Heat Source and Radiation Effects on an Unsteady MHD Free Convective Flow past a Heated Vertical Plate in a Porous Medium

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Abstract- In the present paper, we investigate the effects of heat source and radiation on unsteady magneto hydrodynamic free convection flow past an infinite heated vertical plate in a porous medium. The dimensionless governing equations are solved numerically using finite element method. Numerical evaluatation of the analytical results are carried out for different values of dimensionless parameters. The results are presented graphically for velocity, temperature and concentration profiles, and observed that, when the heat source and radiation parameter increases, the velocity and temperature decrease in the velocity.

Index Terms- MHD, Vertical plate, radiation, heat absorption, Finite Element Method

MSC 2010:76D99, 76W05, 65L60

Nomenclature

A	Small positive parameter
T_w'	Wall temperature
T_∞'	Reference temperature
U'	Dimensional free stream velocity
t'	Dimensional time
g	Acceleration due to gravity
w_0'	Dimensional suction velocity
(u', v', w')	Dimensional velocity components
(x', y')	Dimensional Cartesian coordinates
$H_0'^2$	Constant transverse magnetic field
K	Dimensional porosity parameter
C_p	Specific heat capacity
M^2	Non– dimensional Hartmann number
Pr	Prandtl number
Gr	Grashof number
R^2	Radiation parameter
U_0	Mean velocity of $U'(t')$
q_z'	Radiative heat flux
Ec	Eckert number
S	Heat source
B	Plank's constant

Greek symbols:

ε	Small positive parameter
β	Coefficient of Volume expansion
$\upsilon = \dfrac{\mu}{\rho}$	Kinematic viscosity
σ_C	Electrical conductivity
μ	Permeability
ρ	Fluid density
ω'	Dimensional free stream frequency of oscillation
k	Thermal conductivity
α^2	Absorption coefficient
χ^2	Non Dimensional permeability parameter
δ	Radiation absorption coefficient
λ	Frequency

I. Introduction

Flow through porous medium past infinite vertical plate is common in nature and has many applications in engineering and science. A number of workers have investigated such flows and excellent literature on the properties and phenomenon may be found in literature [9, 10, 13 – 15]. For example, Soundalgekar [13] investigated the effects of free convection currents on the oscillatory type boundary layer flow past an infinite vertical plate with constant suction where the plate temperature differs from the free steam temperature.

Recently, attention has been on the effects of transversely applied magnetic field and thermal perturbation on the flow of electrically conducting viscous fluids such as plasma. Various properties associated with the interplay of magnetic fields and thermal perturbation in porous medium past vertical plate find useful applications in astrophysics, geophysical fluid dynamics, and engineering. Researchers in these fields have been conducted by many investigators [1, 3, 4, 6, 8, 11, 12 and 16]. For example, Soundalgekar [12] investigated a two dimensional steady free – convection flow of an incompressible, viscous, electrically conducting fluid past an infinite vertical porous plate with constant suction and plate temperature when the difference between the plate temperature and free stream is moderately large to cause free–convection currents. In another study Israel–Cookey and Sigalo [7] investigated the problem of unsteady MHD past a semi–infinite to vertical plate in an optically thin environment with simultaneous effects of radiation, free–convection parameters and time – dependent suction. Chamka [5] investigated the unsteady convective heat and mass transfer past a infinite permeable moving plate with heat absorption where it was found that increase in Solutal Grashoff number enhanced the concentration buoyancy effects leading to an increase in the velocity. Anand Rao and Sivaiah [2] studied the chemical reaction effects on an unsteady MHD free convective flow past an infinite vertical porous plate with constant suction and heat source.

The objective of the present paper is to examine the effects of Heat source and radiation on unsteady MHD free convection flow past an infinite heated vertical plate in a porous medium. The equations of continuity, linear momentum, energy which govern the flow field, are solved numerically by using Galerkin finite element method. Similarity solutions are then obtained numerically for various parameters entering into the problem and discussed them from the physical point of view.

