Rotation and Heat Absorption Effects on Unsteady MHD Free Convection Flow in a Porous Medium past an Infinite Inclined Plate with Ramped Wall Temperature

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Abstract: - The combined effects of mass transfer and rotation on unsteady magnetohydrodynamic (MHD) free convection flow in a porous medium past an infinite inclined plate with ramped wall temperature has been investigated. The effects of thermal diffusion and heat absorption are also observed. Exact solution using Laplace transforms technique has been obtained for the velocity, temperature and concentration fields. The analytical expressions for nondimensional skin-friction, Nusselt number and Sherwood number have been computed. The influence of various embedded flow parameters such as Prandtl and Schmidt numbers, inclination angle, and rotation parameter has been analysed through graphs. It is found that, inclination angle tend to retard fluid flow in the primary and secondary flow directions. Whereas rotation has a retarding influence on the primary flow direction but accelerating in the secondary flow direction.

Key-Words: - Mass transfer, rotation, MHD, thermal radiation, inclined plate, porous medium, thermal diffusion, heat absorption, analytic solution

1 Introduction

Heat and mass transfer is important in many engineering application such as food processing, nuclear reactors and polymer. The concentration effects may produce quantitative and qualitative variations to the rate of heat transfer. [1] solved analytically using two-term harmonic and nonharmonic functions of the unsteady MHD convective heat and mass transfer past a semi-infinite vertical permeable moving plate with heat absorption. [2] obtained the effect of MHD heat and mass transfer on free convection flow along a vertical stretching sheet using Nachtsheim-Swigert shooting iteration technique along with sixth order Runge-Kutta integration scheme. [3] took into account the unsteady MHD convective heat and mass transfer past an infinite vertical plate in a porous medium with effects of thermal radiation, heat generation/absorption and chemical reaction. [4] dealt with the combined effect of thermal diffusion and heat absorption on the free convection mass transfer flow of a viscous incompressible fluid past a continuously moving infinite porous plate. [5] conducted the flow of an incompressible viscous fluid past an infinite vertical plate in the presence of foreign mass or constant mass flux and ramped wall temperature. Up to now, [6] investigated the dissipative effects on heat and mass transfer characteristics of natural convection about a continuously moving vertical plate bounding fluid saturated porous medium on one side.

In general, the Coriolis force due to earth's rotation has a strong effect on the hydromagnetic flow in the earth's liquid core. It is essential to study this fluid flow problem due to its application in various branches of fluid engineering and geophysics astrophysics. [7] examined the steady MHD free convection and mass transfer fluid flow through a continuously moving porous medium with thermal diffusion and diffusion thermo past a semi-infinite vertical porous plate in a rotating system. [8, 9] performed the effects of rotation on MHD flow past an accelerated isothermal/variable temperature vertical plate with heat and mass diffusion. [10] reported the rotation and radiation effects on MHD flow past an impulsively started vertical plate with variable temperature and solved by the Laplace transforms technique. Recently, [11] considered the effect of rotation on unsteady hydromagnetic natural convection flow of a viscous incompressible fluid past an impulsively moving vertical plate with ramped temperature in a porous medium.

Nevertheless all the above researches are more on vertical plates. Though in real applications, there are so many flows near the inclined plates or surfaces such as solar energy collectors and crystal growth. [12] developed a mathematical model of hydromagnetic natural convection from an isothermal inclined surface adjacent to a thermally stratified porous medium. [13] investigated the effects of an inner rotating plate on the heat transfer in a differentially heated inclined enclosure. [14] provided an analytical solution for the unsteady free convection flow near an inclined plate in a rotating system. Recently, the effect of thermal radiation on unsteady MHD free convection flow of an optically thin gray gas past an infinite inclined isothermal plate has been obtained analytically by [15].

However, a little work has been performed regarding inclined plate in a rotating system, more exactly solved by using Laplace transforms. The objective of this present paper is to consider the effect of rotation and mass transfer on unsteady MHD free convection flow in a porous medium past an infinite inclined plate with ramped wall temperature. Thermal diffusion and heat absorption effects are also considered. The governing partial differential equations have been solved using Laplace transform technique, which satisfy all the imposed initial and boundary conditions. The exact expressions for velocity, temperature, and concentration are also calculated.

