MHD Free Convective Flow of Dissipative and Radiative Fluid Past an Infinite Vertical Plate in Porous Media In Presence of Inclined Magnetic Field with Joule Effect and Constant Heat Flux

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Abstract: ***Unsteady MHD free convection boundary layer flow of an incompressible, dissipative and radiative fluid with constant viscosity past an infinite vertical plate placed in a porous medium under the effect of inclined magnetic field with Joule effect and constant heat flux is investigated. A parametric study is performed to illustrate the influence of radiation parameter, magnetic parameter, Grashof number, Prandtl number, Eckert number and heat source parameter on the velocity and temperature profiles. Also, the skin-friction at the plate is derived, discussed numerically and shown through table.***

Keywords: MHD flow, porous media, inclined magnetic field, heat source, skin friction.

1. Introduction

In our everyday life, it can be seen that atmospheric flow is driven by temperature differences. The hydromagnetic free convection flow and heat transfer problems have become important scientifically and industrially. The study of hydromagnetic free convection flow finds applications in science and engineering, in areas such as geophysical exploration, solar physics, and astrophysical studies. The electro-magneto-dynamics of fluids was studied by Huges and Yong (1966). Cogley (1968) developed differential approximations for radiative heat transfer in a nonlinear equations-grey gas near equilibrium. The effects of radiation and variable viscosity on a MHD free convection flow past a semi-infinite flat plate with magnetic field in the case of unsteady flow have been reported by Seddeek (2002). Chen (2004) considered the combined heat and mass transfer in MHD free convection from a vertical surface with Ohmic heating and viscous dissipation. Analytical solutions for unsteady free convection flow through a porous media were presented by Magyari (2004). Sharma and Chaturvedi (2005) studied unsteady flow and heat transfer along a plane wall with variable suction and free stream. Unsteady flow and heat transfer along a hot vertical porous plate in the presence of periodic suction and heat source have been analyzed by Sharma and Gupta (2006). Sharma and Singh (2008) investigated unsteady MHD free convective flow and heat transfer along a vertical porous plate with variable suction and internal heat generation. Radiation effects on unsteady MHD free convective flow with hall current and mass transfer through viscous incompressible fluid past a vertical porous plate immersed in porous medium with heat source/sink have been discussed by Sharma et al. (2009). Singh and Gorla (2009) studied free convective heat and mass transfer with Hall current, Joule heating and thermal diffusion. Effects of variable thermal conductivity and viscous dissipation on steady MHD natural convection flow of low Prandtl fluid on an inclined porous plate with Ohmic heating were presented by Sharma and Singh (2010). Sandeep and Sugunamma (2013) analyzed the effect of inclined magnetic field on unsteady free convective flow of dissipative fluid past a vertical plate. Unsteady MHD free convective visco-elastic fluid flow bounded by an infinite inclined porous plate in the presence of heat source, viscous dissipation and Ohmic heating was considered by Umamaheswar et al. (2013). Alizadeh and Rahmdel (2014) studied the MHD free convection flow of a dissipative fluid over a vertical porous plate placed in porous media.

The objective of the present paper is to investigate unsteady MHD free convection boundary layer flow of a Newtonian fluid with constant viscosity past an infinite vertical plate placed in a porous medium under the effect of inclined magnetic field with joule heating, viscous dissipation, radiation and constant heat flux. The governing coupled partial differential equations are transformed in non dimensional form and solved by perturbation method. The effects of various physical parameters on velocity profiles, temperature profiles and skin friction are discussed and shown through graphs and numerical values are presented through table.

2. Mathematical Formulation of the Problem

Unsteady MHD free convective flow of a viscous, incompressible and electrically conducting fluid in an optically thin environment past an infinite vertical plate placed in a porous medium, in the presence of joule effect and heat source is considered. The x^*- axis is taken parallel to the infinite vertical plate and the y^*- axis is perpendicular to the plate. An inclined magnetic field is applied in the presence of thermal radiation. Hence, following Cogley et al. (1968) equilibrium model, the expression of the radiative heat flux is taken as given below

$$\frac{\partial q_r}{\partial y} = 4\left(T^* - T_\infty\right)\int_0^\infty K_{\lambda w}\left(\frac{\partial e_{b\lambda}}{\partial T}\right)_w d\lambda = 4I^*\left(T^* - T_\infty\right), \qquad (1)$$

where $K_{\lambda w}$ is the radiation absorption coefficient at the wall and $e_{b\lambda}$ is the Plank function.

