MHD rotational flow of viscous fluid past a vertical plate with slip and Hall effect through porous media: A theoretical modeling with heat and mass transfer

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Abstract
As the slip at the solid boundary is an essential attribute for fluid flow in different mechanical situations. Therefore this article aims to explain the slip effect over the free convection and rotating flow of viscous fluid over an extended plate with heat and mass transfer in the presence of magnetic field of the constant magnitude through a porous medium. The respective fluid is chemically reacting fluid hence the effect of chemical reaction with the effect of heat absorption is considered in the development of governing equations. To get the better physical understanding of flow model the governing equations are reduced to dimensionless form. The dimensionless governing equations are solved with aid of Laplace transform and closed form solutions are developed for the thermal, concentration and velocity fields. The real and imaginary components of velocity field are also plotted for the variation of different physical parameters and parametric discussion is posted with assistance of these plotted graphs. In the light of parametric discussion it is concluded that with heat and mass transfer there is more bouncy effect in flow domain. Further in the presence of hall effect fluid speeds up while it is slow down with increasing value of magnetic and slip parameters

Keywords
Heat and mass transfer, rotating MHD flow, slip condition, Newtonian heating, chemical reaction, porous media

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Introduction
Free convection flows establish by the combine contribution of both thermal and concentration gradients have useful application in the fields of physical sciences and discussed by many researchers. Chandran et al.\textsuperscript{1} presented the analysis for flow subject to the wall temperature over a plate. Nandy et al.\textsuperscript{2} consider a natural convection flow model and obtained the closed form solution. Pattnaik and Biswal\textsuperscript{3} obtained the closed form solution for thermal and mass diffusion. Uddin et al.\textsuperscript{4} discussed the fluid flow subject to the non-homogenous temperature and concentration fields. Hussain et al.\textsuperscript{5} have explored role of fluctuating fluxes of heat and mass over a convection flow of viscous fluids. Krishna and Reddy\textsuperscript{6} considered the flow of a chemically

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replacing fluid with effect of Hall current. Sheikh and Hasan17 explain the effect of inclination over a free convectional flow micropolar fluid induced by mix convection. Some more study regarding free convection flow are listed in Refs.8–12. In all above studies the no-slip condition is considered as boundary condition, however this concept is realized only when the fluid particles adjacent to surface of boundary does not move in flow the flow direction, that is, adhesion is dominant to the cohesion. There are many practical situations like flow of rubberizer compounds, polyethylene, biological suspensions over the hydrodynamic surfaces where fluids and its boundary have some relative velocity therefore in such flow idea of no-slip condition at boundary is no more applicable. In many complex flows, the viscous fluids can slip over a solid boundary in this circumstances the slip condition is an compiling aspect and have the significant effect.

Moreover slip at flow boundary has the many applicable usages in the flow of biological fluids, lubricants, polishing material, and flow of blood through the heart valves. Hayat et al.13,14 discussed the slip and partial slip flows over flat surfaces. Shah et al.15 considered the slip attribute at boundary for flow of Carreau fluid. Norouzi et al.16 analyzed the flow of non-Newtonian fluid and have explained the effect of slip. Fetecau et al.17 illustrated the influence of MHD and slip for natural flow at the moving plat. Imran et al.18 Vieru et al.,19 and Waqas et al.20 also discussed effect for slip over flow of Newtonian and non-Newtonian fluids.

Rotating flows of fluids with the effect of magnetic fields through a porous media have the significant role in the study of Cosmic and oceanic fluids eddies, rotating food machinery, processing industry, and filtration plants. Singh21 has investigated the results for rotational flow of fluid past an aerated surface. Kumari and Nath22 has explained the unsteady rotating flow in the vicinity MHD field. Muthucumaraswasy et al.23,24 have also considered the rotational effect of over a free convectional motion of viscous fluid for mass diffusion. Imran et al.25 has derived the interesting results of velocity and temperature for the free convectional flow in the rotating frame. Krishna and Reddy26 have presented the effect of reaction and Joule’s current for a rotating flow of fluid with MHD. Farhad et al.27 consider a rotating flow of viscous fluid with effect of MHD and Hall current. Raghunath et al.5 and Sharma et al.28 have also considered rotating flow subject to the thermal and mass transfer.