2 Problem Formulation

Consider the unsteady MHD flow of a viscous incompressible fluid with combined heat and mass transfer by natural convection flow, near an infinite inclined plate embedded in a saturated porous medium. The x^*-axis is along to the plate with the inclination angle ϕ to the vertical, the y^*-axis is taken normal to the plate, and z^*-axis is perpendicular to x^*y^*-plane. The fluid velocity and magnetic field are given by $\vec{q} \equiv \left(u^*, 0, w^*\right)$, $\vec{B}\left(B_x, B_o, B_z\right)$, agreeing with the fundamental equations of MHD in a rotating frame of reference. The fluid is assumed to be electrically conducting, and a uniform magnetic field $\vec{B} \equiv \left(0, B_o, 0\right)$ is applied in the direction perpendicular to the plate. The magnetic Reynolds number is assumed to be small to neglect the effect of induced magnetic field. The plate and the fluid are in a state of rigid body rotation, with a constant angular velocity Ω, about y^*-axis. Initially, for time $t^* \leq 0$, both the fluid and the plate are at rest with the constant temperature T_∞^* and constant concentration C_∞^*. At a time $t^* > 0$, the plate starts moving in x^* direction with a constant velocity u_o. The temperature of the plate is raised or lowered to $T_\infty^* + \left(T_w^* - T_\infty^*\right)t^*/t_o$ when $t^* \leq t_o$. Thereafter, it is maintained at constant temperature T_w^* when $t^* > t_o$. The concentration is raised to constant concentration C_w^*. The flow is assumed laminar, and the effects of the convective and pressure gradient terms in the momentum, energy and concentration equations are neglected. The physical variables become functions of the time t^* and the space y^* only, as a result of the boundary layer approximations.

Under the Boussinesq approximation, the rotating of unsteady MHD natural convection boundary layer flow past an inclined plate flow in a porous medium with effects of thermal diffusion and heat absorption, is governed by the equations [5], [7], [11] and [15]

$$\frac{\partial u^*}{\partial t^*} + 2\Omega w^* = \upsilon \frac{\partial^2 u^*}{\partial y^{*2}} - \frac{\sigma^* B_0^2}{\rho} u^* - \frac{\upsilon}{K_1^*} u^* + g\beta_T \cos\phi\left(T^* - T_\infty^*\right) + g\beta_m \cos\phi\left(C^* - C_\infty^*\right) \quad (1)$$

$$\frac{\partial w^*}{\partial t^*} - 2\Omega u^* = \upsilon \frac{\partial^2 w^*}{\partial y^{*2}} - \frac{\sigma^* B_0^2}{\rho} w^* - \frac{\upsilon}{K_1^*} w^* \quad (2)$$

$$\frac{\partial T^*}{\partial t^*} = \alpha^* \frac{\partial^2 T^*}{\partial y^{*2}} - \frac{Q_o}{\rho c_p}\left(T^* - T_\infty^*\right) \quad (3)$$

$$\frac{\partial C^*}{\partial t^*} = D \frac{\partial^2 C^*}{\partial y^{*2}} \quad (4)$$

with the following initial and boundary conditions:

$$\begin{aligned}
& u^* = w^* = 0, T^* = T_\infty^*, C^* = C_\infty^* \\
& \quad \text{for } y^* \geq 0 \text{ and } t^* \leq 0 \\
& u^* = u_o, w^* = 0, C^* = C_w^* \\
& \quad \text{for } y^* = 0 \text{ and } t^* > 0 \\
& T^* = T_\infty^* + \left(T_w^* - T_\infty^*\right)\frac{t^*}{t_o} \quad \text{at } y^* = 0 \\
& \quad \text{for } 0 < t^* \leq t_o \\
& T^* = T_w^* \text{ at } y^* = 0 \text{ for } t^* > t_o \\
& u^* \to 0, \quad w^* \to 0, \quad T^* \to 0, \quad C^* \to 0 \\
& \quad \text{as } y^* \to \infty \text{ and } t^* > 0
\end{aligned} \quad (5)$$

where T^* and C^* denote the temperature and concentration respectively, υ is the kinematic viscosity, σ^* is the electrical conductivity of the fluid, ρ is the fluid density, $K_1^* > 0$ is the permeability of the porous medium, g is the acceleration due to gravity, β_T and β_m are the thermal expansion and concentration expansion, α^* is the fluid thermal diffusivity, c_p is the specific heat, Q_o is the heat absorption coefficient and D is the mass diffusion.

