MHD Convective Flow of Second Grade Fluid through Porous Medium between Two Vertical Plates with Mass Transfer

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Abstract

In this chapter, an investigation of the heat and mass transfer on the flow of an oscillatory convective MHD viscous incompressible, radiating and electrically conducting second grade fluid in a vertical porous rotating channel in slip flow regime is carried out. The fluid is assumed to be gray, absorbing and emitting radiation out in non scattering medium. The MHD flow is assumed to be laminar and fully developed. A closed form solutions of the equations governing the flow are obtained for the velocity and temperature distributions making use of regular perturbation technique. The velocity, temperature and concentration profiles are discussed through graphically as well as skin friction coefficient, Nusselt number and Sherwood number are evaluated numerically and presented in the form of tables and discussed for different values of governing flow parameters.

Keywords: Hall Effect, radiating fluid, MHD oscillatory flow, rotating channel, slip flow regime.

Nomenclature:

\( (u, v) \) the velocity components along \( x \) and \( y \) directions
\( p \) the modified pressure
\( t \) time
\( C_p \) Specific heat
\( B_0 \) electromagnetic induction
\( g \) Acceleration due to gravity
\( K_1 \) thermal conductivity
\( k \) permeability of the porous medium
\( Q_0 \) Heat absorption
\( T \) temperature of the fluid
\( f_1 \) Maxwell’s reflection co-efficient
\( \mu \) Co-efficient of viscosity
\( L \) mean free path
\( T_0 \) mean temperature
\( w_0 \) suction velocity
\( q_1 \) radiative heat
\( q \) Complex velocity
\( M \) Hartmann number
\( K \) Permeability parameter
\( S \) second grade fluid parameter
\( R \) Rotation parameter
\( Gr \) thermal Grashof number
\( Pr \) Prandtl number
\( D \) the molecular diffusivity
\( K_c \) the chemical reaction parameter
\( C \) concentration
\( C_0 \) mean concentration
\( Q_1 \) Radiation absorption
\( \alpha \) the mean variation absorption coefficient
\( \alpha_1 \) normal stress moduli
\( \theta \) Dimension less temperature
\( \phi \) Dimension less concentration
\( \Omega \) Angular velocity
\( \sigma \) Electrical conductivity of the fluid
\( \rho \) Density of the fluid
\( \nu \) Kinematic viscosity
\( \omega \) the frequency of oscillation
\( \beta \) The coefficient of volume expansion
\( \beta_1 \) The coefficient of volume expansion with concentration

INTRODUCTION

During the past several decades, convective flow through porous media has been a subject of considerable research interest of a large number of scholars due to its diverse engineering applications. These applications include, but are not limited to, for example heat exchangers in high heat flux applications such as electronic equipment, insulation of the heated body, thermal energy storage and sensible heat storage beds, drying process (wood and food products), air conditioning and filtration process. During the last decades, several researchers studied free convection heat and mass transfer in a porous medium [1e3]. Mass transfer effects on flow past an accelerated vertical plate has already been well studied [4,5]. Furthermore, the problem of heat and mass transfer of nonNewtonian fluids in porous media has been a
subject of interest in many research projects [6e10]. In recent years, considerable attention has been devoted to the study of magnetohydrodynamics (MHD) flow and heat. In addition to useful features of MHD flows, such studies can be helpful in prediction of the effects of magnetic intrusions. Raptis and Singh [11] studied MHD free convection flow past an accelerated vertical plate. Taza Gul et al. [12] studied heat transfer of MHD thin film flow of an unsteady second grade fluid past a vertical oscillating belt by analytical techniques. In recent years there has been a growing interest in studying the combined application of MHD flow and porous media. Since the use of magnetic field can influence the heat generation/absorption process in electrically conducting fluid flows, the rate of cooling in many metallurgical processes and consequently the desired properties of the end product can be controlled. Furthermore, the influence of magnetic field on boundary layer flows has brought about its application in geothermal energy recovery, oil extraction and thermal insulations. Abdulhameed et al. [13] obtained exact solution for an unsteady two-dimensional MHD flow of incompressible viscous fluid over a flat plate with wall transpiration embedded in a porous medium. Aldoss et al. [14] investigated combined free and forced convection flow from a vertical plate embedded in a porous medium in the presence of a magnetic field. Chamkha [15] considered a plate embedded in a uniform porous medium which moves with a constant velocity in the flow direction in the presence of a transverse magnetic field. Reddy [16] studied radiation effects on MHD natural convection flow along a vertical cylinder embedded in a porous medium with variable surface temperature and concentration. Also, Olajuwon et al. [17] investigated the effect of thermal radiation and Hall current on MHD flow of a viscoelastic micropolar fluid through a porous medium. Furthermore, unsteady MHD flow in porous media has been studied by several researchers [18-20]. Combined buoyancy-generated heat and mass transfer are characterized by highly non-linear coupled partial differential equations which are required to be solved by numerical computations. In recent years different researchers have used and discussed various numerical modeling techniques [21-25]. Recently, Krishna and Swarnalathamma [26] discussed the peristaltic MHD flow of an incompressible and electrically conducting Williamson fluid in a symmetric planar channel with heat and mass transfer under the effect of inclined magnetic field. Swarnalathamma and Krishna [27] discussed the theoretical and computational study of peristaltic hemodynamic flow of couple stress fluids through a porous medium under the influence of magnetic field with wall slip condition. Veera Krishna and M.G.Reddy [28] discussed MHD free convective rotating flow of visco-elastic fluid past an infinite vertical oscillating plate. Veera Krishna and G.S.Reddy [29] discussed unsteady MHD convective flow of second grade fluid through a porous medium in a Rotating parallel plate channel with temperature dependent source.