The slippage and rotating free convectional flow of viscous fluid in the presence of MHD for a porous regime with heat obreption and chemical reaction is discussed in the present study and such work has not been found in the present literature. The primary goal of this study is to modeled a rotating flow of viscous fluid with slip condition over the boundary and the solved analytically by applying Laplace transform. The expression of temperature, concentration, and velocity is communicated in term of special functions. Further the some graphs of velocity components are plotted and discuss the deportment of parameters of interest.

### Development of model

Suppose a Newtonian fluid is flowing near a vertical plate in the presence of magnetic field of the constant magnitude \( B_0 \) through a porous regime with the effect of heat absorption and chemical reaction. Flow is induced by the combine contribution of mechanical motion of plate, and non homogenous thermal and concentration fields as shown in the Figure 1. For beginning fluid and boundary are at rest and in this state the level of concentration is \( C_w \) with the thermal state \( T_w \). For the time \( t>0 \) suddenly plate start to move with velocity \( u_0(t) \) and at this moment the temperature at wall is \( T_w \) concentration level is \( C_w \). Absorption heat and chemical reaction are also considered. The effect of density variation is also deliberated in the momentum balance. In the light of assumption flow model is governed by the following PDEs9,26

\[
\frac{\partial u(z,t)}{\partial t} - 2\Omega v(z,t) = \nu \frac{\partial^2 u(z,t)}{\partial z^2} - \frac{B_0 J_y}{\rho} - \frac{\nu \phi}{k} u(z,t) + g\beta_T(T(z,t) - T_w) + g \beta_C(C(z,t) - C_w),
\]

(1)

\[
\frac{\partial v(z,t)}{\partial t} + 2\Omega u(z,t) = \nu \frac{\partial^2 v(z,t)}{\partial z^2} - \frac{B_0 J_z}{\rho} - \frac{\nu \phi}{k} v(z,t),
\]

(2)

\[
\rho C_p \frac{\partial T(z,t)}{\partial t} = k \frac{\partial^2 T(z,t)}{\partial z^2} + q_1(T(z,t) - T_w),
\]

(3)

\[
\frac{\partial C(z,t)}{\partial t} = D \frac{\partial^2 C(z,t)}{\partial z^2} + Kr(C(z,t) - C_w),
\]

(4)

\[
u(z,0) = v(z,0) = 0, T(z,0) = 0, C(z,0) = 0.
\]

(5)

\[
u(0,t) - \lambda \frac{\partial u}{\partial z} = u_0(t), v(0,t) - \lambda \frac{\partial v}{\partial z} = 0,
\]

(6)

\[
T(0,t) = T_w, C(0,t) = C_w,
\]

(7)

and

\[
u(z,t) \to 0, v(z,t) \to 0, T(z,t) \to 0, C(z,t) \to 0 as z \to \infty.
\]

(8)

For the magnetic field of the larger magnitude, the modified usual Ohm’s law is stated as follows

\[\mathbf{J} = \frac{\omega_c \tau_c}{B_0} (\mathbf{J} \times \mathbf{B}) = \sigma \left[ \nabla \mathbf{v} + \nabla \times \mathbf{B} + \frac{1}{\epsilon \eta_c} \nabla p_e \right],\]

(9)

where \( \mathbf{J} \) is the space density of current, \( \mathbf{E} \) is the vector of electric field, \( \omega_c \) is frequency of cyclotron, \( \tau_c \) is the
time of electron collision, $e$ is electric charge, $\sigma$ is the fluid electric conductivity, $\eta_e$ is the electron density number, and $p_e$ is pressure develop by electron. In the Eq. (8), the slip of ion, thermos effect of electron motion, electron pressure gradient are not considered. Moreover it is also assumed that the electric field $E = 0$. With these assumption the Ohm’s law rescued to following component form

$$J_x + v \frac{\partial e}{\partial y} = sB_0v,$$

$$J_y - \omega_e \tau_e J_x = -\sigma B_0 u.$$  \hfill (9)