II. MATHEMATICAL FORMULATION

We consider the unsteady flow of an incompressible viscous, radiating hydro magnetic fluid past an infinite porous heated vertical plate with time – dependent suction in an optically thin environment. The physical model and the coordinate system are shown in figure 1. The $x'-$ axis is taken along the vertical infinite porous plate in the upward direction and the $y'-$ axis normal to the plate.

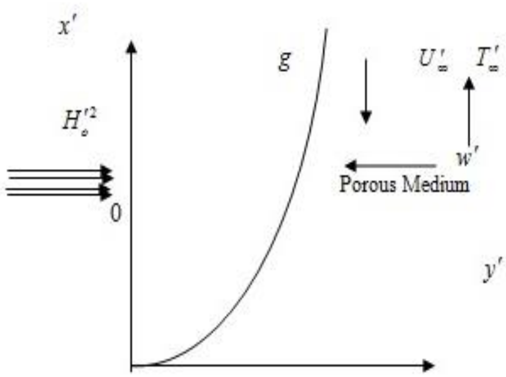

Figure 1. The physical model and coordinate system of the problem

At time $t'=0$, the plate is maintained at a temperature T_w', which is high enough to initiate radiative heat transfer. A constant magnetic field $H_0'^2$ is maintained in the y' direction and the plate moves uniformly along the positive x' direction with velocity U_0. Under Boussinesq approximation the flow is governed by the following equations:

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

$$\frac{\partial u'}{\partial t'}+w'\frac{\partial u'}{\partial y'}=\upsilon\frac{\partial^2 u'}{\partial y'^2}+\frac{\partial U'}{\partial t'}-\left(\frac{\mu^2\sigma_C H_0'^2}{\rho}+\frac{\upsilon}{K}\right)(u'-U')+g\beta\left(T'-T_\infty'\right) \tag{2}$$

$$\frac{\partial T'}{\partial t'} + w'\frac{\partial T'}{\partial y'} = \frac{k}{\rho C_P}\left(\frac{\partial^2 T'}{\partial y'^2} - \nabla q'_{z'}\right) + \frac{\mu}{\rho C_P}\left(\frac{\partial u'}{\partial y'}\right)^2 - \frac{Q_o}{\rho C_P}(T' - T'_\infty) \tag{3}$$

$$\frac{\partial^2 q'_{z'}}{\partial y'^2} - 3\alpha^2 q'_{z'} - 16\alpha\,\sigma\,T_\infty^{\ 3}\frac{\partial T'}{\partial y'} = 0 \tag{4}$$

The boundary conditions are (5)

$u' = 0,\ T' = T'_w,\ on\ \ y' = 0$

$u' = 0, T' = T'_\infty,\ as\ y' \to \infty$ Since the medium is optically thin with relatively low density and $\alpha << 1$ the radiative heat flux given by equation (4) in the spirit of Cogley *et al.* [4] becomes

$$\frac{\partial q'_{z'}}{\partial y'} = 4\alpha^2\left(T' - T'_\infty\right) \tag{6}$$

Where $\alpha^2 = \int_0^\infty \delta\lambda \frac{\partial B}{\partial T'}$ (7)

Further, from equation (1) it is clear that w' is a constant or a function of time only and so we assume $w' = -w'_0\left(1 + \varepsilon A e^{i\omega' t'}\right)$ (8)

Such that $\varepsilon A << 1,$ and the negative sign indicates that the suction velocity is towards the plate.

