacturing industries for the design of reliable equipotent. If the temperature of the surrounding field is rather high, radiation effect plays an important role in space related technology. The effect of radiation on various convective flows under different conditions has been studied by many researchers including Hussain and Takhar (1996), Ahmed and Sarmah (2009), Rajesh and Varma (2010) and Ahmed *et al.*, (2013). Investigation of problems on natural convective radiating flow of electrically conducting fluid past an infinite plate becomes very interesting and fruitful when a magnetic field is applied normal to the plate. Comprehensive literature on various aspects of free convective radiative MHD flows and its applications can be found in Sattar and Maleque (2000), Samad and Rahman (2006), Prasad *et al.,* (2006), Takhar *et al.*, (1996), Ahmed and Sarmah (2009) and Ahmed (2012). The effect of rotation on unsteady hydromagnetic natural convection flow of a viscous incompressible electrically conducting fluid past an impulsively moving vertical plate with ramped wall temperature has been investigated recently by Seth *et al.*, (2011). The geophysical importance of the flows in rotating frame of reference has attracted the attention of a number of scholars. Model studies in this literature have been done by many. Some of them are Vidyanidhu and Nigam (1967) and Jana and Datta (1977). The effects of uniform transverse magnetic field with or without suction on different flow characteristics were investigated by Gupta (1972), Soundalgekar and Pop (1973) and Mazumdar *et al.*, (1976).

The objective of the present work is to study the effects of the applied magnetic field on a three dimensional MHD time dependent flow of a viscous incompressible electrically conducting fluid bounded by an infinite vertical isothermal plate. In addition to magnetic field effect, it is also proposed to investigate the effects of thermal radiation and rotation in the preview of our study.

This work is a generalization to the work done by Vijayalakshmi and Kamalam (2013) to consider the magnetic field effect. In absence of magnetic field, the solutions and the results obtained in the present work are consistent with those of Vijayalakshmi and Kamalam (2013).

Mathematical Formulation

We now consider a three dimensional MHD time dependent flow of a viscous incompressible fluid induced by uniformly accelerated motion of an infinite vertical isothermal plate with uniform mass diffusion in a rotating fluid under the influence of an applied transverse magnetic field. Our investigation is restricted to the following assumptions:

- The variations of all fluid properties other than the variations of density except in so far as they give rise to a body force are ignored completely.
- All the physical variables are functions of Z' and t' only as the plate are infinite in X', Y'.
- The magnetic Reynolds number is so small that the induced magnetic field can be neglected.
- The polarization effects are assumed to be negligible and hence the induced electric field is also negligible.
- The viscous and magnetic energy dissipation in the energy equation is neglected.

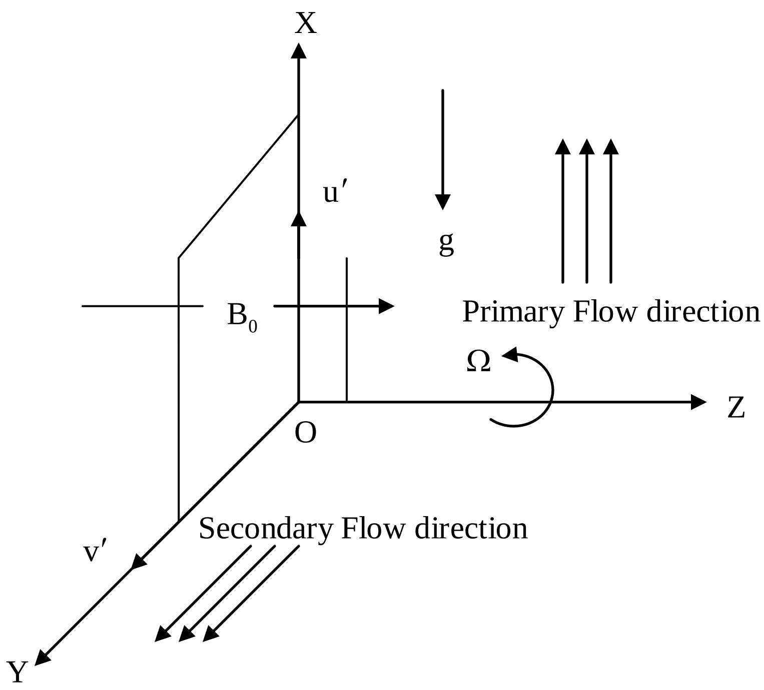

Figure 1: Flow Configuration

We introduce a co-ordinate system (x', y', z') with X - axis vertically upwards along the plate, Y- axis perpendicular to the plate and directed into the fluid region and Z- axis along the width of the plate. Let the components of velocity along with X and Y axes should be u' and v'.

Let these velocity components are chosen in the upward direction along the plate and normal to the plate respectively.

Both the plate and the fluid are in a state of rigid rotation with uniform angular velocity Ω' about the Z-axis.

Initially the plate and fluid is at rest with the temperature T'_∞ and concentration C'_∞ every where. At time $t'>0$, the plate starts moving with velocity ct' in its own plane in the vertical direction against gravitational field, in the presence of thermal radiation. At the same time the plate temperature is raised to T'_w and the concentration to C'_w, which there after maintained constant.

Under the assumptions and closely following Vijayalakshmi and Kamalam (2013), the equations that describe the physical situation are given by

$$\frac{\partial v'}{\partial y'}=0 \tag{1}$$

$$\frac{\partial u'}{\partial t'}-2\Omega' v'=\upsilon\frac{\partial^2 u'}{\partial y'^2}+g\beta\left(T'-T'_\infty\right)+g\beta^*\left(C'-C'_\infty\right)-\frac{\sigma B_0^2 u'}{\rho} \tag{2}$$

$$\frac{\partial v'}{\partial t'}+2\Omega' u'=\upsilon\frac{\partial^2 v'}{\partial z'^2}-\frac{\sigma B_0^2 v'}{\rho} \tag{3}$$

$$\rho C_p\frac{\partial T'}{\partial t'}=K_T\frac{\partial^2 T'}{\partial z'^2}-\frac{\partial q_r}{\partial z'} \tag{4}$$

$$\frac{\partial C'}{\partial t'}=D\frac{\partial^2 C'}{\partial z'^2} \tag{5}$$

The term $\frac{\partial q_r}{\partial z'}$ represents the radiative heat flux with distance normal to the plate with the following initial and boundary conditions:

$$\begin{aligned}
&t'\le 0:\ u'=0,\ T'=T'_\infty,\ C'=C'_\infty \quad \text{for all } z'\\
&t'>0:\ u'=ct',\ T'=T'_w,\ C'=C'_w \quad \text{at } z'=0\\
&\qquad u'=0,\ T'\to T'_\infty,\ C'\to C'_\infty \quad \text{as } z'\to\infty
\end{aligned} \tag{6}$$