Solving equations (9) and (10) for the relation of $J_x$ and $J_y$ we get

$$J_x = \frac{\sigma B_0}{1 + m^2} (v + mu),$$

$$J_y = \frac{\sigma B_0}{1 + m^2} (mv - u),$$  \hfill (11)

where $m = \omega_e \tau_e$ is the hall parameter.

Inserting respective relations of $J_x$ and $J_y$ from equations (11) and (12) in equations (1) and (2) we get

$$\frac{\partial u(z, t)}{\partial t} - 2\Omega v(z, t) = \nu \frac{\partial^2 u(z, t)}{\partial z^2} + \frac{1}{\rho} \frac{\sigma B_0^2}{1 + m^2} (mv - u),$$

$$+ gB_1(T(z, t) - T_\infty) + g\beta_c(C(z, t) - C_\infty),$$  \hfill (13)

$$\frac{\partial v(z, t)}{\partial t} + 2\Omega u(z, t) = \nu \frac{\partial^2 v(z, t)}{\partial z^2} - \frac{1}{\rho} \frac{\sigma B_0^2}{1 + m^2} (v + mu) - \frac{\nu \phi}{k} v(z, t).$$  \hfill (14)

By introducing the following dimensionless relations

$$u^* = \frac{u}{u_0}, v^* = \frac{v}{u_0}, z^* = \frac{z u_0}{\nu},$$

$$t^* = \frac{u_0^2 t}{\nu}, T^* = \frac{T - T_\infty}{T_w - T_\infty}, C^* = \frac{C - C_\infty}{C_w - C_\infty},$$  \hfill (15)

In equations (3)–(7) and in equations (13)–(14) we get

$$\frac{\partial u(z, t)}{\partial t} - 2 E_k v(z, t) = \frac{\partial^2 u(z, t)}{\partial z^2} - \frac{1}{k_o} u(z, t)$$

$$+ \frac{M^2}{1 + m^2} (mv - u) + GrT(z, t) + Gm C(z, t),$$  \hfill (16)

$$\frac{\partial v(z, t)}{\partial t} + 2 E_k u(z, t) = \frac{\partial^2 v(z, t)}{\partial z^2} - \frac{1}{\nu} (v + mu),$$  \hfill (17)

$$\frac{\partial T(z, t)}{\partial t} = \frac{1}{Pr} \frac{\partial^2 T(z, t)}{\partial z^2} + q_o T(z, t),$$  \hfill (18)

$$\frac{\partial C(z, t)}{\partial t} = \frac{1}{Sc} \frac{\partial^2 C(z, t)}{\partial z^2} + K_o C(z, t).$$  \hfill (19)
with non-dimensional conditions

\[ u(z, 0) = 0, v(z, 0) = 0, T(z, 0) = 0, C(z, 0) = 0, \]  \hspace{1cm} (20)

\[ u(0, t) - \lambda_o \frac{\partial u}{\partial z} = f(t), v(0, t) - \lambda_o \frac{\partial v}{\partial z} = 0, \]  \hspace{1cm} (21)

\[ T(0, t) = 1, C(0, t) = 1, \]

\[ u(z, t) \rightarrow 0, v(z, t) \rightarrow 0, T(z, t) \rightarrow 0, C(z, t) \rightarrow 0 \]  \hspace{1cm} as \ z \rightarrow \infty, \]  \hspace{1cm} (22)

where

\[ \frac{1}{k_o} = \frac{\nu^2 \phi}{k_i u_o^2}, \]

\[ M = \frac{\sigma B_o^2 \sigma}{u_o \rho (1 - m)}, \]