In view of the above facts, in this chapter, an investigation of the heat and mass transfer on the flow of an oscillatory convective MHD viscous incompressible, radiating and electrically conducting second grade fluid in a vertical porous rotating channel in slip flow regime is carried out.

FORMULATION AND SOLUTION OF THE PROBLEM

Consider the flow of a viscous, incompressible and electrically conducting second grade fluid through a porous medium bounded by two infinite vertical insulated plates at distance apart under the influence of uniform transverse magnetic field with magnetic flux density vector $\mathbf{B}_0$ normal to the channel.

We introduce a Cartesian co-ordinate system with $x$-axis oriented vertically upward along the centreline of this channel and $z$-axis taken perpendicular to the planes of the plates which is the axis of the rotation and the entire system comprising of the channel and the fluid are rotating as a solid body about this axis with constant angular velocity $\Omega$. A constant injection velocity $w_0$ is applied at the plate $z = -d/2$ and the same constant suction velocity, $w_0$, is applied at the plate $z = d/2$. The schematic diagram of the physical problem is shown in the Fig. 1.

![Figure 1. Physical Configuration of the Problem](image-url)
Since the plates of the channel occupying the planes
\( z = \pm \frac{d}{2} \) are of infinite extent, all the physical quantities
depend upon only on \( z \) and \( t \) only. Under the Boussinesq
approximation the flow of the fluid through the porous
medium in a rotating channel is governed by the following
equation:

\[
\frac{\partial w}{\partial z} = 0
\]  
(2.1)

\[
\frac{\partial u}{\partial t} - 2i\Omega v + w_0 \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + v \frac{\partial^2 u}{\partial z^2} + \alpha_1 \frac{\partial^3 u}{\partial z^3 \partial t} - \frac{\sigma B_0^2}{\rho} \frac{\partial^3 u}{\partial z^3 \partial t} - \frac{\nu}{k} u + g\beta T + g\beta_e C
\]  
(2.2)

\[
\frac{\partial v}{\partial t} + 2i\Omega u + w_0 \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \frac{\partial^2 v}{\partial z^2} + \alpha_0 \frac{\partial^3 z}{\partial z^3 \partial t} - \frac{\sigma B_0^2}{\rho} \frac{\partial^3 v}{\partial z^3 \partial t} - \frac{\nu}{\kappa} v
\]  
(2.3)

\[
\rho C_p \left( \frac{\partial T}{\partial t} + w_0 \frac{\partial T}{\partial z} \right) = K_1 \frac{\partial^2 T}{\partial z^2} - Q_0 T + Q_1 C - \frac{\partial q_1}{\partial z}
\]  
(2.4)

\[
\frac{\partial C}{\partial t} + w_0 \frac{\partial C}{\partial z} = D \frac{\partial^2 T}{\partial z^2} - K_c C
\]  
(2.5)

The boundary conditions are

\[
u = \frac{2 - f_1 t}{f_1}, L \frac{\partial u}{\partial z} = L \frac{\partial v}{\partial z}, \frac{\partial v}{\partial z}, T = 0, C = 0 \quad \text{at} \quad z = -\frac{d}{2}
\]  
(2.6)

\[
u = 0, \quad T = T_0 \cos \omega t, C = C_0 \cos \omega t \quad \text{at} \quad z = \frac{d}{2}
\]  
(2.7)

Where, \( L = \mu \left( \frac{\pi}{2\rho} \right)^{1/2} \) is the mean free path which is constant for an incompressible fluid.