In view of equations (4), (8) and (9), equations (2) and (3) become

$$\frac{1}{4}\frac{\partial u}{\partial t} - \left(1 + \varepsilon A\, e^{i\omega t}\right)\frac{\partial u}{\partial y} = \frac{1}{4}\frac{\partial U}{\partial t} + \frac{\partial^2 u}{\partial y^2} - (M^2 + \chi^2)(u - U) + Gr\theta \tag{9}$$

$$\frac{1}{4}\Pr\frac{\partial \theta}{\partial t} - \Pr\left(1 + \varepsilon A\, e^{i\omega t}\right)\frac{\partial \theta}{\partial y} = \left(\frac{\partial^2}{\partial y^2} - R^2\right)\theta + \Pr Ec\left(\frac{\partial u}{\partial y}\right)^2 - \Pr S\theta \tag{10}$$

Where we have used the following dimensionless variables

$$\left.\begin{array}{l} t = \dfrac{w_0'^2 t'}{4\upsilon},\quad y = \dfrac{w'_0 y'}{\upsilon},\quad u = \dfrac{u'}{U_0},\quad \omega = \dfrac{4\upsilon\omega'}{w_0'^2},\quad U = \dfrac{U'}{U_0},\quad \theta = \dfrac{T' - T'_\infty}{T'_w - T'_\infty}\ , \\ \Pr = \dfrac{\mu\, c_p}{k},\ Gr = \dfrac{g\beta\,\upsilon\left(T'_w - T'_\infty\right)}{U_0 w_0'^2},\quad Ec = \dfrac{U_0^2}{C_P\left(T'_w - T'_\infty\right)}\ ,\quad \chi^2 = \dfrac{\upsilon^2}{K\, w_0'^2}. \\ R^2 = \dfrac{4\alpha^2}{\rho\, C_P k w_0'^2}(T'_w - T'_\infty), S = \dfrac{\upsilon\, Q_o}{\rho c_p w_0'^2},\ M^2 = \dfrac{\mu^2 \sigma_C H_0'^2}{\upsilon\rho w_0'^2}, \\ . \end{array}\right\} \tag{11}$$

Equations (9) and (10) are now subject to the boundary conditions

$$\left.\begin{array}{l} u = 0,\quad \theta = 1,\ on\ \ y = 0 \\ u \to 0\,,\ \theta \to 0,\ as\ \ y \to \infty \end{array}\right\} \tag{12}$$

The mathematical statement of the problem is now complete and embodies the solution of equations (9) and (10) subject to boundary conditions (11).

III. METHOD OF SOLUTION

By applying Galerkin finite element method for equation (9) over the element (e) ,($y_j \le y \le y_k$) is:

$$\int_{y_j}^{y_k} \left\{ N^{(e)T} \left[4\frac{\partial^2 u^{(e)}}{\partial y^2} - \frac{\partial u^{(e)}}{\partial t} + 4B\frac{\partial u^{(e)}}{\partial y} - Du^{(e)} + P \right] \right\} dy = 0 \tag{13}$$

Where $P = \frac{\partial U}{\partial t} + 4(Gr)\theta + DU$, $B = 1 + \varepsilon A e^{i\omega t}$, $D = 4(M^2 + \chi^2)$;

Integrating the first term in equation (13) by parts one obtains

$$4N^{(e)T}\left\{\frac{\partial u^{(e)}}{\partial y}\right\}_{y_j}^{y_k} - \int_{y_j}^{y_k}\left\{4\frac{\partial N^{(e)T}}{\partial y}\frac{\partial u^{(e)}}{\partial y} + N^{(e)T}\left(\frac{\partial u^{(e)}}{\partial t} - 4B\frac{\partial u^{(e)}}{\partial y} + Du^{(e)} - P\right)\right\}dy = 0 \tag{14}$$

Neglecting the first term in equation (14), one gets:

$$\int_{y_j}^{y_k}\left\{4\frac{\partial N^{(e)T}}{\partial y}\frac{\partial u^{(e)}}{\partial y} + N^{(e)T}\left(\frac{\partial u^{(e)}}{\partial t} - 4B\frac{\partial u^{(e)}}{\partial y} + Du^{(e)} - P\right)\right\}dy = 0$$

Let $u^{(e)} = N^{(e)}\phi^{(e)}$ be the linear piecewise approximation solution over the element (e) ($y_j \le y \le y_k$) where