\[ E_k = \frac{\Omega \nu}{u_o^2}, \quad Gr = \frac{\nu}{u_o^2} g \beta_r (T_w - T_\infty), \]

\[ q_o = \frac{v q_1}{u_o^2 \rho C_p}, \quad G_m = \frac{\nu}{u_o^2} g \beta_c (C_w - C_\infty), \]

\[ \nu = \frac{v p C_\nu}{\kappa}, \quad Sc = \frac{\nu}{D}, \quad k_0 = k_r \frac{\nu}{u_o^2}, \quad \lambda_o = \frac{\lambda u_o}{\nu}, \]

are porosity, magnetic parameter, rotational parameter, thermal Grashof number, heat generation parameter, mass Grashof, Prandtl, Schmidt numbers, chemical reaction, and slip parameter respectively.

**Solution of problem**

**Temperature**

Apply Laplace to equation (18)

\[ q\tilde{T}(z, q) = \frac{1}{Pr} \frac{\partial^2 \tilde{T}(z, q)}{\partial z^2} + q_o \tilde{T}(z, q). \]  \hspace{1cm} (24)

Equation (24) is hold for the following transformed boundary conditions

\[ T(0, q) = \frac{1}{q}, \quad \text{and} \quad T(z, q) \rightarrow 0 \quad \text{as} \quad z \rightarrow \infty. \]  \hspace{1cm} (25)

Equation (24) is solved with conditions in (25) as

\[ \tilde{T}(z, q) = \frac{1}{q} e^{-\sqrt{Pr}(q - q_o)}. \]  \hspace{1cm} (26)

In equivalent form

\[ \tilde{T}(z, q) = \frac{q - q_o}{q} \frac{1}{q - q_o} e^{-\sqrt{Pr}(q - q_o)}, \]  \hspace{1cm} (27)

\[ \tilde{T}(z, q) = \frac{1}{q - q_o} e^{-\sqrt{Pr}(q - q_o)} - \frac{1}{q q - q_o} e^{-\sqrt{Pr}(q - q_o)}. \]  \hspace{1cm} (28)

Applying inverse Laplace transformation

\[ T(z, t) = \text{erfc} \left( \frac{z}{2 \sqrt{t}} \right) e^{\theta o t} - \int_0^t \text{erfc} \left( \frac{z}{2 \sqrt{\tau}} \right) e^{\theta o \tau} d\tau. \]  \hspace{1cm} (29)

**Solution of concentration**

Apply Laplace to equation

\[ q\tilde{C}(z, q) = \frac{1}{Sc} \frac{\partial^2 \tilde{C}(z, q)}{\partial z^2} + k_o \tilde{C}(z, q). \]  \hspace{1cm} (30)

Transform Boundary condition,

\[ C(0, q) = \frac{1}{q}, \quad \text{and} \quad T(z, q) \rightarrow 0 \quad \text{as} \quad z \rightarrow \infty. \]  \hspace{1cm} (31)

Solution of (30)

\[ \tilde{C}(z, q) = \frac{1}{q} e^{-\sqrt{Sc(q - q_0)}}. \]  \hspace{1cm} (32)

In suitable form

\[ \tilde{C}(z, q) = \frac{1}{q} \frac{q - q_o}{q - k_0} e^{-\sqrt{Sc(q - q_0)}}, \]  \hspace{1cm} (33)

\[ \tilde{C}(z, q) = \frac{1}{q - k_0} e^{-\sqrt{Sc(q - q_0)}} - \frac{1}{q q - k_0} e^{-\sqrt{Sc(q - q_0)}}. \]  \hspace{1cm} (34)

Applying inverse Laplace transformation

\[ C(z, t) = \text{erfc} \left( \frac{z}{2 \sqrt{t}} \right) e^{\theta o t} - k_o \int_0^t \text{erfc} \left( \frac{z}{2 \sqrt{\tau}} \right) e^{\theta o \tau} d\tau. \]  \hspace{1cm} (35)