Introducing the following dimensionless variables

$$y=\frac{y^*}{u_o t_o},\ t=\frac{t^*}{t_o},\ t_o=\frac{\upsilon}{u_o^2},\ (u,w)=\frac{(u^*,w^*)}{u_o},$$
$$Gm=\frac{g\beta_m\upsilon(C_w^*-C_\infty^*)}{u_o^3},\ \Pr=\frac{\upsilon}{\alpha^*},\ \Phi=\frac{\upsilon Q_o}{\rho c_\rho u_o^2},\quad (6)$$
$$M=\frac{\sigma^* B_o^2\upsilon}{\rho u_o^2},K_1=\frac{K_1^* u_o^2}{\upsilon^2},\ Gr=\frac{g\beta_T\upsilon(T_w^*-T_\infty^*)}{u_o^3}$$
$$T=\frac{T^*-T_\infty^*}{T_w^*-T_\infty^*},\ C=\frac{C^*-C_\infty^*}{C_w^*-C_\infty^*},\ K^2=\frac{\Omega\upsilon}{u_o^2},\ Sc=\frac{\upsilon}{D}$$

where T, C, K^2, M, K_1, Gr, Gm, Pr, Φ and Sc are nondimensional fluid temperature, nondimensional fluid concentration, rotation parameter, magnetic parameter known as Hartmann number, porosity parameter, thermal Grashof number and the mass Grashof number, Prandtl number, nondimensional heat absorption coefficient and Schmidt number, respectively.

Using equations (6), equations (1), (2), (3) and (4) can be expressed as

$$\frac{\partial u}{\partial t}+2K^2 w=\frac{\partial^2 u}{\partial y^2}-Mu-\frac{1}{K_1}u+GrT\cos\phi+GmC\cos\phi \quad (7)$$
$$\frac{\partial w}{\partial t}-2K^2 u=\frac{\partial^2 w}{\partial y^2}-Mw-\frac{1}{K_1}w \quad (8)$$
$$\frac{\partial T}{\partial t}=\frac{1}{\Pr}\frac{\partial^2 T}{\partial y^2}-\Phi T \quad (9)$$
$$\frac{\partial C}{\partial t}=\frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} \quad (10)$$

And using complex system to combine equations (7) and (8), we obtain

$$\frac{\partial f}{\partial t}-2ifK^2=\frac{\partial^2 f}{\partial y^2}-Mf-\frac{f}{K_1}+GrT\cos\phi+GmC\cos\phi \quad (11)$$

where

$$f=u+iw$$

Combining velocity form, the initial and boundary condition (5) are

$$\begin{aligned}&f=0,\ T=0,\ C=0\ \text{ for } y\ge 0 \text{ and } t\le 0\\ &f=1,\ C=1\ \text{ for } y=0 \text{ and } t>0\\ &T=t,\ \text{ for } y=0 \text{ and } 0<t\le 1\\ &T=1,\ \text{ for } y=0 \text{ and } t>1\\ &f\to 0,\ T\to 0,\ C\to 0\\ &\text{for } y\to\infty \text{ and } t>0\end{aligned}\quad (12)$$

3 Problem Solution

We can see that the energy equation (9) and concentration equation (10) is uncoupled from the momentum equation (11). Therefore, we can solve for the temperature variable $T(y,t)$ and concentration variable $C(y,t)$ whereupon the solution of $f(y,t)$ can also be gained. In order to solve these equations, taking Laplace transforms of equations (9), (10) and (11) with respect to t, in concurrence with equation (12), and solving the result from differential equations, we obtain