Following Cogley et al [22] the last term in the energy equation stand for radiative heat flux which is given by

\[
\frac{\partial q_1}{\partial z} = 4\alpha^2 T
\]  
(2.8)

Where \( \alpha \) is the mean variation absorption coefficient.

Introducing non-dimensional variables,

\[
z^* = \frac{z}{d}, x^* = \frac{x}{d}, y^* = \frac{y}{d}, u^* = \frac{u}{d}, v^* = \frac{v}{d}, \theta = \frac{T}{T_0}, \phi = \frac{C}{C_0}, \tau = \frac{t w_0}{d}, \omega^* = \frac{\omega}{w_0}
\]

Making use of non-dimensional variables, the equations (2.2), (2.3) and (2.4) reduces to (dropped asterisks)

\[
\text{Re} \left( \frac{\partial u}{\partial t} + \frac{\partial u}{\partial z} \right) - 2iRe = -\text{Re} \left( \frac{\partial p}{\partial x} + \frac{\partial^2 u}{\partial z^2} + S \frac{\partial^2 u}{\partial z^2 \partial t} - \left( M^2 + \frac{1}{K} \right) u \right) + Gr \theta + Gc \phi
\]
(2.9)

\[
\text{Re} \left( \frac{\partial v}{\partial t} + \frac{\partial v}{\partial z} \right) + 2iRu = -\text{Re} \left( \frac{\partial p}{\partial y} + \frac{\partial^2 v}{\partial z^2} + S \frac{\partial^2 v}{\partial z^2 \partial t} - \left( M^2 + \frac{1}{K} \right) v \right)
\]
(2.10)

\[
\text{RePr} \left( \frac{\partial \theta}{\partial t} + \frac{\partial \theta}{\partial z} \right) = \frac{\partial^2 \theta}{\partial z^2} - Pr \phi \theta + Re^3 Pr Q \phi - Pr N^2 \theta
\]
(2.11)
\[
\text{Sc Re}\left( \frac{\partial \phi}{\partial t} + \frac{\partial \phi}{\partial z} \right) = \frac{\partial^2 \phi}{\partial z^2} - \text{Sc Re} \text{Kc} \phi
\]  

(2.12)

The corresponding boundary conditions in non dimensional form are

\[
u = h \frac{\partial u}{\partial z}, \quad \nu = h \frac{\partial v}{\partial z}, \quad T = 0 \quad \text{at} \quad z = -\frac{1}{2}
\]  

(2.13)

\[
u = v = 0, \quad T = T_0 \cos \omega t \quad \text{at} \quad z = \frac{1}{2}
\]  

(2.14)

Where, \( \text{Re} = \frac{\omega_d d}{v} \) is Reynolds number, \( R = \frac{\Omega d^2}{v} \) is the rotation parameter, \( K = \frac{k}{d^2} \) is the permeability parameter, 

\[
\text{Gr} = \frac{g \beta_d T_0^2}{\nu w_0} \]

is the thermal Grashof number, \( \text{Gc} = \frac{g \beta_d d^2 C_0}{\nu w_0} \) is the mass Grashof number, \( \text{Pr} = \frac{\mu C_p}{\kappa} \) is the Prandtl number, \( \text{Sc} = \frac{v}{D} \) is the Schmidt number, \( \text{Kc} = \frac{K_c d}{w_0} \) is the chemical reaction parameter, \( N = \frac{2 \alpha d}{\sqrt{K_1}} \) is the Radiation parameter, \( \phi_i = \frac{Q o d}{\mu C_p} \) is the Heat absorption parameter, \( Q = \frac{Q o v C_0}{\rho C_p w_0^2 T_0} \) is the Radiation absorption number, \( M^2 = \frac{\sigma B_0^2 d^2}{\mu} \) is the Hartmann number and \( S = \frac{\alpha_i}{\rho d^2} \) is the second grade fluid parameter.