**Solution of complex velocity**

Introducing the complex velocity \( F(z, t) = u(z, t) + iv(z, t) \) and by applying the operation equations (16) + iequation (17) we get

\[ \frac{\partial F(z, t)}{\partial t} + 2iE_k F(z, t) = \frac{\partial^2 F(z, t)}{\partial z^2} \frac{F(z, t)}{k_o}, \]  \hspace{1cm} (36)

\[ \frac{F(z, 0)}{k_o} = 0, \]  \hspace{1cm} (37)

\[ F(z, t) - \lambda_o \frac{\partial F(z, t)}{\partial z} = f(t), F(z, t) \rightarrow 0 \quad \text{as} \quad z \rightarrow \infty. \]  \hspace{1cm} (38)

Equation (36) in the light of initial condition in (37) under the Laplace transform reduced to the

\[ \frac{\partial^2 \tilde{F}(z, q)}{\partial z^2} = \left( q + \frac{1}{k_o} + \frac{M^2}{1 - im} + 2iE_k \right) \tilde{F}(z, q) \]  \hspace{1cm} (39)

Equation (39) holds for the transformed boundary conditions given below

\[ \tilde{F}(0, q) - \lambda_o \frac{\partial \tilde{F}(z, q)}{\partial z} = f(q), \tilde{F}(z, t) \rightarrow 0 \quad \text{as} \quad z \rightarrow \infty. \]  \hspace{1cm} (40)
Solution of equation (39) with conditions (40) is

\[ F(z, q) = \frac{f(q)e^{-z^{2}/q + M_0}}{1 + \lambda_0\sqrt{q} + M_o} + \frac{Gm(1 + \lambda_\sqrt{Pr(q - q_o))}}{Pr(q - q_o) - (q + M_o)q} \left[ e^{-z^{2}/q + M_0} + e^{-z^{2}/(Pr(q - q_o))} \right] \]

where, \( M_o = \frac{1}{K} + \frac{M^2}{1 + \epsilon} + 2iE_k \).

In suitable form

\[ F(z, q) = \frac{f(q)e^{-z^{2}/q + M_0}}{1 + \lambda_0\sqrt{q} + M_o} + \frac{Gm(1 + \lambda_\sqrt{Pr(q - q_o))}}{Pr(q - q_o) - (q + M_o)q} \left[ e^{-z^{2}/q + M_0} + e^{-z^{2}/(Pr(q - q_o))} \right] \]

where, \( M_o = \frac{1}{K} + \frac{M^2}{1 + \epsilon} + 2iE_k \).

now applying the inverse Laplace transform

\[ F(z, t) = \int_0^t f(t - s)f(l, s)ds \]

where

\[ f_1(z, t) = \frac{1}{\lambda_0\sqrt{\pi t}} \exp \left( \frac{z^2}{4t} - M_0 t \right) \]}

and

\[ f_2(z, t) = \frac{1}{\lambda_0\sqrt{\pi t}} \exp \left( \frac{z^2}{4t} - K_0 t \right) \]

**Parametric discussion**

This article aims to explain the rotating flow of viscous fluid past an extended surface in the presence of magnetic field of the constant magnitude through a porous medium with slip. The respective fluid is chemically reacting fluid with the effect of heat absorption is considered for construction development of governing equations. To get the better physical understanding of flow model the governing equations are reduced to dimensionless form. The dimensionless partial differential equations are solved with aid of Laplace transform and exact solutions for the thermal, concentration and velocity fields are developed.

The temperature profile is plotted in Figure 2 due to \( Pr \) and \( q_0 \) respectively. From figures it is revealed that thermal profiles fall down with increment of \( Pr \) and rises with the increment of heat absorption parameter \( q_0 \). Larger value of \( q_0 \) is referred to the more heat in the flow domain so temperature of fluid is raised with increasing value of \( q_0 \).