$$\bar{C}=\frac{1}{s}e^{-y\sqrt{S_c s}} \quad (13)$$
$$\bar{T}=\left(\frac{1-e^{-s}}{s^2}\right)e^{-y\sqrt{\Pr(\Phi+s)}} \quad (14)$$
$$\begin{aligned}\bar{f}=&\frac{e^{-y\sqrt{\lambda+s}}}{s}-\left(\frac{a_1}{a_2^2}.\frac{1}{s-a_2}-\frac{a_1}{a_2^2}.\frac{1}{s}-\frac{a_1}{a_2}.\frac{1}{s^2}\right)\\ &(1-e^{-s})e^{-y\sqrt{\lambda+s}}-\left(\frac{a_3}{a_4}.\frac{1}{s-a_4}-\frac{a_3}{a_4}.\frac{1}{s}\right)\\ &\left(e^{-y\sqrt{\lambda+s}}\right)+\left(\frac{a_1}{a_2^2}.\frac{1}{s-a_2}-\frac{a_1}{a_2^2}.\frac{1}{s}-\frac{a_1}{a_2}.\frac{1}{s^2}\right)\\ &(1-e^{-s})e^{-y\sqrt{\Pr(\Phi+s)}}+\\ &\left(\frac{a_3}{a_4}.\frac{1}{s-a_4}-\frac{a_3}{a_4}.\frac{1}{s}\right)e^{-y\sqrt{S_c s}}\end{aligned}\quad (15)$$

where

$$\lambda=\frac{1}{K_1}+M-2iK^2,\ a_1=\frac{Gr\cos\phi}{1-\Pr},$$
$$a_2=\frac{\Phi\Pr-\lambda}{1-\Pr},\ a_3=-\frac{Gm\cos\phi}{Sc-1},\ a_4=\frac{\lambda}{Sc-1}$$

The exact solutions for the concentration, temperature and complex velocity fields can be obtained from equations (13), (14) and (15) by using inverse Laplace transforms. These solutions are

$$C(y,t)=erfc\left(\frac{y\sqrt{Sc}}{2\sqrt{t}}\right) \quad (16)$$
$$T(y,t)=T_1(y,t)-T_1(y,t-1)H(t-1) \quad (17)$$

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$$f(y,t)= f_1(t,\lambda,y)+F_1(y,t) - H(t-1)F_1(y,t-1)+F_2(y,t) \quad (18)$$

where

$$T_1(y,t)=\left(\frac{t}{2}+\frac{y}{4}\sqrt{\frac{\Pr}{\Phi}}\right)e^{y\sqrt{\Phi \Pr}}erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}}+\sqrt{\Phi t}\right)+ \left(\frac{t}{2}-\frac{y}{4}\sqrt{\frac{\Pr}{\Phi}}\right)e^{-y\sqrt{\Phi \Pr}}erfc\left(\frac{y}{2}\sqrt{\frac{\Pr}{t}}-\sqrt{\Phi t}\right)$$

$$f_1(t,b,c)=\frac{1}{2}\left[e^{c\sqrt{b}}erfc\left(\frac{c}{2\sqrt{t}}+\sqrt{bt}\right)+e^{-c\sqrt{b}}erfc\left(\frac{c}{2\sqrt{t}}-\sqrt{bt}\right)\right]$$

$$f_2(t,b,c)=\frac{1}{2}\left[\left(t+\frac{c}{2\sqrt{b}}\right)e^{c\sqrt{b}}erfc\left(\frac{c}{2\sqrt{t}}+\sqrt{bt}\right)+\left(t-\frac{c}{2\sqrt{b}}\right)e^{-c\sqrt{b}}erfc\left(\frac{c}{2\sqrt{t}}-\sqrt{bt}\right)\right]$$

$$f_3(t,a,b,c)=\frac{e^{at}}{2}\left[e^{c\sqrt{a+b}}erfc\left(\frac{c}{2\sqrt{t}}+\sqrt{(a+b)t}\right)+e^{-c\sqrt{a+b}}erfc\left(\frac{c}{2\sqrt{t}}-\sqrt{(a+b)t}\right)\right]$$

$$F_1(y,t)=\frac{a_1}{a_2^2}\left[f_3\left(t,a_2,\Phi,y\sqrt{\Pr}\right)-f_3(t,a_2,\lambda,y)\right] -\frac{a_1}{a_2^2}\left[f_1\left(t,\Phi,y\sqrt{\Pr}\right)-f_1(t,\lambda,y)\right]- \frac{a_1}{a_2}\left[f_2\left(t,\Phi,y\sqrt{\Pr}\right)-f_2(t,\lambda,y)\right]$$

$$F_2(y,t)=\frac{a_3}{a_4}\left[f_1(t,\lambda,y)-f_1\left(t,0,y\sqrt{Sc}\right)\right] -\frac{a_3}{a_4}\left[f_3(t,a_4,\lambda,y)-f_3\left(t,a_4,0,y\sqrt{Sc}\right)\right]$$