$N^{(e)} = \begin{bmatrix} N_j & N_k \end{bmatrix}$, $\phi^{(e)} = \begin{bmatrix} u_j & u_k \end{bmatrix}^T$ and $N_j = \frac{y_k - y}{y_k - y_j}$, $N_k = \frac{y - y_j}{y_k - y_j}$ are the basis functions. One obtains:

$$4\int_{y_j}^{y_k}\left\{\begin{bmatrix} N_j' N_j' & N_j' N_k' \\ N_j' N_k' & N_k' N_k' \end{bmatrix}\begin{bmatrix} u_j \\ u_k \end{bmatrix}\right\}dy + \int_{y_j}^{y_k}\left\{\begin{bmatrix} N_j N_j & N_j N_k \\ N_j N_k & N_k N_k \end{bmatrix}\begin{bmatrix} \dot{u}_j \\ \dot{u}_k \end{bmatrix}\right\}dy - 4B\int_{y_j}^{y_k}\left\{\begin{bmatrix} N_j N_j' & N_j N_k' \\ N_j' N_k & N_k' N_k \end{bmatrix}\begin{bmatrix} u_j \\ u_k \end{bmatrix}\right\}dy$$

$$+ D\int_{y_j}^{y_k}\left\{\begin{bmatrix} N_j N_j & N_j N_k \\ N_j N_k & N_k N_k \end{bmatrix}\begin{bmatrix} u_j \\ u_k \end{bmatrix}\right\}dy = P\int_{y_j}^{y_k}\begin{bmatrix} N_j \\ N_k \end{bmatrix}dy$$

Simplifying we get

$$\frac{4}{l^{(e)^2}}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}\begin{bmatrix} u_j \\ u_k \end{bmatrix} + \frac{1}{6}\begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}\begin{bmatrix} \dot{u}_j \\ \dot{u}_k \end{bmatrix} - \frac{4B}{2l^{(e)}}\begin{bmatrix} -1 & 1 \\ -1 & 1 \end{bmatrix}\begin{bmatrix} u_j \\ u_k \end{bmatrix} + \frac{D}{6}\begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}\begin{bmatrix} u_j \\ u_k \end{bmatrix} = \frac{P}{2}\begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

Where prime and dot denotes differentiation w.r.t y and time t respectively. Assembling the element equations for two consecutive elements $(y_{i-1} \le y \le y_i)$ and $(y_i \le y \le y_{i+1})$ following is obtained:

$$\frac{4}{l^{(e)^2}}\begin{bmatrix}1 & -1 & 0\\ -1 & 2 & -1\\ 0 & -1 & 1\end{bmatrix}\begin{bmatrix}u_{i-1}\\ u_i\\ u_{i+1}\end{bmatrix}+\frac{1}{6}\begin{bmatrix}2 & 1 & 0\\ 1 & 4 & 1\\ 0 & 1 & 2\end{bmatrix}\begin{bmatrix}\dot{u}_{i-1}\\ \dot{u}_i\\ \dot{u}_{i+1}\end{bmatrix}-\frac{4B}{2l^{(e)}}\begin{bmatrix}-1 & 1 & 0\\ -1 & 0 & 1\\ 0 & -1 & 1\end{bmatrix}\begin{bmatrix}u_{i-1}\\ u_i\\ u_{i+1}\end{bmatrix}+$$

$$\frac{D}{6}\begin{bmatrix}2 & 1 & 0\\ 1 & 4 & 1\\ 0 & 1 & 2\end{bmatrix}\begin{bmatrix}u_{i-1}\\ u_i\\ u_{i+1}\end{bmatrix}=\frac{P}{2}\begin{bmatrix}1\\ 2\\ 1\end{bmatrix} \qquad (15)$$

Now put row corresponding to the node i to zero, from equation (15) the difference schemes with $l^{(e)} = h$ is:

$$\frac{4}{h^2}\left[-u_{i-1}+2u_i-u_{i+1}\right]+\frac{1}{6}\left[\dot{u}_{i-1}+4\dot{u}_i+\dot{u}_{i+1}\right]-\frac{4B}{2h}\left[-u_{i-1}+u_{i+1}\right]+\frac{D}{6}\left[u_{i-1}+4u_i+u_{i+1}\right]=P \qquad (16)$$