By Rosselend approximation (Singh and Singh, 2000; Singh *et al.*, 2007), radiative heat flux of an optically thin gray gas is expressed by:

$$\frac{\partial q_r}{\partial z'}=-4k\sigma'\left(T'^4_\infty-T'^4\right) \tag{7}$$

It is assumed that the temperature differences within the flow are sufficiently small that T'^4 may be expressed as a linear function of the temperature. This is accomplished by expanding T'^4 in a Taylor series about T'_∞ and neglecting the higher order terms, thus

$$T'^4\cong 4T'^3_\infty T'-3T'^4_\infty \tag{8}$$

By using equations (7) and (8), Equation (4) reduces to

$$\rho C_p\frac{\partial T'}{\partial t'}=K_T\frac{\partial^2 T'}{\partial z'^2}+16k\sigma' T'^3_\infty\left(T'_\infty-T'\right) \tag{9}$$

In order to write the governing equations and the boundary conditions in dimensional form, the following non-dimensional quantities are introduced:

$$u=\frac{u'}{(\upsilon c)^{\frac{1}{3}}},\ v=\frac{v'}{(\upsilon c)^{\frac{1}{3}}},z=z'\left(\frac{c}{\upsilon^2}\right)^{\frac{1}{3}},\ t=t'\left(\frac{c^2}{\upsilon}\right)^{\frac{1}{3}},\ Gr=\frac{g\beta\left(T'_w-T'_\infty\right)}{c},$$

$$Gm=\frac{g\beta^*\left(C'_w-C'_\infty\right)}{c},\theta=\frac{T'-T'_\infty}{T'_w-T'_\infty},Pr=\frac{\upsilon}{\alpha},M=\frac{\sigma B_0{}^2(\upsilon c)^{\frac{1}{3}}}{\rho c},$$

$$\Omega=\Omega'\left(\frac{\upsilon}{c^2}\right)^{\frac{1}{3}},R=\frac{16k\sigma'\upsilon T'^3_\infty}{K_T}\left(\frac{\upsilon}{c^2}\right)^{\frac{1}{3}},C=\frac{C'-C'_\infty}{C'_w-C'_\infty},Sc=\frac{\upsilon}{D} \qquad (10)$$

On introduction of the complex velocity q=u+iv, $i=\sqrt{-1}$, the equations (2)-(5) reduce to the following non-dimensional equations:

$$\frac{\partial q}{\partial t}+2i\Omega q=Gr\theta+Gm\phi+\frac{\partial^2 q}{\partial z^2}-Mq \qquad (11)$$

$$\frac{\partial\theta}{\partial t}=\frac{1}{Pr}\frac{\partial^2\theta}{\partial z^2}-\frac{R}{Pr}\theta \qquad (12)$$

$$\frac{\partial\phi}{\partial t}=\frac{1}{Sc}\frac{\partial^2\phi}{\partial z^2} \qquad (13)$$

The initial and boundary conditions in non-dimensional form are:

$$\begin{aligned} &q=0,\ \theta=0_\infty,\ \phi=0 \ \text{ for all } z\le 0\ \&\ t\le 0\\ t>0:\ &q=t,\ \theta=1,\ \phi=1 \ \text{ at } z=0\\ &q=0,\ \theta\to 0,\ \phi\to o \ \text{ as } z\to\infty \end{aligned} \qquad (14)$$

All the physical variables are defined in the nomenclature.

Method of Solution

On taking Laplace Transform of the equations (11), (12) and (13), the combined initial and boundary value problem reduce to a boundary value problem governed by the equations:

$$s\bar{q}+\left(2i\Omega+M\right)\bar{q}=Gr\bar{\theta}+Gm\bar{\phi}+\frac{d^2\bar{q}}{dz^2} \qquad (15)$$

$$s\bar{\theta}=\frac{1}{Pr}\frac{d^2\bar{\theta}}{dz^2}-\frac{R}{Pr}\bar{\theta} \qquad (16)$$

$$s\bar{\phi}=\frac{1}{Sc}\frac{d^2\bar{\phi}}{dz^2} \qquad (17)$$

Subject to the boundary conditions:

$$\bar{q}=\frac{1}{s^2}\left(1-e^{-s}\right),\ \bar{\theta}=\frac{1}{s},\ \bar{\phi}=\frac{1}{s} \ \text{ at } z=0 \qquad (18)$$

$$\bar{q}=0,\ \bar{\theta}=0,\ \bar{\phi}=0 \ \text{ at } z\to\infty \qquad (19)$$

The equations (15)-(17) are ordinary coupled second order differential equations and the solutions of these equations subject to the conditions (18) and (19) are as follows:

$$\bar{\theta}=\frac{1}{s}e^{-\sqrt{Pr}\sqrt{s+B_1}z} \qquad (20)$$

$$\bar{\phi} = \frac{1}{s} e^{-\sqrt{Sc}\sqrt{s}z} \tag{21}$$

$$\bar{q} = \left[\frac{1}{s^2}\left(1 - e^{-s}\right) - \frac{T_1}{s} + \frac{P_1}{s + I_1} - \frac{R_1}{s + K_1} \right] e^{-\sqrt{s+M_1}z} + \frac{P_1}{s} e^{-\sqrt{Pr}\sqrt{s+B_1}z}$$
$$- \frac{P_1}{s + I_1} e^{-\sqrt{Pr}\sqrt{s+B_1}z} - \frac{R_1}{s} e^{-\sqrt{Sc}\sqrt{s}z} + \frac{R_1}{s + K_1} e^{-\sqrt{Sc}\sqrt{s}z} \tag{22}$$