erfc(x) being the complimentary error function defined by

$$erfc(x)=1-erf(x), \quad erf(x)=\frac{2}{\sqrt{\pi}}\int_0^x e^{-\eta^2}d\eta$$

and $H(\bullet)$ is Heaviside unit step function. The component *u(y,t)*, *w(y,t)* of the velocity field are given by

$$u(y,t)=\text{Re}[f(y,t)], \quad w(y,t)=\text{Im}[f(y,t)]$$

3.1 Skin friction, Nusselt Number and Sherwood Number

The expression for skin-friction is given by

$$\tau=-\frac{\tau^* t_o}{\rho\upsilon}=-\left.\frac{\partial u}{\partial y}\right|_{y=0}=\text{Re}\left[\left.\frac{\partial u(y,t)}{\partial y}\right|_{y=0}\right] =\text{Re}\left\{\frac{e^{-\lambda t}}{\sqrt{\pi t}}+\sqrt{\lambda}erf\sqrt{\lambda t}-S_1(t)- S_1(t-1)H(t-1)-S_2(t)\right\} \quad (19)$$

where $S_1(t)$ and $S_2(t)$ are defined by

$$S_1=\left.\frac{\partial F_1(y,t)}{\partial y}\right|_{y=0}=\frac{a_1}{a_2^2}\left[\sqrt{a_2+\lambda}e^{a_2t}erf\sqrt{(a_2+\lambda)t} -\sqrt{\Pr(a_2+\Phi)}e^{a_2t}erf\sqrt{(a_2+\Phi)t}+ \sqrt{\Pr\Phi}erf\sqrt{\Phi t}-\sqrt{\lambda}erf\sqrt{\lambda t}\right]+ \frac{a_1}{a_2}\left[\sqrt{\Pr}\left(\frac{1}{2\sqrt{\Phi}}+t\sqrt{\Phi}\right)erf\sqrt{\Phi t}- \left(\frac{1}{2\sqrt{\lambda}}+t\sqrt{\lambda}\right)erf\sqrt{\lambda t}+\sqrt{\frac{\Pr t}{\pi}}e^{-\Phi t}-\sqrt{\frac{t}{\pi}}e^{-\lambda t}\right]$$

$$S_2=\left.\frac{\partial F_2(y,t)}{\partial y}\right|_{y=0}=\frac{a_3}{a_4}e^{a_4t}\left\{\left[\sqrt{a_4+\lambda}erf \sqrt{(a_4+\lambda)t}-\sqrt{a_4Sc}erf\sqrt{a_4t}\right]-\sqrt{\lambda}erf\sqrt{\lambda t}\right\}$$

Nusselt number, the rate of heat transfer is given as

$$Nu=-\frac{u_ot_o}{\left(T_w^*-T_\infty^*\right)}\frac{\partial T^*}{\partial y^*}=-\left.\frac{\partial T}{\partial y}\right|_{y=0} =\frac{e^{-\Phi t}}{2\sqrt{\pi}}\left[2\sqrt{\Pr t}+e^{\Phi t}\sqrt{\pi} \left(\sqrt{\frac{\Pr}{\Phi}}+2t\sqrt{\Phi\Pr}\right)erf\sqrt{\Phi t} -\left[2e^{\Phi}\sqrt{\Pr(t-1)} +e^{\Phi t}\sqrt{\pi}\left(\sqrt{\frac{\Pr}{\Phi}}+2(t-1)\sqrt{\Phi\Pr}\right) erf\sqrt{\Phi(t-1)}\right]H(t-1)\right] \quad (20)$$

and Sherwood number, the rate of mass transfer is given as

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$$Sh = \frac{u_o t_o}{\rho \upsilon \left(C_w^* - C_\infty^*\right)} = \left.\frac{\partial C}{\partial y}\right|_{y=0}$$
$$= -\frac{\sqrt{Sc}}{\sqrt{\pi t}} \qquad (21)$$

4 Conclusion

An exact solution to the problem of heat and mass transfer for MHD free convection flow with rotation and radiation effect passing through a porous medium near an inclined plate is presented. In order to get into the physical understanding of the problem, the effects of various parameters such as Hartmann number M, permeability of the porous medium K_1, rotation parameter K^2, heat absorption parameter Φ, and inclination angle ϕ are analysed. The results for concentration C, temperature T, and velocity f are discussed and presented graphically.