All the flow variables are independent of x^* since the plate is infinite in extent and so their derivatives with respect to x^* vanish. Only non-zero velocity component is in the x^*-direction. The non-zero velocity component and temperature are functions of y^* and t^* only. The radiative heat flux is considered negligible in the x^*- direction in comparison to the y^*- direction. Hence, the equation of continuity is automatically satisfied. The unsteady flow and temperature fields within the frame work of the above assumptions are governed by the following equations

$$\rho\frac{\partial u^*}{\partial t^*}=\mu\frac{\partial^2 u^*}{\partial y^{*2}}+g\rho\beta(T^*-T_\infty)-(\frac{\mu}{K^*}+\sigma B_0^2\sin^2\psi)u^*, \quad (2)$$

$$\rho C_p\frac{\partial T^*}{\partial t^*}=\kappa\frac{\partial^2 T^*}{\partial y^{*2}}+\mu\left(\frac{\partial u^*}{\partial y^*}\right)^2+Q^*\left(T^*-T_\infty\right)-4I\left(T^*-T_\infty\right)+\sigma B_0^2 u^{*2}, \quad (3)$$

where ρ is the density, u^* is the velocity component in x^*-direction, t^* is the time, μ is the viscosity, g is the acceleration due to gravity, β is the thermal expansion coefficient, T^* is the temperature of the fluid in the boundary layer, T_∞ is the temperature of the fluid far away from the plate, σ is the electrical conductivity, B_0 is the magnetic field intensity, ν is the kinematic viscosity, K^* is the permeability of porous medium, κ is the thermal conductivity, C_p is the specific heat at constant pressure, Q^* is the heat source parameter.

The initial and boundary conditions are:

For $t^*\le 0$, $u^*=0$, $T^*=T_\infty$ for all y^*

For $t^*>0$, at $y^*=0$: $u^*=U\left(1+\varepsilon e^{i\omega^* t^*}\right)$, $\dfrac{\partial T^*}{\partial y^*}=-\dfrac{q}{\kappa}$;

at $y^*\to\infty$: $u^*=0$, $T^*=T_\infty$. (4)

where U is the mean velocity of plate and $\varepsilon<<1$.

3. Method of Solution

Introducing the following non-dimensional quantities

$$y=\frac{Uy^*}{\nu}, u=\frac{u^*}{U}, t=\frac{U^2t^*}{\nu}, \omega=\frac{\nu\omega^*}{U^2}, \theta=\frac{\kappa U(T^*-T_\infty)}{q\nu},$$
$$Gr=\frac{g\beta\nu^2 q}{\kappa U^4}, K=\frac{K^*U^2}{\nu^2}, M=\frac{\sigma B_0^2\nu}{\rho U^2}, \Pr=\frac{\mu C_p}{\kappa},$$
$$R=\frac{4I^*\nu}{\rho C_p U^2}, Ec=\frac{\kappa U^3}{C_p\nu q}, Q=\frac{Q^*\nu}{\rho C_p U^2}; \quad (5)$$

into the equations (2) and (3), we get

$$\frac{\partial u}{\partial t}=\frac{\partial^2 u}{\partial y^2}+Gr\theta-\left(M\sin^2\psi+\frac{1}{K}\right)u, \quad (6)$$

$$\frac{\partial\theta}{\partial t}=\frac{1}{\Pr}\frac{\partial^2\theta}{\partial y^2}-(R-Q)\theta+Ec\left(\frac{\partial u}{\partial y}\right)^2+Ec\,M\,u^2. \quad (7)$$

where u is the non-dimensional velocity along x-axis, θ is the non-dimensional temperature, t is the time, Gr is the Grashof number for heat transfer, M is the Hartmann number, K is the permeability parameter, Pr is the Prandtl number, R is the radiation parameter, Ec is the Eckert number, Q is the heat source parameter.

The corresponding boundary conditions are reduced to

for $t\le 0$, $u=0$, $\theta=0$ for all y

for $t^*>0$, at $y=0$: $u=1+\varepsilon e^{i\omega t}$, $\dfrac{\partial\theta}{\partial y}=-1$;

at $y\to\infty$: $u=0$, $\theta=0$. (8)

In view of boundary conditions, the velocity and temperature distributions are separated into steady and unsteady parts as given below

$$u(y,t)=u_0(y)+\varepsilon e^{i\omega t}u_1(y),$$
$$\theta(y,t)=\theta_0(y)+\varepsilon e^{i\omega t}\theta_1(y). \quad (9)$$

Substituting (9) into the equations (6) and (7), and equating the harmonic and non-harmonic terms, we obtain