Now taking the inverse Laplace Transforms of $\bar{\theta}, \bar{\phi}$ and $\bar{q}$ we have:

$$\theta = \psi_1 \tag{23}$$

$$\phi = \psi_2 \tag{24}$$

$$q = \psi_3 - \psi_4 - T_1\psi_5 + P_1 e^{-I_1 t}\psi_{11} + R_1 e^{-K_1 t}\psi_{12} + P_1\psi_8 - R_1\psi_2 \tag{25}$$

Skin-friction

The non-dimensional form of skin-friction at the plate is given by :

$$Cf = \tau = \left[\frac{\partial q}{\partial z}\right]_{z=0} = \tau_x + i\tau_y = \xi_1 - \xi_2 - T_1\phi_1 + P_1 e^{-I_1 t}\left(\phi_2 - \phi_3\right) +$$
$$R_1 e^{-K_1 t}\left(\phi_4 - \phi_5\right) + P_1\phi_6 - R_1\gamma_1$$

Nusselt Number

The non-dimensional form of Nusselt number at the plate is given by :

$$Nu = -\left[\frac{\partial \theta}{\partial z}\right]_{z=0} = -\varsigma_1$$

Sherwood Number

The non-dimensional form of Sherwood number at the plate is given by :

$$Sh = \left[\frac{\partial \phi}{\partial z}\right]_{z=0} = \zeta_1$$

The constants and the functions involved in the solutions are defined in the section ‘Appendix’.

RESULTS AND DISCUSSION

In order to get the physical insight in to the problem, numerical computations from the analytical solutions for the representative concentration field, temperature field, velocity field (Primary and Secondary), the co-efficient of skin friction, the rate of heat transfer in terms of Nusselt number and the rate of mass transfer in terms of Sherwood number have been carried out by assigning some arbitrarily chosen specific values to the physical parameters involved in the problem, viz, Hartmann number M, Rotation parameter Ω , Thermal Grashof number Gr , Solutal Grashof number Gm, Prandtl number Pr, Radiation parameter R and Schmdit number Sc . The numerical results computed from the analytical solutions of the problem have been displayed in figures 2-22.

The Primary and Secondary velocity profiles under the influence of Hartmann number M, rotation parameter Ω , thermal Grashof number Gr , solutal Grashof number Gm and radiation parameter R versus z are exhibited in figures 2-11.

It is inferred from figure 2 that, an increase in magnetic parameter M has an inhibiting effect on the primary fluid velocity. The fluid velocity is continuously reduced with increasing M. In other words the imposition of the transverse magnetic field tends to retard the fluid flow. This phenomenon has an excellent agreement with the physical fact that the Lorentz force generated in the present flow model due to interaction of the transverse magnetic field and the fluid velocity acts as a resistive force to the fluid flow which serves to decelerate the flow. In figure 3, we observe the same trend of behavior in case of the secondary velocity also as its magnitude is concerned.

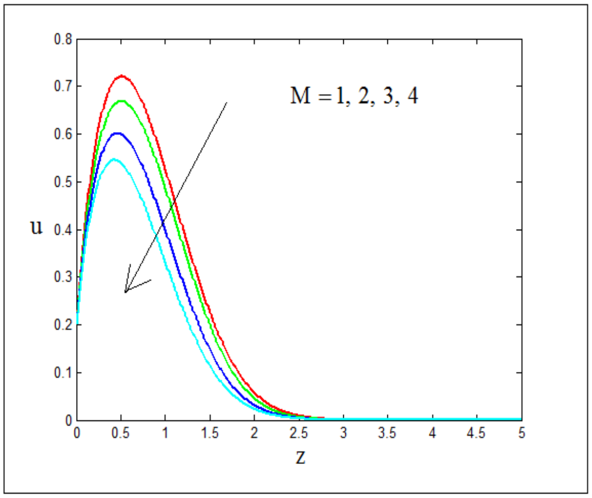

Figure 2: Primary velocity versus z for Ω=.5, Gr=5, Gm=5, Pr=.71, R=.2, Sc=.60, t=.2

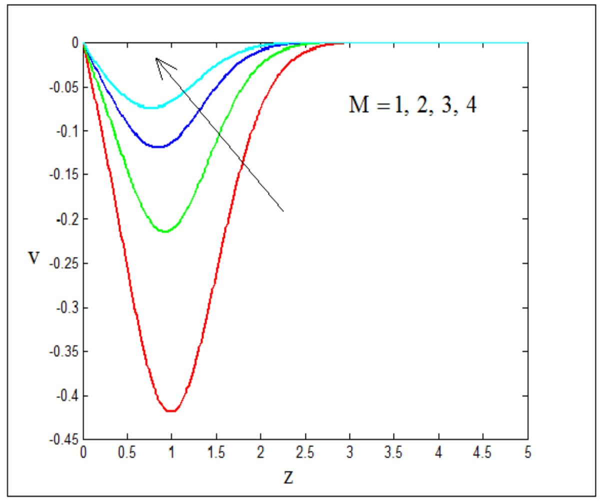

Figure 3: Secondary velocity versus z for Ω=.5, Gr=5, Gm=5, Pr=.71, R=.2, Sc=.60, t=.2

It is depicted from figure 4 that the primary velocity is decelerated under the action of rotation parameter but when magnitude is concerned and it is seen from figure 5 that the magnitude of the secondary fluid velocity is increased initially and then reduces when we move further away from the plate.

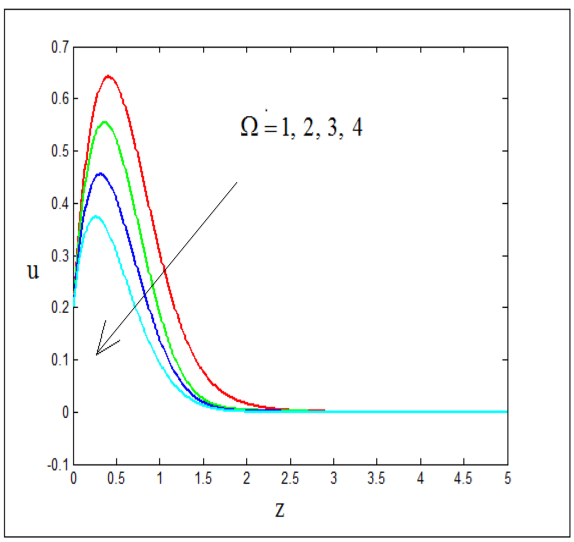

Figure 4: Primary velocity versus z for M=1, Gr=5, Gm=5, Pr=.71, R=.2, Sc=.60, t=.2