Applying the trapezoidal rule, following system of equations in Crank – Nicholson method are obtained:

$$A_1u_{i-1}^{n+1}+A_2u_i^{n+1}+A_3u_{i+1}^{n+1}=A_4u_{i-1}^{n}+A_5u_i^{n}+A_6u_{i+1}^{n}+P^* \qquad (17)$$

Now from equations (11) and (12) following equations are obtained:

$$B_1\theta_{i-1}^{n+1}+B_2\theta_i^{n+1}+B_3\theta_{i+1}^{n+1}=B_4\theta_{i-1}^{n}+B_5\theta_i^{n}+B_6\theta_{i+1}^{n}+Q^* \qquad (18)$$

Where $A_1=2+12Brh+Dk-24r,\ A_2=8+4Dk+48r,\ A_3=2-12Brh+Dk-24r,$
$A_4=2-12Brh-Dk+24r,\ A_5=8-4Dk-48r,\ A_6=2+12Brh+Dk+24r,$

$$B_1=2(\Pr)+12(\Pr)Brh+4R^2k-24r+4S(\Pr)k,\ B_2=8(\Pr)+48r+16R^2k+16S(\Pr)k,$$

$$B_3=2(\Pr)-12(\Pr)Brh+4R^2k-24r+4S(\Pr)k,$$

$$B_4=2(\Pr)-12(\Pr)Brh-4R^2k+24r-4S(\Pr)k,$$

$$B_5=8(\Pr)-48r-16R^2k-16S(\Pr)k,$$

$$B_6=2(\Pr)+12(\Pr)Brh-4R^2k+24r-4S(\Pr)k,$$

$$P^*=12Pk=12k\left(\frac{\partial U}{\partial t}+4(Gr)\theta+DU\right),\ Q^*=12Qk=48(\Pr)k(Ec)\left(\frac{\partial u}{\partial y}\right)^2,$$

Here r= $\frac{k}{h^2}$ and h, k are mesh sizes along y –direction and time–direction respectively. Index i refers to space and j refers to the time. In the equations (17) and (18) taking $i=1(1)n$ and using boundary conditions (12), then the following system of equations are obtained:

$$A_iX_i=B_i \quad i=1(1)2 \qquad (19)$$

where $A_i^{'}$s are matrices of order n and X_i, $B_i^{'}$s are column matrices having n – components. The solutions of above system of equations are obtained by using Thomas algorithm for velocity, temperature and concentration. Also, numerical solutions for these equations are obtained by C – programme. In order to prove the convergence and stability of Galerkin finite element method, the same C – programme was run with smaller values of h and k no significant change was observed in the values of u, θ and C. Hence the Galerkin finite element method is stable and convergent.

IV. RESULTS AND DISCUSSION

In the previous sections, we have formulated and solved the problem of an unsteady MHD free convection flow past an infinite heated vertical plate in a porous medium with radiation. By invoking, the optically thin differential approximation for the radiative heat flux in the energy equation. In the numerical computation, the Prandtl number ($Pr = 0.71$) which corresponds to air and various values of the material parameters are used. In addition, the boundary condition $y \to \infty$ is approximated by $y_{max} = 3$, which is sufficiently large for the velocity to approach the relevant stream velocity. For various values of Grashof number the velocity profiles u are plotted in figures (2). The Grashof number (Gr) signifies the relative effect of the thermal buoyancy force to the viscous hydrodynamic force in the boundary layer. As expected, it is observed that there is a rise in the velocity due to the enhancement of thermal buoyancy force. Also, as (Gr) increases, the peak values of the velocity increases rapidly near the porous plate and then decays smoothly to the free stream velocity.. Figure (3) illustrate the velocity profiles for different values of Prandtl number Pr. The numerical results show that the effect of increasing values of Prandtl number result in decreasing velocity. The effect of the magnetic field parameter M is shown in figure (4) in case of cooling of the plate. It is observed that the velocity of the fluid decreases with the increase of the magnetic field parameter values. The decrease in the velocity as the Hartmann number M increases is because the presence of a magnetic field in an electrically conducting fluid introduces a force called the Lorentz force, which acts against the flow if the magnetic field is applied in the normal direction, as in the present study. This resistive force slows down the fluid velocity component as shown in figure (4). The influence of the viscous dissipation parameter i.e., the Eckert number Ec on the velocity and temperature are shown in figures (5) and (10) respectively. The Eckert number Ec expresses the relationship between the kinetic energy in the flow and the enthalpy. It embodies the conversion of kinetic energy into internal energy by work done against the viscous fluid stresses. Greater viscous dissipative heat causes a rise in the temperature as well as the velocity.