Zeroth order equations

$$u_0''-\left(M\sin^2\psi+\frac{1}{K}\right)u_0=-Gr\theta_0, \quad (10)$$

$$\theta_0''-\Pr\left(R-Q\right)\theta_0=-Pr\,Ec\,u_0'^2-Pr\,Ec\,M\,u_0^2, \quad (11)$$

First order equations

$$u_1''-\left(M\sin^2\psi+\frac{1}{K}+i\omega\right)u_1=-Gr\theta_1, \quad (12)$$

$$\theta_1''-\Pr\left(R-Q+i\omega\right)\theta_1=-2Pr\,Ec\,u_0'u_1'-2Pr\,Ec\,M\,u_0u_1. \quad (13)$$

Here, prime denotes the differentiation with respect to y.

Now, the corresponding boundary conditions are reduced to

$y=0$: $u_0=1$, $u_1=1$, $\theta_0'=-1$, $\theta_1'=0$;

$y\to\infty$: $u_0\to 0$, $u_1\to 0$, $\theta_0\to 0$, $\theta_1\to 0$. (14)

The equations (10) to (13) are still coupled ordinary second order differential equations. Since the Eckert number Ec is very small for incompressible fluid flows, therefore $u_0, u_1, \theta_0, \theta_1$ can be expanded in the powers of Ec as given below

$$F(y)=F_0(y)+Ec\,F_1(y)+O\left(Ec^2\right)+\ldots, \quad (15)$$

where F stands for any u_0, u_1, θ_0 or θ_1. Substituting (16) into the equations (11) to (14), equating the coefficients of like powers of Ec and neglecting terms of $O(Ec^2)$, we get

Zeroth order equations

$$u_{00}''-\left(M\sin^2\psi+\frac{1}{K}\right)u_{00}=-Gr\theta_{00}, \quad (16)$$

$$u_{10}''-\left(M\sin^2\psi+\frac{1}{K}+i\omega\right)u_{10}=-Gr\theta_{10}, \quad (17)$$

$$\theta_{00}''-\Pr\left(R-Q\right)\theta_{00}=0, \quad (18)$$

$$\theta_{10}''-\Pr\left(R-Q+i\omega\right)\theta_{10}=0, \quad (19)$$

First order equations

$$u''_{01} - \left(M\sin^2\psi + \frac{1}{K}\right)u_{01} = -Gr\theta_{01}, \tag{20}$$

$$u''_{11} - \left(M\sin^2\psi + \frac{1}{K} + i\omega\right)u_{11} = -Gr\theta_{11}, \tag{21}$$

$$\theta''_{01} - \Pr\left(R-Q\right)\theta_{01} = -Pr\, u'^2_{00} - Pr\, M\, u^2_{00}, \tag{22}$$

$$\theta''_{11} - \Pr\left(R-Q+i\omega\right)\theta_{11} = -2Pr\, u'_{00}u'_{10} - 2Pr\, M\, u_{00}u_{10}. \tag{23}$$

Now, the corresponding boundary conditions are reduced to

$$\begin{aligned} &y=0: u_{00}=1, u_{01}=0, u_{10}=1, u_{11}=0, \theta'_{00}=-1, \theta'_{01}=0,\\ &\qquad \theta'_{10}=0, \theta'_{11}=0;\\ &y\to\infty: u_{00}\to 0, u_{01}\to 0, u_{10}\to 0, u_{11}\to 0, \theta_{00}=0,\\ &\qquad \theta_{01}=0, \theta_{10}=0, \theta_{11}=0. \end{aligned} \tag{24}$$

Now, the equations (16) to (23) are ordinary second order coupled differential equations and solved under the boundary conditions (24). Thus, through straight forward calculations the expressions for velocity and temperature distribution are known and given by

$$\begin{aligned} u(y,t) = {} & (1+A_1)e^{-\sqrt{\alpha}y} - A_1 e^{-\sqrt{\beta}y} + Ec\,(A_{20}e^{-\sqrt{\alpha}y} - A_{16}e^{-\sqrt{\beta}y}\\ & - A_{17}e^{-2\sqrt{\alpha}y} - A_{18}e^{-2\sqrt{\beta}y} - A_{19}e^{-\gamma y}) + \varepsilon e^{i\omega t}\{e^{-\sqrt{\alpha_1}y} +\\ & Ec\,(A_{24}e^{-\sqrt{\alpha_1}y} - A_{21}e^{-\sqrt{\beta_1}y} - A_{22}e^{-A_{10}y} - A_{23}e^{-A_{12}y})\}, \end{aligned} \tag{25}$$

$$\begin{aligned} \theta(y,t) = {} & \frac{1}{\sqrt{\beta}}e^{-\sqrt{\beta}y} + Ec\,(A_8 e^{-\sqrt{\beta}y} + A_5 e^{-2\sqrt{\alpha}y} + A_6 e^{-2\sqrt{\beta}y}\\ & + A_7 e^{-\gamma y}) + \varepsilon e^{i\omega t} Ec(A_{15}e^{-\sqrt{\beta_1}y} + A_{13}e^{-A_{10}y} +\\ & A_{14}e^{-A_{12}y}). \end{aligned} \tag{26}$$

where A_1 to A_{24} are constants, whose expressions are not given here due to sake of brevity.