Fig. 1 is prepared for concentration profiles for various values of Sc. Following [2], the values of the Schmidt number are chosen, 0.22 (hydrogen), 0.60 (water vapour), and 1.0 (Methanol). It is noticed that the concentration of the fluid decreases as the Schmidt number increases. The concentration falls gradually and progressively for hydrogen in distinction to other gases. Physically, it is true since increases of Sc mean decrease of molecular diffusivity, which results in decreases of concentration boundary layer. Hence, the concentration of species is smaller for higher values of Sc.

Fig. 2 shows temperature profiles for various values of heat absorption Φ. The temperature of the fluid increases with decreasing values of heat absorption parameter. The thermal boundary layer was always starting to be thickened when heat absorption is existence. This is due to the fact that the heat absorption provides an additional means to diffuse energy. The temperature profiles for different values of Prandtl number Pr is shown in Fig. 3. We observed that the temperature decreases on increasing Pr, because lower Pr value has more uniform temperature distribution across the thermal boundary layer as compared to higher Pr value. This phenomenon occurs when the lesser values of Prandtl number are equivalent to increasing thermal conductivity. Therefore, heat is capable to diffuse away from the heated surface more quickly compare to bigger values of Prandtl number. Thus, the temperature of water(7) falls more rapidly compared to air(0.71) and mercury(0.015). Near the plate, the temperature is maximum and approaches zero in the free stream region asymptotically.

Fig. 4 and Fig. 5 depict the effect of inclination angle ϕ on the primary and secondary velocities. As inclination angle ϕ decreases the primary and secondary velocity increases for both ramped temperature and isothermal plate. This implies that inclination angle ϕ accelerates the fluid motion along the plate. This is towards the fact that as the plate is inclined from the vertical, the buoyancy force effect due to the thermal and mass diffusion, decreases as ϕ increases. In this case, lower buoyancy for the same temperature difference occurs at $\phi = 90^o$, because cos ϕ value increases as ϕ decreases from 90^o to 0^o.

Fig. 6 and 7 demonstrate the effects of rotation parameter K^2 on the primary velocity u and secondary velocity w. For ramped temperature plate, as rotation parameter K^2 decreases the primary velocity u increases whereas secondary velocity w decreases. This indicates that rotation retards fluid flow in the primary flow direction, but it accelerates fluid flow in the secondary flow direction. This is due to the fact that the Coriolis force acts as a constraint in the main fluid flow when the moving plate is suddenly set into motion. We can say that Coriolis force ended fluid flow in the primary flow direction to induce cross flow and secondary flow in the flow field.