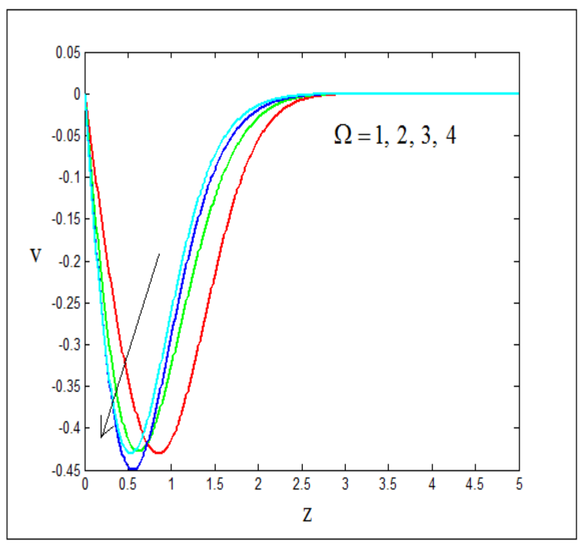

Figure 5: Secondary velocity versus z for M=1, Gr=5, Gm=5, Pr=.71, R=.2, Sc=.60, t=.2

The effects of thermal Grashof number and solutal Grashof number against both primary and secondary velocity are presented in figures 6-9. It is found from figures 6 and 8 that the primary fluid motion is accelerated under thermal as well as solutal buoyancy forces. It is inferred from the figures 7 and 9 that the secondary velocity field falls under the effects of thermal Grashof number or solutal Grashof number which establishes the fact that the fluid motion is retarded due to thermal buoyancy force and concentrated buoyancy force.

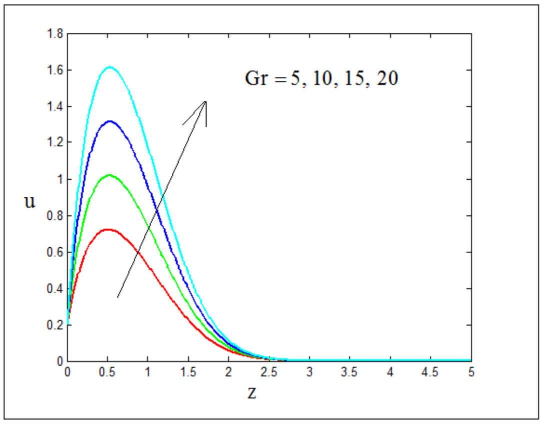

Figure 6: Primary velocity versus z for M=1, Ω=5, Gm=5, Pr=.71, R=.2, Sc=.60, t=.2

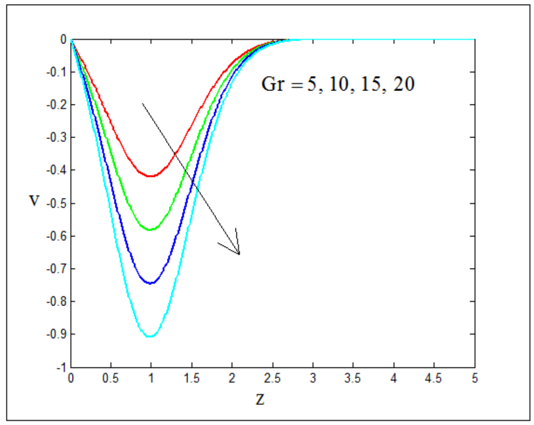

Figure 7: Secondary velocity versus z for M=1, Ω=5, Gm=5, Pr=.71, R=.2, Sc=.60, t=.2

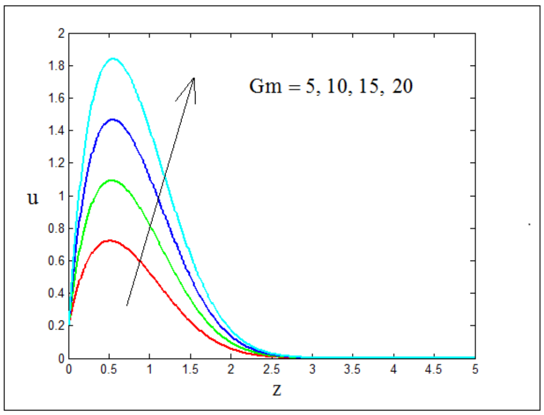

Figure 8: Primary velocity versus z for M=1, Ω=5, Gr=5, Pr=.71, R=.2, Sc=.60, t=.2

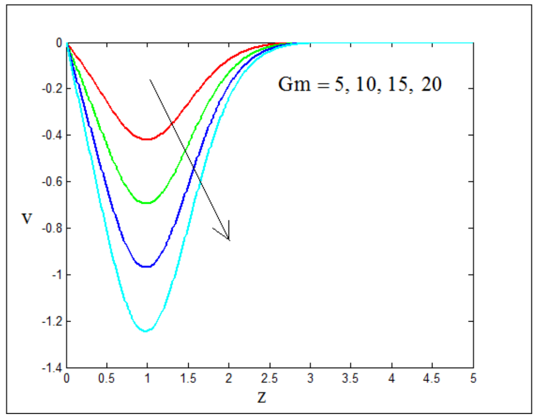

Figure 9: Secondary velocity versus z for M=1, Ω=5, Gr=5, Pr=.71, R=.2, Sc=.60, t=.2

Figures 10 and 11 have presented the variation of primary and secondary velocities under the influence of radiation parameter.