3.1. Skin friction coefficient

The coefficient of skin-friction at the plate is given by

$$\begin{aligned} C_f &= \left(\frac{\partial u}{\partial y}\right)_{y=0}\\ &= -\sqrt{\alpha}(1+A_1) + \sqrt{\beta}A_1 + Ec(-\sqrt{\alpha}A_{20} + \sqrt{\beta}A_{16} + 2\sqrt{\alpha}A_{17}\\ &\quad + 2\sqrt{\beta}A_{18} + \gamma A_{19}) + \varepsilon e^{i\omega t}\{-\sqrt{\alpha_1} + Ec(-\sqrt{\alpha_1}A_{24} +\\ &\quad \sqrt{\beta_1}A_{21} + A_{10}A_{22} + A_{12}A_{23})\} \end{aligned} \tag{27}$$

4. Results and Discussion

The effects of the various physical parameters on the fluid velocity and fluid temperature are shown through graphs when $\epsilon = 0.01, t = 1$ and $\omega = 2$. From figures 1 to 8, it is observed that fluid velocity increases by increasing the Grashof number for heat transfer, the Eckert number, the permeability parameter or the heat source parameter while it decreases by increasing the Hartmann number, the Prandtl number, the radiation parameter or the angle of inclination of magnetic field. The effects of Eckert number, Hartmann number, heat source parameter or angle of inclination of magnetic field on temperature field are shown through figure 9 to 12. It is found that fluid temperature enhances with the increase of these physical parameters. Further, the effects of Grashof number for heat transfer, permeability parameter, Prandtl number or radiation parameter on temperature field are shown through figure 13 to 16. It is observed that the fluid temperature decreases with the increase of these physical parameters.

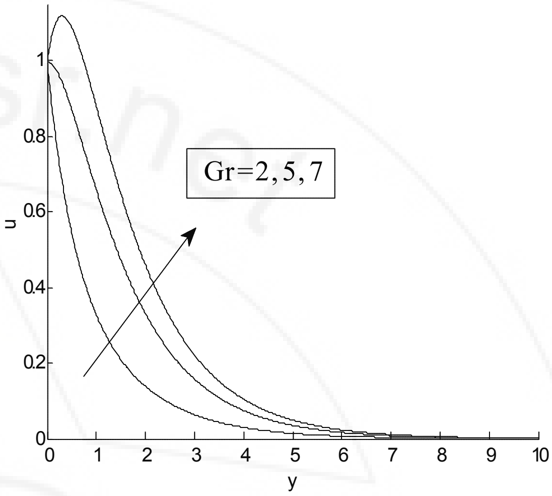

Figure 1: Velocity distribution versus y when $K = 1$, $M = 4, \Pr = 0.71, Ec = 0.01, R = 1, Q = 0.2, \psi = \frac{\pi}{2}$.

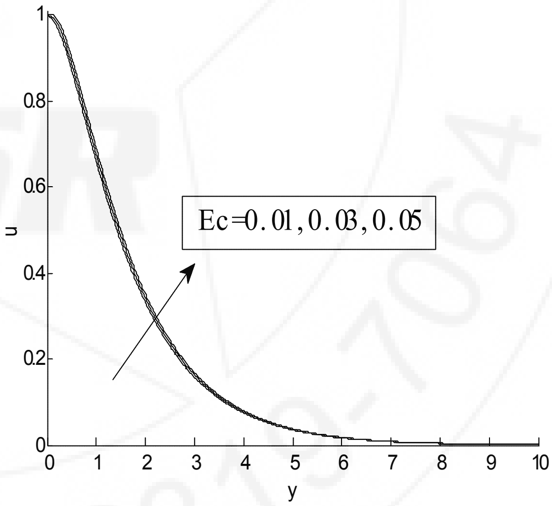

Figure 2: Velocity distribution versus y when $Gr = 5$, $K = 1, M = 4, \Pr = 0.71, R = 1, Q = 0.2, \psi = \frac{\pi}{2}$.