The effect of the thermal radiation parameter R on the primary velocity and temperature profiles in the boundary layer are illustrated in figures (6) and (12) respectively. Increasing the thermal radiation parameter R produces significant increase in the thermal condition of the fluid and its thermal boundary layer. This increase in the fluid temperature induces more flow in the boundary layer causing the velocity of the fluid there to increase. Figure (7) and (11) has been plotted to depict the variation of velocity and temperature profiles against y for different values of heat source parameter S by fixing other physical parameters. From this Graph we observe that velocity and temperature decrease with increase in the heat source parameter S because when heat is absorbed, the buoyancy force decreases the temperature profiles. Figure (8) shows the effects of Darcy number χ on the velocity profiles for cooling as well as heating of the plate. For a cooling plate fluid velocity increases, whereas for a heating plate it decreases with increase of χ. Darcy number is the measurement of the porosity of the medium. As the porosity of the medium increases, the value of χ increases. For large porosity of the medium fluid gets more space to flow as a consequence its velocity increases. Figure (9) illustrate the temperature profiles for different values of Prandtl number Pr. It is observed that the temperature decrease as an increasing the Prandtl number. The reason is that smaller values of Pr are equivalent to increase in the thermal conductivity of the fluid and therefore heat is able to diffuse away from the heated surface more rapidly for higher values of Pr. Hence in the case of smaller Prandtl number the thermal boundary layer is thicker and the rate of heat transfer is reduced.

V. CONCLUSIONS

In conclusion therefore, the flow of an unsteady MHD free convection past an infinite heated vertical plate in a porous medium under the simultaneous effects of viscous dissipation, radiation and heat source is affected by the material parameters. The governing equations are approximated to a system of linear partial differential equations by using Galerkin finite element method. The results are presented graphically and we can conclude that the flow field and the quantities of physical interest are significantly influenced by these parameters.

1. The velocity increases as Grashof number Gr, Eckert number Ec, Thermal radiation parameter R, Darcy parameter χ , Ec and Soret number Sr increases. However, the velocity was found to decreases as the Hartmann number M, Prandtl number Pr, Schmidt number Sc, and Heat source parameter S are increases.
2. The fluid temperature was found to decreases as the Heat source parameter S and Prandtl number Pr are

increases and found to increase as Eckert number Ec, and thermal radiation parameter R are increases.