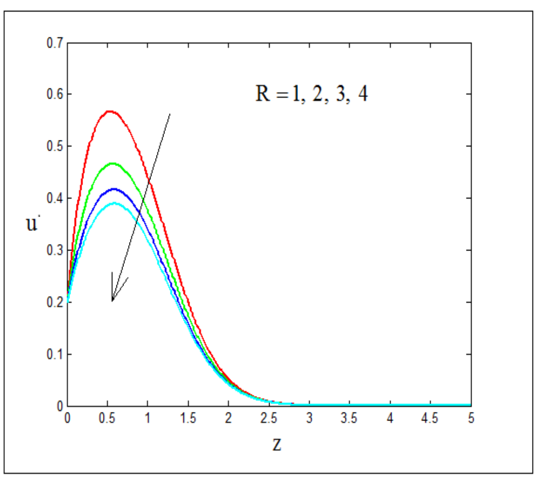

Figure 10: Primary velocity versus z for M=1, Ω=5, Gr=5, Pr=.71, Gm=5, Sc=.60, t=.2

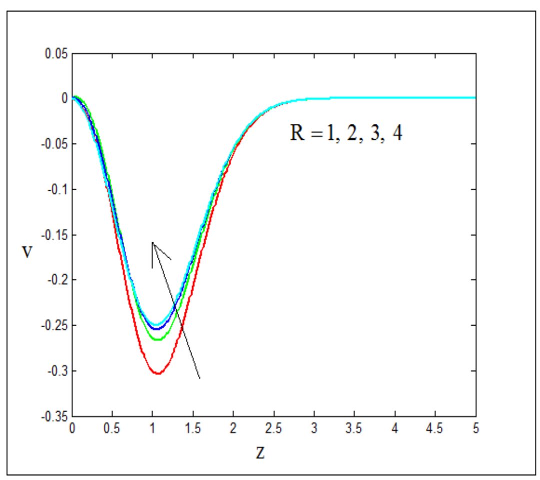

Figure 11: Secondary velocity versus z for M=1, Ω=5, Gr=5, Pr=.71, Gm=5, Sc=.60, t=.2

It is observed from figure 10 that an increase in radiation parameter R leads to a decrease in primary fluid velocity. That is to say that the primary fluid velocity falls under low thermal conductivity. An opposite character of behavior for secondary velocity profile is observed in figure 11.

Figures 12 to 13 correspond to the temperature distribution θ against z under the effects of the Prandtl number Pr and radiation parameter R. Increasing Pr or R shows an opposing influence on θ indicating the fact that the fluid temperature falls steadily for large values of Pr and R. It is further noticed from these figures that the fluid temperature as expected asymptotically falls from its maximum value at $z = 0$ to its minimum value at $z \to \infty$.

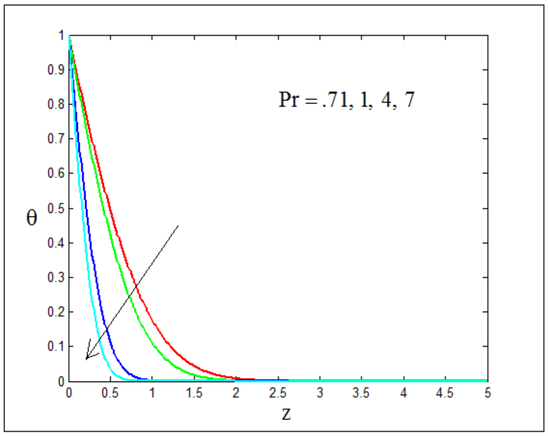

Figure 12: Temperature versus z for R=.2, t=.2

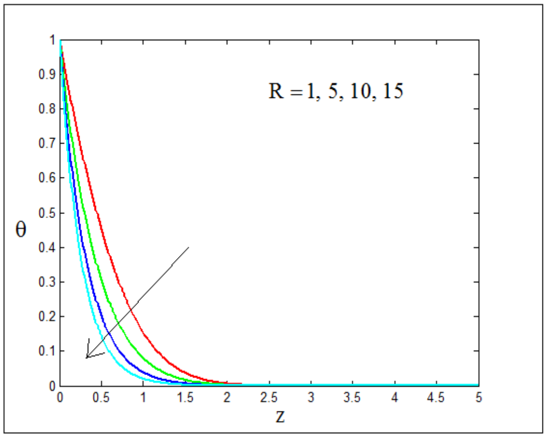

Figure 13: Temperature versus z for Pr=.71, t=.2

The effects of the Schmdit number Sc and time t on species concentration have been displayed in figures 14 and 15. It is inferred from figure 14 that the concentration level of the fluid drops for increasing Schmdit number Sc. It indicates that the concentration level rises up due to high mass diffusivity. It is marked from figure 15 that as time progresses the species concentration gets increased.

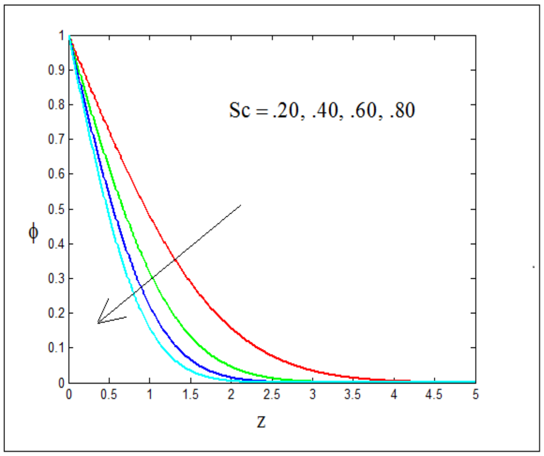

Figure 14: Concentration versus z for t=.2

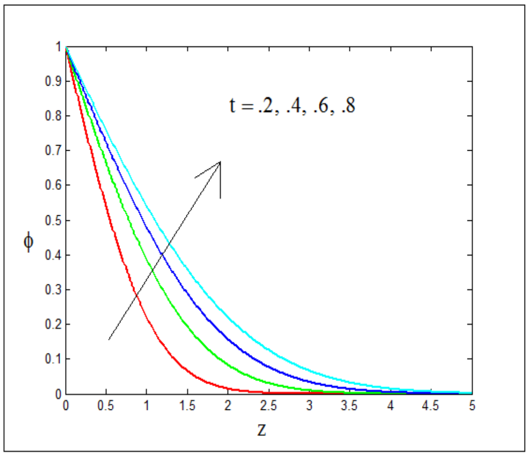

Figure 15: Concentration versus z for t=.2

The variations of both primary and secondary skin friction against Hartmann number M and radiation parameter R are presnted in figures 16-19. It is seen from figures 16 and 18 that the primary skin friction decreases with the increase in magnetic parameter M and radiation parameter R which indicates the fact that the viscous drag at the plate falls under the action of transverse magnetic field and low thermal conductivity. As magnitude is concerned, it is depicted from the figures 17 and 19 that the secondary skin friction also falls due to large values of Hartmann number M and radiation parameter R.