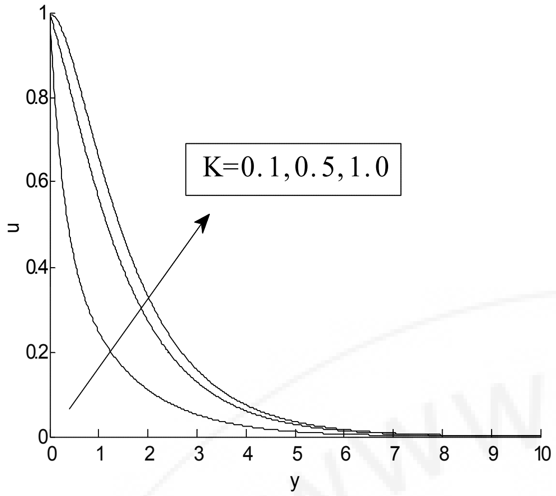

Figure 3: Velocity distribution versus y when $Gr = 5$, $M = 4, \Pr = 0.71, Ec = 0.01, R = 1, Q = 0.2, \psi = \frac{\pi}{2}$.

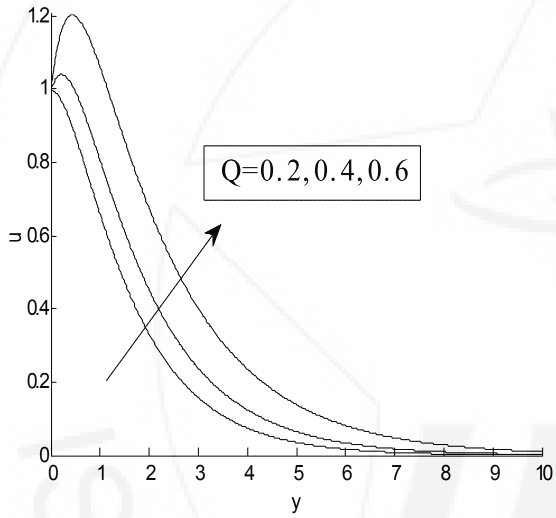

Figure 4: Velocity distribution versus y when $Gr = 5$, $K = 1, M = 4, \Pr = 0.71, Ec = 0.01, R = 1, \psi = \frac{\pi}{2}$.

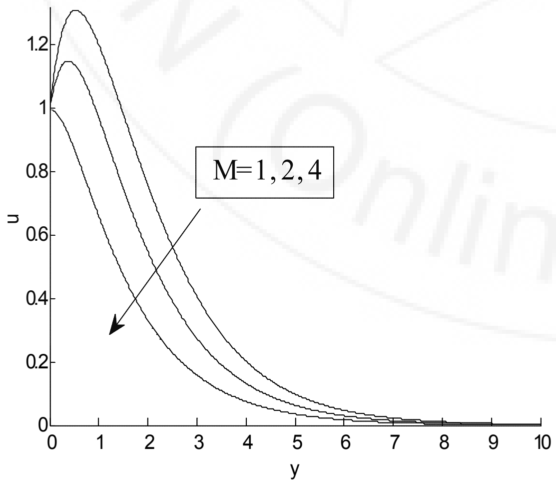

Figure 5: Velocity distribution versus y when $Gr = 5$, $K = 1, \Pr = 0.71, Ec = 0.01, R = 1, Q = 0.2, \psi = \frac{\pi}{2}$.

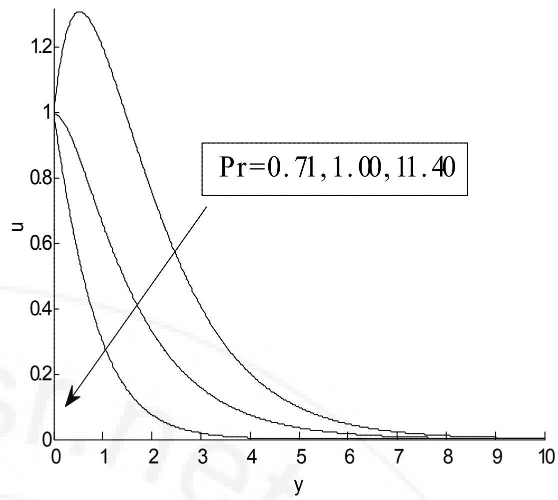

Figure 6: Velocity distribution versus y when $Gr = 5$, $K = 1, M = 4, Ec = 0.01, R = 1, Q = 0.2, \psi = \frac{\pi}{2}$.