The concentration profile is plotted in Figure 3 due to \( Sc \) and \( K_0 \) respectively. From figures it is revealed that concentration profiles fall down with increment of \( Pr \) and rises with the increment of chemical reaction \( K_0 \). Larger value of \( K_0 \) is referred to the more species in the flow domain so concentration is raised with increasing value of \( K_0 \).
The velocity components are also plotted for the variation of different physical parameters and parametric discussion is posted with assistance of these plotted graphs in the Figures 4 to 14. In Figure 4 velocity field is plotted for thermal Grashof number $Gr$ and outline of the figures reveal that the increasing value of $Gr$ provides a support to the both components of fluid’s velocity. The same behavior of velocity components against the variation of mass Grashof number is also observed in Figure 5 and the physical reason behind this behavior of velocity is that $Gr$ and $Gm$ are the ratio of bouncy force due to temperature and concentration gradients respectively to the viscous force. Therefore more the bouncy force there are more convectional currents which provide a supports to fluid flow. The Figures 6 and 7 are drawn to study the significance of $Pr$ and $Sc$. The both components of fluid velocity show a decreasing trend for increasing values of $Pr$ and $Sc$, larger $Pr$ and $Sc$ refer to more momentum diffusivity which slows downs the fluid’s velocity. The
velocity’s components are sketched in Figure 8 for due variation of magnetic parameter M and decaying trend is seen. This decaying trend in velocity profiles is due the magnetic field in the flow domain so some resistive force is induced that retards fluid flow. The effect of porosity \( k_0 \) is discussed in the Figure 9 and increasing behavior is observed for the increasing value of \( k_0 \). The larger the value of \( k_0 \) there are larger the volume of voids in the porous media therefore there is more flow through the porous medium. The subjectivity of velocity’s components for heat absorption parameter \( q_0 \) is studies in the Figure 10 and heat absorption mean that there is more heat in the flow domain which accelerates the fluid with larger velocity.

The Figure 11 is sketched to discussed influence of reacting parameter \( K_0 \) over the components and decreasing trend is noted in the velocity components for \( K_0 \) variation. Some type of the species are created in the flow domain for reacting fluid and due to this fluid become thick and flow with small velocity. The slippage attribute \( \lambda \) is studies in the Figure 12 and velocity components speed up for increasing value of \( \lambda_0 \). More
slip there is more support to flow the fluid that is why both components of velocity increase with the increasing values of slip parameter. Rotational parameter $E_k$ is discussed in the Figure 13 for enhancing $E_k$ the fluid flows with the reduced real component while enhanced imaginary component.

In Figure 14 the Hall parameter $m$ is discussed and it is noted that both components of velocity are enhanced for increasing value of $m$. As Hall effect is due to Lorentz forces acting on ionized fluid in the presence of magnetic of the larger strength. An extra voltages generated in the flow field which a rise in the velocity of flowing fluid.

A comparison for components of present velocity profiles with Farhad et al. is presented in Figure 15 and the absence of bouncy effect due to temperature and concentration gradient, our result for both components of velocity overlap with the results obtained by Farhad.

The heat and mass flow rate at the boundary are discussed numerical in terms of Nusselt and Sherwood...
numbers respectively and obtained result are presented in the tabular in Table 1.

**Conclusion**

In this article the slippage and rotating free convectional flow of viscous fluid in the presence of MHD in a porous medium regime with the effect of heat obrep- traction and chemical reaction in the flow domain has been investigated. The expression for temperature, concentration, and velocity is expressed in term of special function. Further effect of parameters over the velocity profile are also explained by plotting the real and imaginary components of velocity. Concluded remarks of the present study are listed as:

- Temperature field shows a decreasing trend for increasing Prandtl number Pr while an increasing trend is seen for increasing values of heat obrep- traction parameter.
Concentration field shows a decreasing trend for increasing mass Prandtl number $Sc$ while an increasing trend is seen for increasing chemical reaction parameter $K_0$.

Both real and imaginary components are increasing functions of parameters $Gr$, $GM$, $q_0$, and $k_0$.