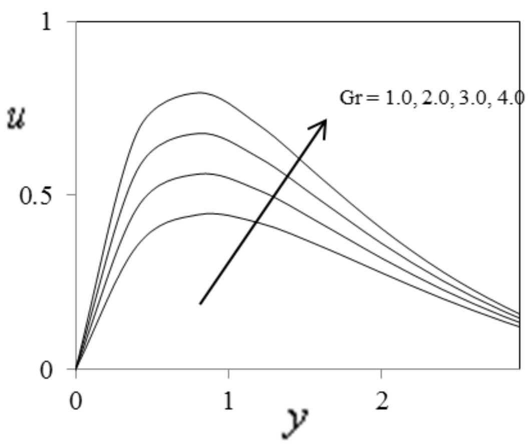

Figure 2. Velocity profiles for different values of *Gr*

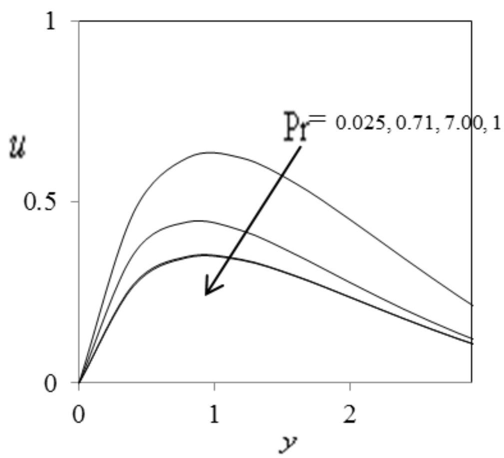

Figure 3. Velocity profiles for different values of Pr

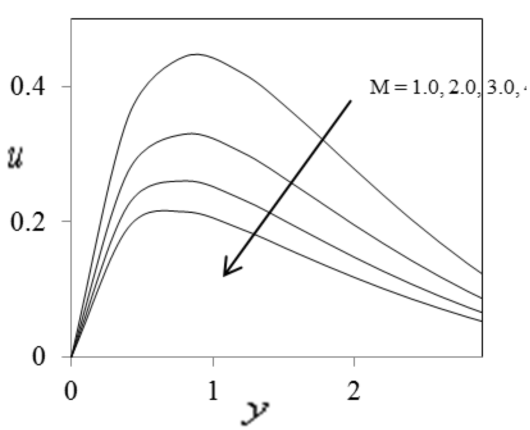

Figure 4. Velocity profiles for different values of *M*

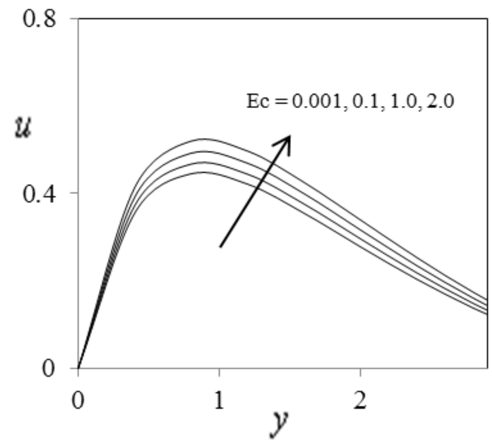

Figure 5. Velocity profiles for different values of *Ec*

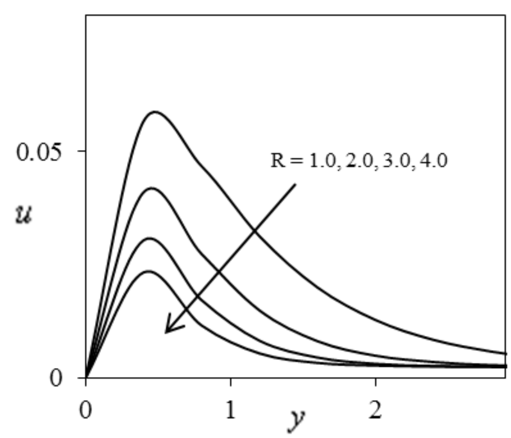

Figure 6. Velocity profiles for different values of *R*

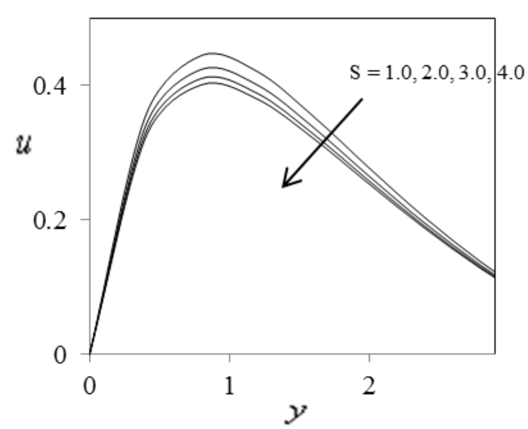

Figure 7.Velocity profiles for different values of *S*