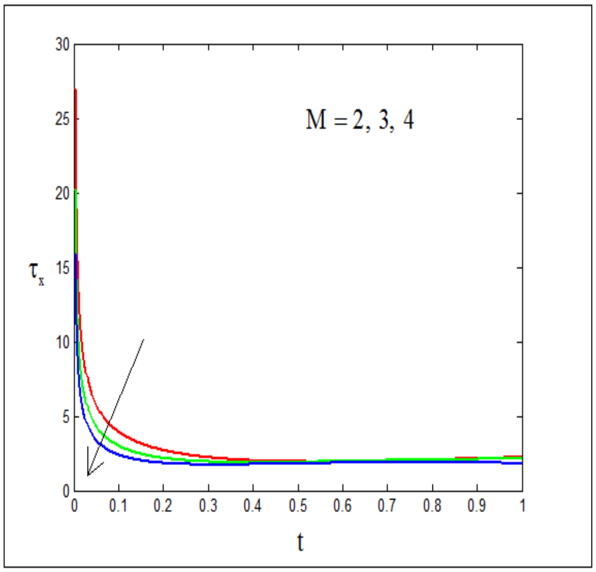

Figure16: Primary skin friction versus t for Ω =.5, Gr=5, Gm=5, Pr=.71, R=.2, Sc=.60

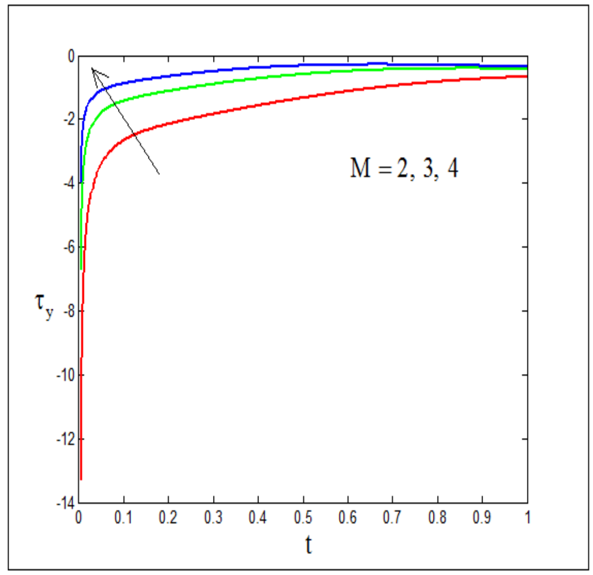

Figure17: Secondary skin friction versus t for Ω =.5, Gr=5, Gm=5, Pr=.71, R=.2, Sc=.60

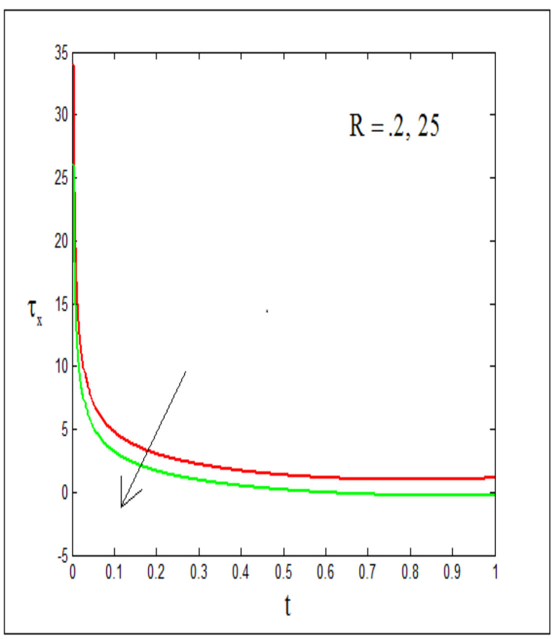

Figure 18: Primary skin friction versus t for Ω =.5, Gr=5, Gm=5, Pr=.71, M=1, Sc=.60

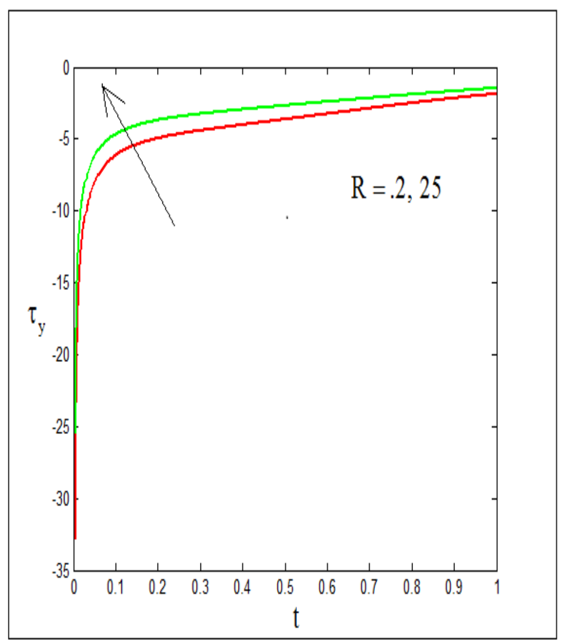

Figure 19: Secondary skin friction versus t for Ω =.5, Gr=5, Gm=5, Pr=.71, M=1, Sc=.60

The effects of Prandtl number Pr and radiation parameter R on the co-efficient of rate of heat transfer in terms of Nusselt number have been displayed in figures 20-21. It is found from figure (20) that the magnitude of the rate of heat transfer increases with the increase in Prandtl number Pr. This simulates that low thermal diffusivity leads the substantial rise in the heat transfer rate. Figure 21 demonstrates that the co-efficient of rate of heat transfer is enhanced with the rise of radiation parameter R. ie the energy flux is raised due to low thermal conductivity.