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Appendix

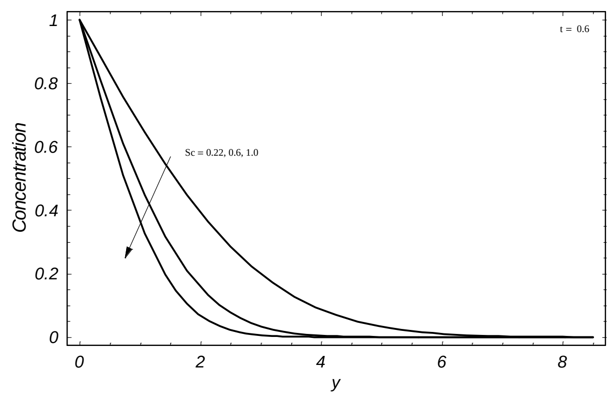

Fig. 1 Concentration profiles at various Sc

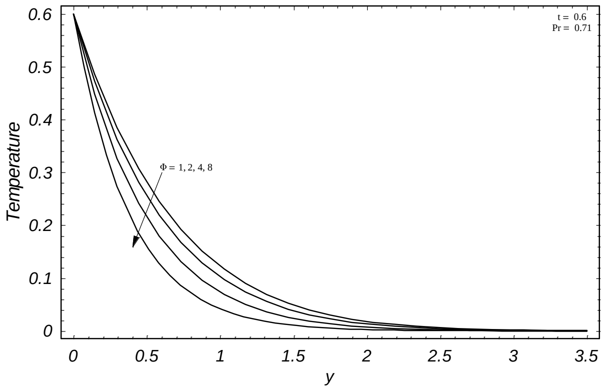

Fig. 2 Temperature profiles at various Φ

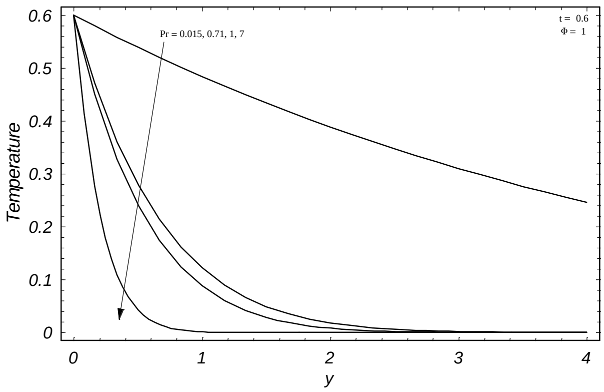

Fig. 3 Temperature profiles at various Pr

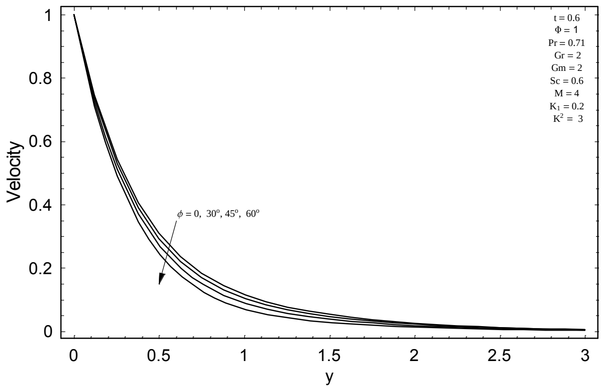

Fig. 4 Primary velocity profiles at various ϕ

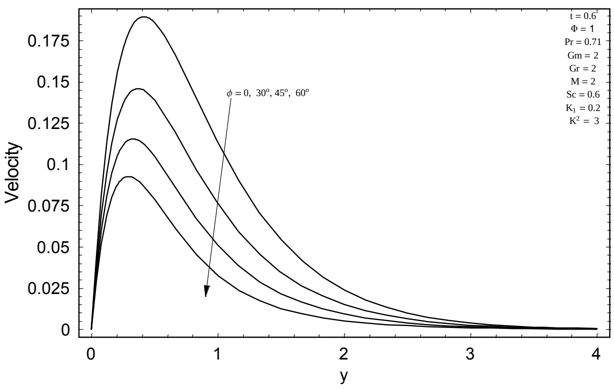

Fig. 5 Secondary velocity profiles at various ϕ

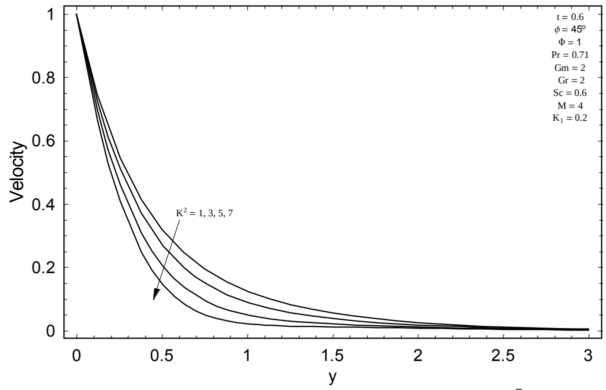

Fig. 6 Primary velocity profiles at various K^2

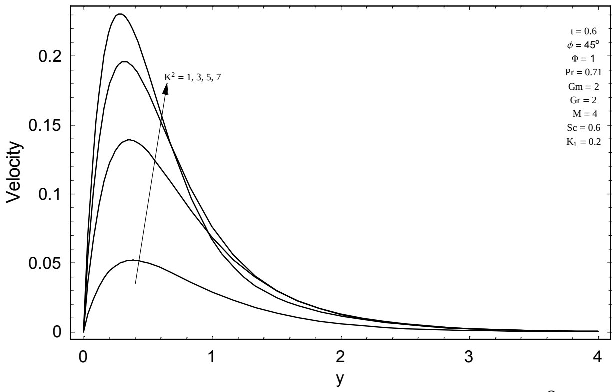

Fig. 7 Secondary velocity profiles at various K^2

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