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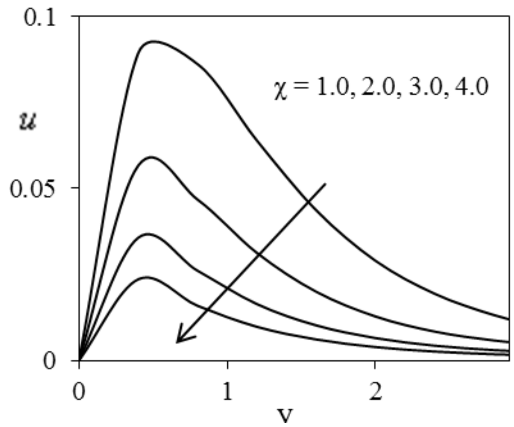

Figure 8. Velocity profiles for different values of χ

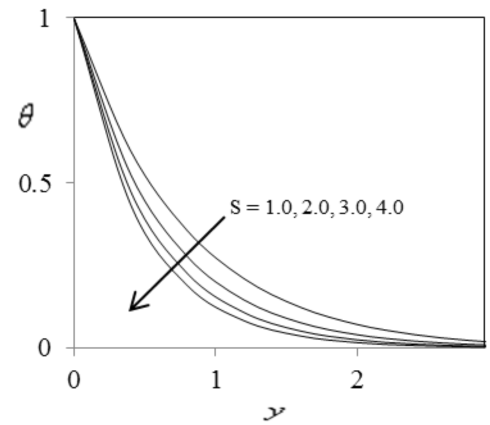

Figure 11. Temperature profiles for different values of S

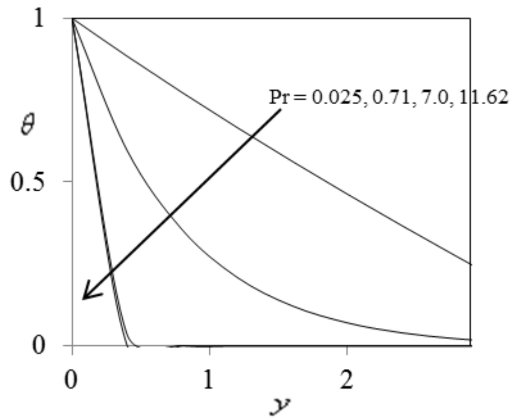

Figure 9. Temperature profiles for different values of $\Pr$

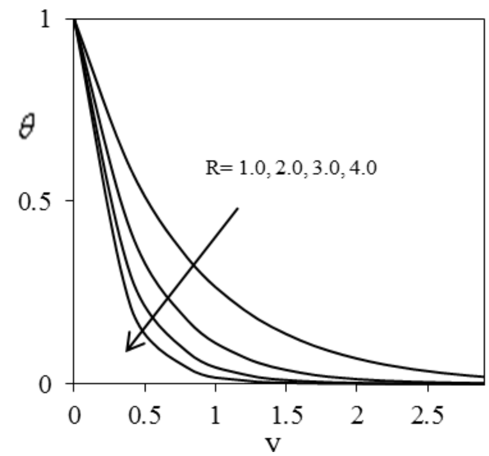

Figure 12. Temperature profiles for different values of R

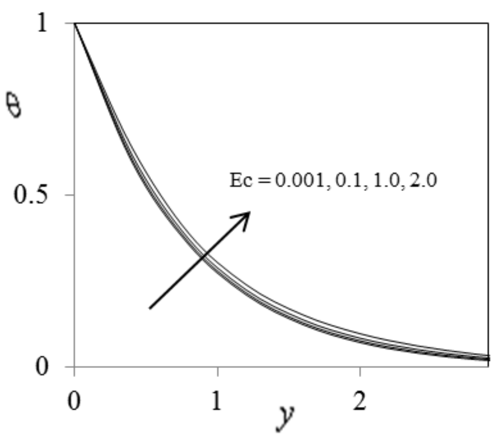

Figure 10. Temperature profiles for different values of Ec

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