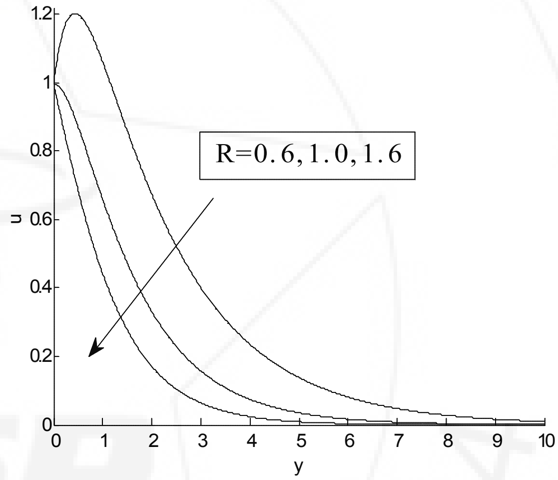

Figure 7: Velocity distribution versus y when $Gr = 5$, $K = 1, M = 4, \Pr = 0.71, Ec = 0.01, Q = 0.2, \psi = \frac{\pi}{2}$.

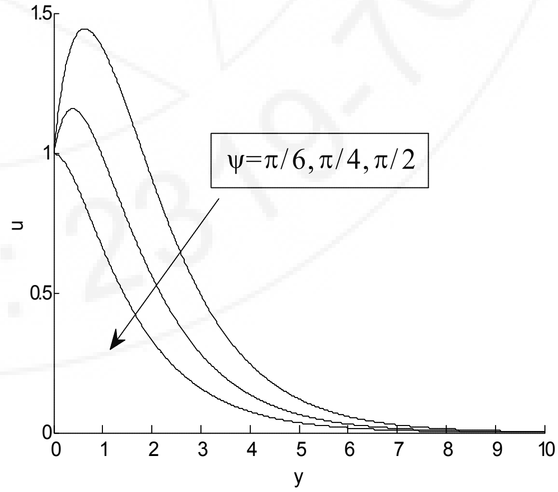

Figure 8: Velocity distribution versus y when $Gr = 5$, $K = 1, M = 4, \Pr = 0.71, Ec = 0.01, R = 1, Q = 0.2$

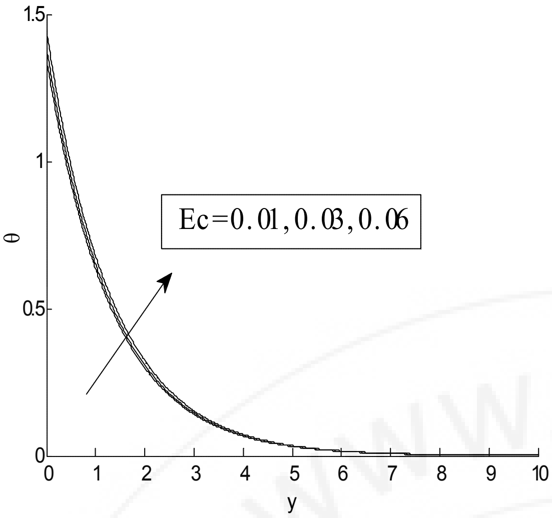

Figure 9: Temperature distribution versus y when $Gr=5$, $K=1, M=4, \Pr=0.71, R=1, Q=0.2, \psi=\frac{\pi}{2}$

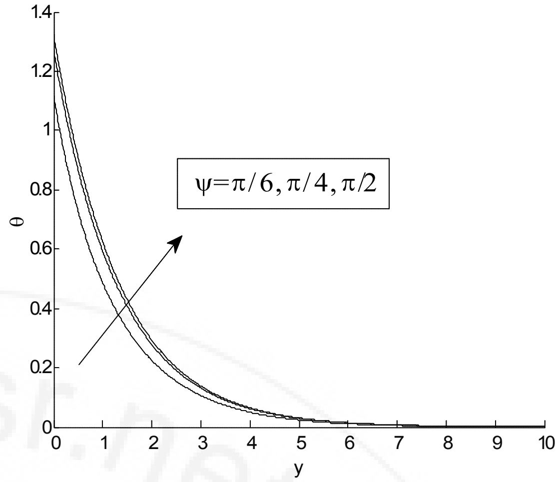

Figure 12: Temperature distribution versus y when $R=1$, $Gr=5, K=1, M=4, Ec=0.01, \Pr=0.71, Q=0.2$.