Combining equations (2.9) and (2.10), let \( q = u + iv \) and \( \xi = x - iv \), we obtain

\[
\text{Re} \left( \frac{\partial q}{\partial t} + \frac{\partial q}{\partial z} \right) = -\text{Re} \frac{\partial p}{\partial \xi} + \frac{\partial^2 q}{\partial z^2} + S \frac{\partial^3 q}{\partial z^3} - \left( M^2 + 2iR + \frac{1}{K} \right) q + \text{Gr} \theta + \text{Gc} \phi
\]  

(2.15)

We assume the flow under the influence of pressure gradient varying periodically with time, 

\[
\frac{\partial p}{\partial \xi} = A \cos \omega t
\]  

(2.16)

The equation (2.16) is substituting in the equation (2.15) we obtain

\[
\text{Re} \left( \frac{\partial q}{\partial t} + \frac{\partial q}{\partial z} \right) = \text{Re} A \cos \omega t + 0 \frac{\partial^2 q}{\partial z^2} + S \frac{\partial^3 q}{\partial z^3} - \left( M^2 + 2iR + \frac{1}{K} \right) q + \text{Gr} \theta + \text{Gc} \phi
\]  

(2.17)

The corresponding boundary conditions are

\[
q = h \frac{\partial q}{\partial z}, \quad \theta = 0, \quad \phi = 0 \quad \text{at} \quad z = -\frac{1}{2}
\]  

(2.18)

\[
q = 0, \quad \theta = \cos \omega t, \quad \phi = \cos \omega t \quad \text{at} \quad z = \frac{1}{2}
\]  

(2.19)

In order to solve the equations (2.17), (2.11) and (2.12) with the boundary conditions (2.18) & (2.19) following Choudary et al. [23] we assume the solution of the form

\[
q(z, t) = q_0(z)e^{i\alpha t}
\]  

(2.20)

\[
\theta(z, t) = \theta_0(z)e^{i\alpha t}
\]  

(2.21)

\[
\phi(z, t) = \phi_0(z)e^{i\alpha t}
\]  

(2.22)
Substituting the equations (2.20), (2.21) and (2.22) in (2.17), (2.11) and (2.12) respectively, the resulting equations are,

We find the Skin Fraction \( \tau_L \) at the left plate in terms of its amplitude and the phase angle as

\[
\tau_L = \left( \frac{\partial q}{\partial z} \right)_{z=-\frac{1}{2}} = |q| \cos(\omega t + \gamma)
\]

The rate of heat transfer (Nu) in terms of amplitude and the phase angle can be obtained as

\[
Nu = \left( \frac{\partial T}{\partial z} \right)_{z=-\frac{1}{2}} = |r| \cos(\omega t + \psi)
\]

**Sherwood number:**

The rate of mass transfer (Sh) in terms of amplitude and the phase angle can be obtained as

\[
Sh = \left( \frac{\partial \phi}{\partial z} \right)_{z=-\frac{1}{2}} = |s| \cos(\omega t + \eta)
\]

All the constants used above have been mentioned in the appendix.

**RESULTS AND DISCUSSIONS**

The effect of the Rotation number \( R \), second grade fluid parameter \( S \) on the velocity profile shown by the Figs. 2. We noticed that the magnitude of velocity components \( u \) and \( v \) enhance with increasing \( R \) and \( S \) throughout the fluid region. Similar behaviour is observed for increasing thermal Grashof number \( Gr \), permeability of the porous medium \( K \) and the amplitude of the pressure gradient \( A \) (Figs. 3).

The variations in the temperature profile are presented in the figs (4-7). It is observed from this Fig. 7 that the temperature profiles decrease with the increasing Reynolds number \( Re \) and the Prandtl number \( Pr \). The similar behaviour is observed with increasing the radiation parameter \( N \) and Schmidt number \( Sc \). The temperature profile is diminished with increasing chemical reaction parameter \( Kc \), the radiation absorption parameter \( Q \), the frequency of oscillation \( \omega \) and it increases with the heat absorption parameter for \( 0 \leq \Phi_i \leq 1 \) and decreases for \( \Phi_i \geq 1 \) (Figs. 5-7).

A variation in the concentration profile is plotted in the Fig (8-9) and it is evident from the study of this figure that the amplitude of the concentration profile decreases with all the parameters Reynolds number \( Re \), chemical reaction parameter \( Kc \), Schmidt number \( Sc \) and the frequency of oscillation \( \omega \) effecting the concentration equation.