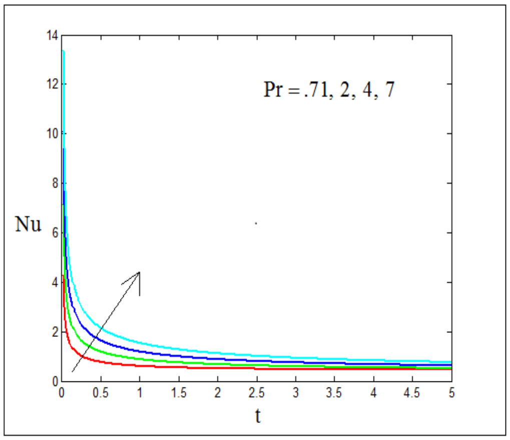

Figure 20: Nusselt number versus t for R=.2

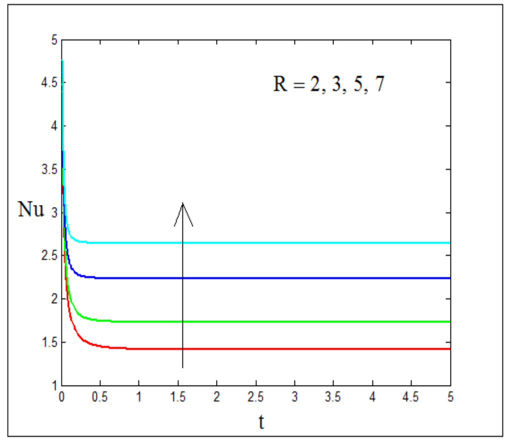

Figure 21: Nusselt number versus t for Pr=.71

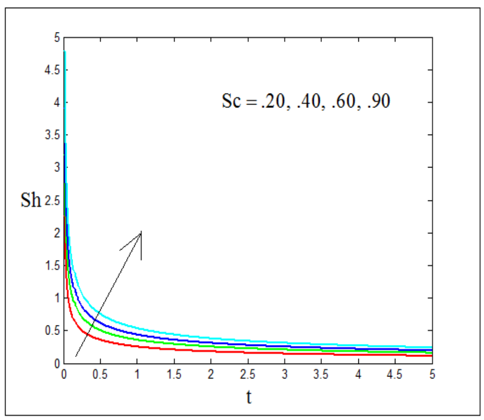

Figure 22: Sherwood number versus t

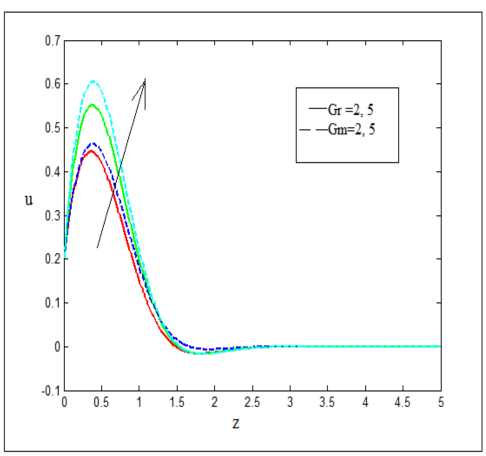

Figure 23: Primary velocity versus z for M=0, Ω =5, Pr=.71, R=.2, Sc=.60, t=.2

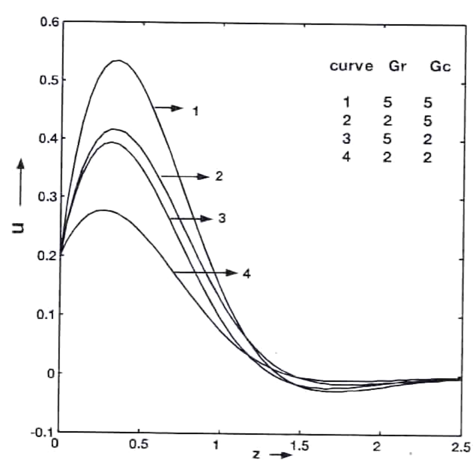

Figure 24 (Figure 5 of Vijayalakshmi and Kamalam (2013)): Primary velocity versus z for Ω =5, Pr=.71, R=.2, Sc=.60, t=.2

Figure 22 presents the variation of the rate of mass transfer from the plate to the fluid. It is inferred from the figure that Sherwood number increases under Schmdit number. i.e. the mass flux from the plate to the fluid get increased under the influence of mass diffusivity.

Comparison of Results

To compare results of the present paper, the work of Vijayalakshmi and Kamalam (2013) is considered.
Comparing figure 23 with the figure 24 (the figure 5 of the work done by Vijayalakshmi and Kamalam (2013), we observe that the two figures are almost identical in nature as the behavior of the primary fluid velocity versus normal coordinate z is concerned. That is there is an excellent agreement between the results obtained by Vijayalakshmi and Kamalam (2013) and the present authors.

Conclusion

Our investigation of the problem setup leads to the following conclusions:
1. The primary fluid motion is decelerated under the action of transverse magnetic field.
2. Temperature falls due to low thermal conductivity and low thermal diffusivity.
3. The mass diffusivity raises the concentration level steadily. i.e. the concentration level of the fluid, drops due to increasing Schmdit number.
4. The viscous drag at the plate may be inhibited by increasing the strength of the applied magnetic field.
5. The energy flux rises due low thermal conductivity.
6. The fluid motion and the fluid friction may be successfully controlled to some extent by imposing the transverse magnetic field. As such the magnetic field is an effective regulatory mechanism for the flow regime.

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Nomenclature

Symbol	Description	Dimension	M.K.S Unit
K_T	Thermal conductivity	$\left[MLT^{-3}\theta^{-1}\right]$	$\frac{W}{mK}$
B_0	Strength of the applied magnetic field $\left(y-\text{component of } \vec{B}\right)$	$\left[MT^{-1}Q^{-1}\right]$	Tesla
C_p	Specific heat at constant pressure	$\left[L^2T^{-2}\theta^{-1}\right]$	$\frac{Joule}{kg\times K}$
σ	Electrical conductivity	$\left[M^{-1}L^{-3}TQ^2\right]$	$\left(Ohm\times meter\right)^{-1}$ -
Ω	Non-dimensional rotation parameter	-	-