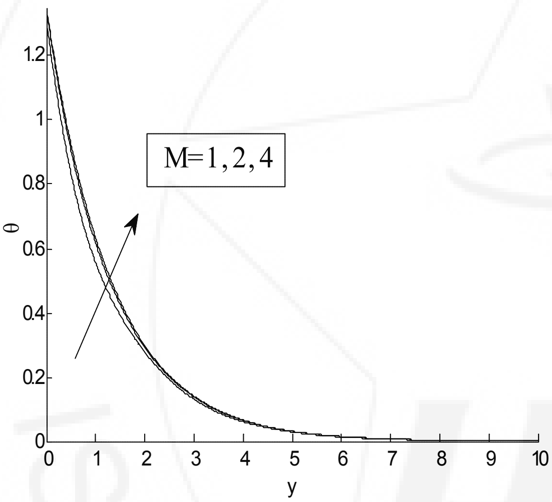

Figure 10: Temperature distribution versus y when $R=1$, $Gr=5, K=1, \Pr=0.71, Ec=0.01, Q=0.2, \psi=\frac{\pi}{2}$.

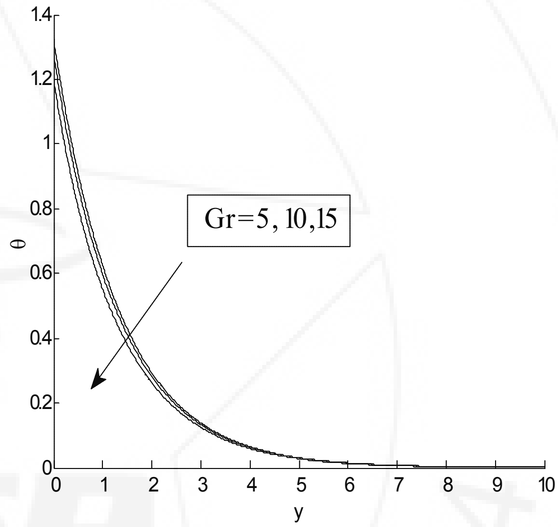

Figure 13: Temperature distribution versus y when $R=1$, $K=1, M=4, \Pr=0.71, Ec=0.01, Q=0.2, \psi=\frac{\pi}{2}$.

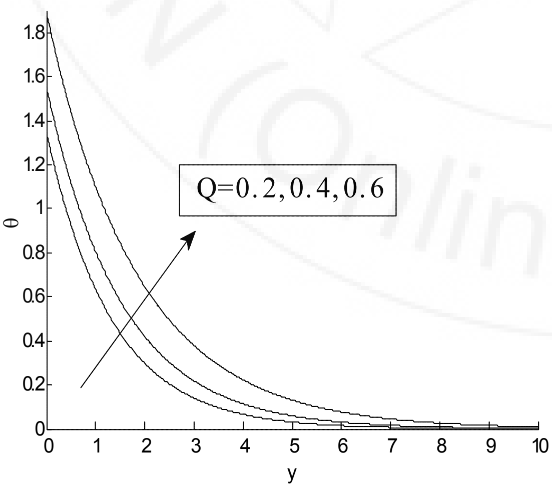

Figure 11: Temperature distribution versus y when $R=1$, $Gr=5, K=1, M=4, \Pr=0.71, Ec=0.01, \psi=\frac{\pi}{2}$.

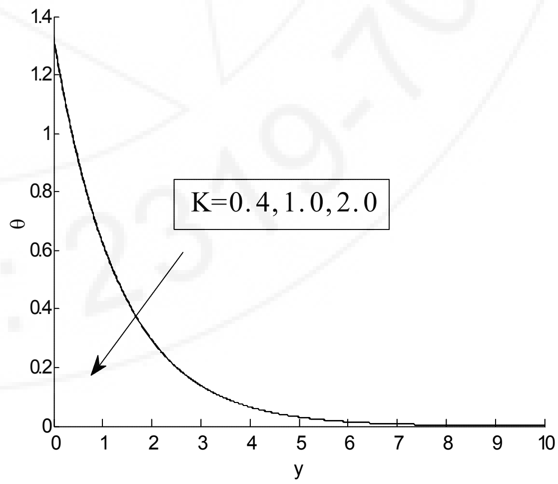

Figure 14: Temperature distribution versus y when $R=1$, $Gr=5, M=4, \Pr=0.71, Ec=0.01, Q=0.2, \psi=\frac{\pi}{2}$.