The skin friction, Nusselt number and Sherwood number are evaluated analytically and tabulated in the tables. The amplitude and phase angle of the skin friction are shown in Table-1. The negative values in this table indicate that there is always a phase lag and this phase goes on increasing with increasing frequency of oscillation. We noticed that, the amplitude of stress \( |q| \) and phase angle \( \gamma \) are enhanced with increasing the parameters \( K, R, S, Gr \) and \( Kc \). Likewise the amplitude of the stress and the magnitude of the phase angle increases with \( Gc, Pr, N, A, Q \) and \( \Phi_i \). The amplitude of stress \( |q| \) reduces and phase angle \( \gamma \) increases with increasing \( M, h \) and \( \omega \). The reversal behaviour is observed with increasing \( Sc \). From the table 2, we found that the amplitude \( |r| \) and phase angle \( \psi \) of the Nusselt number increases with increasing \( Re, Pr, Sc \) and \( Kc \). Also the amplitude of the Nusselt number decreases while phase angle \( \psi \) of the Nusselt number increases with increasing with \( N, \Phi_i \) and \( \omega \).

The opposite behaviour is observed with increasing \( Q \).

Finally, from the table 3, we found that the amplitude \( |s| \) and phase angle \( \eta \) of the Sherwood number decreases with increasing \( Re, Kc \) and \( \omega \). Also the amplitude of the Sherwood number decreases while phase angle \( \psi \) of the Sherwood number increases with increasing with \( Sc \).
**Figure 2.** The velocity profiles for $u$ and $v$ against $R$, $m$ and $S$ with

$$Gr = 3, M = 0.5, Pr = 0.71, K = 0.5, A = 5, h = 0.2, \phi_1 = 0.1, N = 1, \omega = \pi / 6, Gc = 5, Kc = 1, Q = 1$$

**Figure 3.** The velocity profiles for $u$ and $v$ against $Gr$, $K$ and $A$ with

$$R = 1, M = 0.5, Pr = 0.71, S = 1, h = 0.2, \phi_1 = 0.1, N = 1, \omega = \pi / 6, Gc = 5, Kc = 1, Q = 1$$

**Figure 4.** The Temperature profiles for $\theta$ against $Re$ and $Pr$

$$Q = 0.5, Sc = 0.22, Kc = 1, \phi_1 = 0.1, \omega = \pi / 6, N = 1$$
Figure 5. The Temperature profiles for $\theta$ against $Re$ and $Pr$

$Re = 2, Q = 0.5, Kc = 1, \phi_1 = 0.1, \omega = \pi/6, Pr = 0.71$

Figure 6. The Temperature profiles for $\theta$ against $\phi_1$ and $Kc$

$Re = 2, Q = 0.5, Sc = 0.22, \omega = \pi/6, Pr = 0.71, N = 1$

Figure 7. The Temperature profiles for $\theta$ against $Q$ and $\omega$

$Re = 2, Sc = 0.22, Kc = 1, \phi_1 = 0.1, Pr = 0.71, N = 1$
Figure 8. The Concentration profiles for $\phi$ against Re and Kc with $\text{Sc} = 0.22, \omega = \pi / 6$

Figure 9. The Concentration profiles for $\phi$ against Sc and $\omega$ with $\text{Sc} = 0.22, \omega = \pi / 6$

Table 1: Amplitude and Phase angle of Skin friction for $\text{Re} = 0.5, t = 0.1$