Gr	Grashof number for heat transfer	-	-
g	Acceleration due to gravity	$\left[LT^{-2}\right]$	ms^{-2}
Gm	Grashof number for mass transfer	-	-
M	Hartmann number	-	-
Pr	Prandtl number	-	-
p	Pressure	$\left[ML^{-1}T^{-2}\right]$	$Newton / m^2$ (Pascal)
$\vec{q}$	Fluid velocity vector	-	-
R	Radiation parameter	-	-
q_r	Radiative flux in magnitude	$\left[MT^{-3}\right]$	W/m^2
t'	Time	$[T]$	Second(s)
D	Mass diffusivity		m^2s^{-1}
T'_w	Reference temperature	$[\theta]$	K
T'_∞	Temperature far away from the plate	$[\theta]$	K
t	Non-dimensional time	-	-
T'	Fluid temperature	$[\theta]$	K
C'	concentration	-	kgm^{-3}
u'	X component of $\vec{q}$	$\left[LT^{-1}\right]$	m/s
u	Non-dimensional primary fluid velocity	-	-
(x', y', z')	Cartesian coordinates	$[L]$	m
y	Non-dimensional y coordinate	-	-
v	Non-dimensional secondary fluid velocity		-
Sc	Schmdit number	-	-
ρ	Fluid density	$\left[ML^{-3}\right]$	kg/m^3
μ	Co-efficient of viscosity	$\left[ML^{-1}T^{-1}\right]$	$\frac{kg}{ms}$
k	Mean absorption coefficient		m^{-1}
σ'	Stefan-Boltzman constant		$Wm^{-2}K^{-4}$
β^*	Volumetric co-efficient of expansion with concentration		$\frac{1}{K}$
ϕ	Non-dimensional concentration		
β	Volumetric co-efficient of thermal expansion	$\left[\theta^{-1}\right]$	$\frac{1}{K}$

υ	Kinematic viscosity		m^2s^{-1}
θ	Non-dimensional temperature	-	-
Subscript $_w$	Refers to the values of physical quantities at the plate	-	-
Subscript $_\infty$	Refers to the values of the physical quantities away from the plate	-	-

APPENDIX

$$\psi_1 = f\left(\Pr,\ B_1,\ z,\ t\right), \psi_2 = \psi\left(Sc,\ z,\ t\right)$$

$$\psi_3 = \gamma\left(M_1, z, t\right), \psi_4 = \gamma\left(M_1, z, t-1\right)H\left(t-1\right)$$

$$\psi_5 = \chi\left(M_1, z, t\right), \psi_6 = \chi\left(M_1 - I_1, z, t\right)$$

$$\psi_7 = \chi\left(M_1 - K_1, z, t\right), \psi_8 = \psi_1$$

$$\psi_9 = f\left(\Pr,\ B_1 - I_1,\ z,\ t\right), \psi_{10} = f\left(Sc,\ -K_1,\ z,\ t\right)$$

$$\psi_{11} = \psi_6 - \psi_9, \psi_{12} = \psi_{10} - \psi_7$$

$$\varsigma_1 = \varphi\left(\Pr,\ B_1, t\right),\ \ \zeta_1 = \varpi\left(Sc, t\right)$$

$$\xi_1 = \beta\left(\ M_1, t\right)_, \xi_2 = \beta\left(\ M_1, t-1\right)H\left(t-1\right)$$

$$\phi_1 = \vartheta\left(\ M_1, t\right)_, \phi_2 = \varphi\left(\ \Pr, B_1 - I_1, t\right)$$

$$\phi_3 = \vartheta\left(\ M_1 - I_1, t\right)_, \phi_4 = \vartheta\left(\ M_1 - K_1, t\right)$$

$$\phi_5 = \varphi\left(\ Sc,\ -K_1, t\right)\ \phi_6 = \varsigma_1$$

$$\gamma_1 = \zeta_1$$

$$f\left(\xi,\eta,z,t\right) = \frac{1}{2}\left[e^{\sqrt{\xi\eta}z}\operatorname{erfc}\left(\frac{z\sqrt{\xi}}{2\sqrt{t}} + \sqrt{\eta t}\right) + e^{-\sqrt{\xi\eta}z}\operatorname{erfc}\left(\frac{z\sqrt{\xi}}{2\sqrt{t}} - \sqrt{\eta t}\right)\right]$$

$$\gamma\left(\xi,z,t\right) = \left(\frac{t}{2} + \frac{z}{4\sqrt{\xi}}\right)e^{\sqrt{\xi}z}\operatorname{erfc}\left(\frac{z}{2\sqrt{t}} + \sqrt{\xi t}\right) + \left(\frac{t}{2} - \frac{z}{4\sqrt{\xi}}\right)e^{-\sqrt{\xi}z}\operatorname{erfc}\left(\frac{z}{2\sqrt{t}} - \sqrt{\xi t}\right)$$

$$\psi\left(\xi,z,t\right) = \operatorname{erfc}\left(\frac{\sqrt{\xi}z}{2\sqrt{t}}\right)$$

$$\chi\left(\eta,z,t\right) = \frac{1}{2}\left[e^{\sqrt{\eta}z}\operatorname{erfc}\left(\frac{z}{2\sqrt{t}} + \sqrt{\eta t}\right) + e^{-\sqrt{\eta}z}\operatorname{erfc}\left(\frac{z}{2\sqrt{t}} - \sqrt{\eta t}\right)\right]$$

$$\varphi\left(\xi,\eta,t\right) = \left[-\frac{\sqrt{\xi}}{\sqrt{\pi t}}e^{-\eta t} - \sqrt{\xi\eta}\ \operatorname{erf}\left(\sqrt{\eta t}\right)\right]$$

$$\varpi\left(\xi,t\right) = \left[-\frac{\sqrt{\xi}}{\sqrt{\pi t}}\right]$$

$$\beta(\eta,t)=\left[-\frac{\sqrt{t}}{\sqrt{\pi}}e^{-\eta t}-\left(t\eta+\frac{1}{2\sqrt{\eta}}\right)\operatorname{erf}\left(\sqrt{\eta t}\right)\right]$$

$$\vartheta(\xi,t)=\left[-\frac{1}{\sqrt{\pi t}}e^{-\xi t}-\sqrt{\xi}\ \operatorname{erf}\left(\sqrt{\xi t}\right)\right]$$

$$H(t-1)=\begin{cases}0, & t<1\\ 1, & t>1\end{cases}$$

$$B_1=\frac{Pr}{R},\ m=2i\Omega,\ M_1=m+M,\ D_1=Pr-1,\ E_1=-\left(Pr\,B_1+M_1\right),\ F_1=Sc-1,\ G_1=-M_1,$$

$$H_1=-\frac{Gr}{D_1},\ I_1=\frac{E_1}{D_1},\ J_1=\frac{Gm}{F_1},\ K_1=\frac{G_1}{F_1},\ P_1=\frac{H_1}{I_1},\ R_1=\frac{J_1}{K_1},\ T_1=P_1-R_1$$