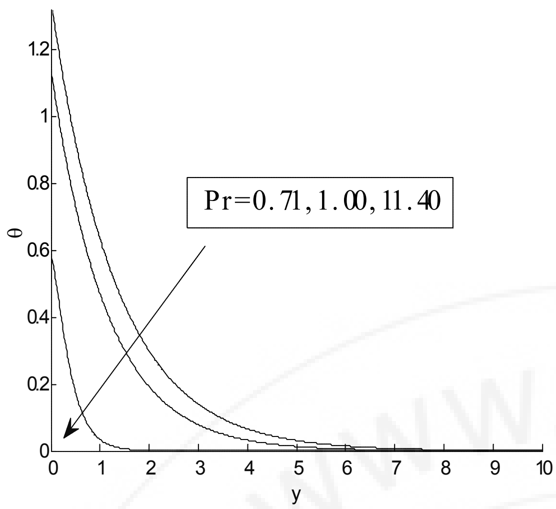

Figure 15: Temperature distribution versus y when $R=1$, $Gr=5, K=1, M=4, Ec=0.01, Q=0.2, \psi=\frac{\pi}{2}$.

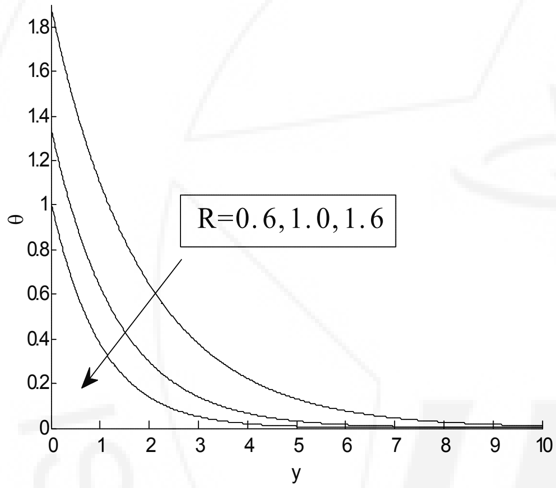

Figure 16: Temperature distribution versus y when $K=1$, $Gr=5, M=4, \Pr=0.71, Ec=0.01, Q=0.2, \psi=\frac{\pi}{2}$.

The physical quantity of interest to engineers is the skin friction coefficient. The skin friction is the non-dimensional rate of shear stress. Numerical results of skin friction coefficient at the plate for various values of the physical parameters are calculated and shown through Table 1.

Table 1: Numerical values of skin friction coefficient at the plate for various values of physical parameters when $t=1$ and $\omega=2$.

ϵ	Pr	R	Ec	Gr	Q	M	K	ψ	Cf
0.00	0.71	1	0.01	5	0.2	2	1	π/2	0.9397
0.01	0.71	1	0.01	5	0.2	2	1	π/2	0.9490
0.01	1.00	1	0.01	5	0.2	2	1	π/2	0.4468
0.01	0.71	2	0.01	5	0.2	2	1	π/2	0.1538
0.01	0.71	1	0.02	5	0.2	2	1	π/2	0.9587
0.01	0.71	1	0.01	10	0.2	2	1	π/2	3.3249
0.01	0.71	1	0.01	5	0.4	2	1	π/2	1.4511
0.01	0.71	1	0.01	5	0.2	4	1	π/2	0.0370
0.01	0.71	1	0.01	5	0.2	2	0.4	π/2	0.2175
0.01	0.71	1	0.01	5	0.2	2	1	π/6	2.0729

It is observed from Table 1 that the skin friction coefficient increases due to increase in the Eckert number, the Grashof number for heat transfer, the permeability parameter or the heat source parameter; while it decreases due to increase in the Prandtl number, the radiation parameter, the Hartmann number or the angle of inclination of magnetic field.

5. Conclusions

An unsteady radiative free convective flow of a viscous, incompressible and electrically conducting fluid in an optically thin environment past an infinite vertical plate placed in a porous media with viscous dissipation effect and joule effect in the presence of heat source, constant heat flux and inclined magnetic field are analyzed and the following conclusions are made;

1. An increase in the Grashof number for heat transfer, permeability parameter or heat source parameter leads to a rise in the magnitude of fluid velocity.
2. An increase in the radiation parameter, Hartmann number or Prandtl number leads to decrease in the magnitude of fluid velocity.
3. The fluid temperature increases with the increase of Eckert number, Hartmann number or heat source parameter, while it decreases with the increase of the Prandtl number, Grashof number for heat transfer, permeability parameter or radiation parameter.
4. As radiation parameter, Hartmann number or Prandtl number increases, the skin friction coefficient decreases.
5. The skin friction coefficient rises with the increase of Eckert number, Grashof number for heat transfer, permeability parameter or heat source parameter.

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