Both components of velocity decreases for parameters $Pr$, $Sc$, $M$, and $K_0$.

Effect of slip parameter $\lambda_0$ over the velocity’s components is significant only near the plate while away from plate the slip effect is irrelevant.

Real components of the velocity is reduced while the imaginary component is enhanced by increasing value of rotational parameter $Ek$.

In the presence of hall effect fluid speeds up.

Figure 10. Components of velocity verses $z$ subject to $q_0$ for $\lambda_0 = 0.5$.

Figure 11. Components of velocity verses $z$ subject to $K_0$ for $\lambda_0 = 0.5$. 
Figure 12. Components of velocity verses z subject to $\lambda_0$.

Figure 13. Components of velocity verses z subject to $E_k$.

Table 1. Nusselt Number and Sherwood number for Pr and Sc respectively.

| $t$ | $Pr = 2.2$ | $Pr = 2.4$ | $Pr = 2.6$ | $Sc = 0.2$ | $Sc = 0.5$ | $Sc = 0.8$ |
|-----|------------|------------|------------|------------|------------|------------|
| 0.1 | 0.35833201 | 0.63438120 | 1.29323441 | 1.10429543 | 1.21272314 | 1.08938910 |
| 0.2 | 0.58903345 | 0.84024642 | 1.28016572 | 1.30582303 | 1.21304572 | 1.15036784 |
| 0.3 | 0.81214314 | 1.14682341 | 1.41903478 | 1.40982718 | 1.17557059 | 1.33456213 |
| 0.4 | 1.03499521 | 1.50321450 | 1.63002345 | 1.57901239 | 1.21376360 | 1.50457821 |
| 0.5 | 1.2567805 | 1.83267891 | 1.71090141 | 1.80213456 | 1.19035623 | 2.60235677 |
| 0.6 | 1.80324678 | 2.02167931 | 1.91023590 | 2.02890321 | 1.1454580 | 2.76737382 |
| 0.7 | 1.93583103 | 2.50934562 | 2.09814218 | 2.20924567 | 1.1494653 | 2.8064034 |
| 0.8 | 2.09012894 | 2.20328543 | 2.31032678 | 2.30427890 | 1.31534522 | 2.93457023 |
| 0.9 | 2.56900322 | 2.40256721 | 2.50921478 | 2.52932567 | 2.45890123 | 2.17691038 |
| 1.0 | 2.83237820 | 2.50324567 | 2.60936892 | 2.60457328 | 2.61610801 | 2.17712268 |

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### Appendix

#### Notation

- $k$: Thermal conductivity [$Wm^{-1}K^{-1}$]
- $Gr$: Grashof number [-]
- $Pr$: Prandtl number [-]
- $Re$: Real part of complex number
- $g$: Gravitational acceleration [$ms^{-2}$]
- $Cp$: Specific heat at constant pressure [$JKg^{-1}K^{-1}$]
- $Ek$: Ekman number [-]
- $T$: Dimensionless Fluid temperature [K]
- $T_w$: Temperature far away from the plate [K]
- $Tw$: Wall temperature [K]
- $\mu$: Dynamic viscosity [$Kgm^{-1}s^{-1}$]
- $\nu$: Kinematic viscosity [$m^2s^{-1}$]
- $u$: velocity component along x-axis [$ms^{-1}$]
- $v$: velocity component along y-axis [$ms^{-1}$]
| Symbol | Description | Unit |
|--------|-------------|------|
| $\sigma$ | Stefan-Boltzmann constant | $Wm^{-2}K^{-4}$ |
| $\lambda$ | Slip parameter | [-] |
| $\Omega$ | Angular velocity of the fluid | $s^{-1}$ |
| $\beta_0$ | External Magnetic field | $K^{-1}$ |
| $\lambda_0$ | Nondirectional slip parameter | [-] |
| $q_0$ | Heat absorption parameter | [-] |
| $K_0$ | Reaction parameter | [-] |
| $k_0$ | Porosity parameter | [-] |