| $M$ | $K$ | $R$ | $S$ | Gr | $\text{Ge}$ | Pr | $N\_A$ | $h$ | $\omega$ | $Q$ | $K\_c$ | $\text{Sc}$ | $\phi_\| | | Amplitude $|q|$ | Phase angle $\gamma$ |
|-----|-----|-----|-----|-----|---------|----|--------|----|--------|----|--------|--------|-----|-----------------|----------------|
| 0.5 | 0.5 | 1   | 1   | 3   | 5       | 0.71| 1      | 5   | 0.2    | $\pi / 6$ | 1      | 1     | 0.22             | 1              | 2.41838 | 0.283666 |
| 1   |     |     |     |     |         |     |        |     |        |     |        |        | 2.08139 | 0.493308 |
| 1.5 |     |     |     |     |         |     |        |     |        |     |        |        | 1.84239 | 0.912284 |
| 1   |     |     |     |     |         |     |        |     |        |     |        |        | 4.12001 | 0.361881 |
| 2   |     |     |     |     |         |     |        |     |        |     |        |        | 4.74557 | 0.546996 |
| 1.5 |     |     |     |     |         |     |        |     |        |     |        |        | 2.60643 | 0.702051 |
| 2   |     |     |     |     |         |     |        |     |        |     |        |        | 2.93479 | 0.953428 |
| 3   |     |     |     |     |         |     |        |     |        |     |        |        | 3.56638 | 0.449328 |
| 4   |     |     |     |     |         |     |        |     |        |     |        |        | 4.52993 | 0.530073 |
| 5   |     |     |     |     |         |     |        |     |        |     |        |        | 6.10330 | 1.22620 |
| 6   |     |     |     |     |         |     |        |     |        |     |        |        | 10.9613 | 1.40566 |
| 10  |     |     |     |     |         |     |        |     |        |     |        |        | 2.76792 | -0.494756 |
Table 2: Amplitude and Phase angle of Nusselt number for \( t = 0.1 \)

| Re | Pr | N | \( \phi_1 \) | Sc | Kc | \( \omega \) | Amplitude \(|r|\) | Phase angle \(\varphi\) |
|----|----|---|---------|----|----|--------|----------------|-----------------|
| 2  | 0.71 | 1  | 0.2     | 0.22 | 0.2 | 1 \( \pi/6 \) | 4.31112 | 0.538747 |
| 3  |      |    |         |      |     | 12.6750 | 1.230090 |
| 4  |      |    |         |      |     | 16.1478 | 1.527450 |
|    |      | 3  |         |      |     | 21.6871 | 1.405730 |
|    |      | 7  |         |      |     | 45.0290 | 1.536470 |
|    |      | 2  |         |      |     | 4.22257 | 1.466980 |
|    |      | 3  |         |      |     | 3.93830 | 1.491090 |
| 0.5|      |    |         |      |     | 2.79348 | 0.667940 |
| 1  |      |    |         |      |     | 2.33856 | 1.104290 |
|    |      | 0.3|         |      |     | 5.57300 | 0.627978 |
|    |      | 0.6|         |      |     | 16.0440 | 1.447030 |
|    |      | 0.4|         |      |     | 5.36079 | 1.377640 |
|    |      | 0.6|         |      |     | 5.82016 | 1.541990 |
|    |      | 2  |         |      |     | 7.58466 | 0.355346 |
|    |      | 3  |         |      |     | 10.9587 | 0.283540 |
|    |      | \( \pi/4 \) |    |      |     | 4.27767 | 0.853784 |
|    |      | \( \pi/3 \) |    |      |     | 4.15536 | 1.011080 |
Table 3: Amplitude and Phase angle of Sherwood number for \( t = 0.1 \)

<table>
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<th>Re</th>
<th>Sc</th>
<th>Kc</th>
<th>( \omega )</th>
<th>Amplitude</th>
<th>Phase angle</th>
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<tr>
<td>4</td>
<td>0.3</td>
<td>0.6</td>
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<td>0.661697</td>
<td>1.56853</td>
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<tr>
<td>0.6</td>
<td>0.4</td>
<td>0.6</td>
<td>( 0.739937 )</td>
<td>1.54045</td>
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<tr>
<td>( \pi / 4 )</td>
<td></td>
<td></td>
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CONCLUSIONS

The resultant velocity enhances with increasing \( R, S, Gr, K \) and \( A \) throughout the fluid region. The velocity profile is diminished with the increasing \( \phi, h, \omega, M, Pr \) and \( N \). The resultant velocity enhances with increasing \( Gc \) and continuously reduces with increasing \( Kc \) and \( Q \) in the entire fluid region. The temperature profiles decrease with the increasing \( Re, Pr, N \) and \( Sc \). The temperature profile is diminished with increasing \( Kc \) and \( \omega \). The concentration profile decreases with all \( Re, Kc, Sc \) and \( \omega \). The amplitude and phase angle of frictional force are enhanced with increasing the parameters \( K, R, S, Gr \) and \( Kc \). The amplitude and phase angle of the Nusselt number increases with increasing \( Re, Pr, Sc \) and \( Kc \). Also the amplitude of the Nusselt number decreases while phase angle of the Nusselt number increases with increasing \( N \). The amplitude and phase angle of the Sherwood number decreases with increasing \( Re, Kc \) and \( \omega \).

REFERENCES


