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Effects of Radiation on Unsteady MHD Boundary Layer Flow about an Inclined Porous Stretching Sheet with Variable Thermal Conductivity

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ABSTRACT
The goal of this study is to investigate the effects of radiation on unsteady MHD boundary layer flow of an incompressible, electrically conducting and viscous fluid about an inclined stretching sheet with variable thermal conductivity embedded in porous medium. The flow is considered under the influence of a stretching velocity and a uniform magnetic field. The governing partial differential equations are transformed into ordinary differential equations by using similarity transformation and stretching variable. The governing momentum boundary layer, thermal boundary layer and concentration boundary layer equations with the boundary conditions are transformed into a system of first order ordinary differential equations which are then solved numerically by using Runge-Kutta fourth-fifth order method along with shooting technique. The effects of the flow parameters on the velocity, temperature and species concentration are computed, discussed and have been graphically represented in figures and also the shearing stress and rate of heat transfer are shown in table for various values of different parameters. The results presented graphically illustrate that velocity field decrease due to increasing of Magnetic parameter, porosity parameter and unsteadiness parameter and reverse trend arises for the increasing values of stretching parameter but there is no effect of Radiation and perturbation parameter on velocity profile. The temperature field decreases for Magnetic parameter, porosity parameter but the temperature field increases for the increasing values of stretching parameter, unsteadiness parameter, radiation and perturbation parameter. Again, concentration profile decreases for increasing the values of Magnetic parameter, unsteadiness parameter, porosity parameter, radiation and perturbation parameter but concentration increases for increasing the values of stretching parameter. By considering the hot plate the numerical results for the skin friction and the local Nusselt number are compared with the results reported by other author when the magnetic field and modified Grashof number are absent. The present results in this paper are in good agreement with the work of the previous author.

Keywords: MHD; unsteadiness; stretching sheet; radiation; porosity

1. Introduction

Heat transfer in boundary layer over a stretching sheet has important applications in extrusion of plastic sheets, polymer, spinning of fibers, cooling of elastic sheets etc. The quality of final product depends on the rate of heat transfer as a result the cooling procedure has to be controlled effectively. The MHD boundary layer flow of heat and mass transfer problems about an stretching sheet have become in view of its significant applications in industrial manufacturing processes such as plasma studies, petroleum industries, Magneto-hydrodynamics power generator, cooling of Nuclear reactors, boundary layer control in aerodynamics, glass fiber production and paper production. The MHD flow in electrically conducting fluid can control the rate of cooling and the desired quality of product can be achieved. In this regard many investigators have studied the boundary layer flow of electrically conducting fluid, heat and mass transfer due to stretching sheet in presence of magnetic field. Accordingly, Elbashbeshy and Bazid [1] presented an exact similarity solution for unsteady momentum and heat transfer flow whose motion is caused solely by the linear stretching of a horizontal stretching surface, Alharbi et.al [2] studied heat and mass transfer in MHD visco-elastic fluid flow through a porous medium over a stretching sheet with chemical reaction, Seddeek and Abdel Meguid [3] analyzed the effects of radiation and thermal diffusivity on heat transfer over a stretching surface with variable heat flux , Ali et al. [4] studied the radiation and thermal diffusion effects on a steady MHD free convection heat and mass transfer flow past an inclined stretching sheet with Hall current and heat generation, Ibrahim and Shanker [5] investigated the unsteady MHD boundary layer flow and heat transfer due to stretching sheet in the presence of heat source or sink by Quasi-linearization technique. Ishak et al. [6] investigated the solution to unsteady mixed convection boundary layer flow and heat transfer due to a stretching vertical surface. Further, Ishak [7] studied unsteady laminar MHD flow and heat transfer due to continuously stretching plate immersed in an electrically conducting fluid. Ebashbeshy and Aldawody [8] analyzed heat transfer over an unsteady stretching surface with variable heat flux in presence of heat source or sink, Fadzilah et al. [9] studied the steady MHD boundary layer flow and heat transfer of a viscous and electrically conducting fluid over a stretching sheet with an induced magnetic field. Also, Bachok et al. [10] analyzed the similarity solution of the unsteady laminar boundary of an incompressible micro-polar fluid and heat transfer due to a stretching sheet and Mohebujjaman et al. [11] studied MHD heat transfer mixed convection flow along a vertical stretching

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sheet with heat generation using shooting technique. So the present work focused on unsteady MHD boundary layer flow of an incompressible, electrically conducting and viscous fluid about an inclined stretching sheet with variable thermal conductivity embedded in porous medium by Quasi-linearization technique.

2. Mathematical Formulation of the Problem and Similarity Analysis

Consider a two dimensional unsteady laminar MHD viscous incompressible electrically conducting fluid along an inclined stretching sheet with an acute angle (α) , X- direction is taken along the leading edge of the inclined stretching sheet and Y is normal to it and extends parallel to X-axis. A magnetic field of strength B_0 is introduced to the normal to the direction to the flow. The uniform plate temperature T_w ($>T_\infty$), where T_∞ is the temperature of the fluid far away from the plate. Let u and v be the velocity components along the X and Y axis respectively in the boundary layer region. Under the above assumptions and usual boundary layer approximation, the dimensional governing equations of continuity, momentum, concentration and energy under the influence of externally imposed magnetic field are:

Equation of continuity:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

Momentum equation:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\frac{\partial^2 u}{\partial y^2}+ g\beta(T-T_\infty)\cos\alpha+g\beta^*(C-C_\infty)\cos\alpha -\frac{\sigma B_0^2 u}{\rho}-\frac{\nu}{K}u \tag{2}$$

Energy Equation:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\kappa}{\rho c_p}\frac{\partial^2 T}{\partial y^2}-\frac{\partial q_r}{\partial y} \tag{3}$$

Concentration Equation:

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_m\frac{\partial^2 C}{\partial y^2}+\frac{D_m K_T}{T_m}\frac{\partial^2 \mathrm{T}}{\partial \mathrm{y}^2} \tag{4}$$

Using free stream $u=U(x,t)=\dfrac{bx}{\sqrt{1-\gamma t}}$, we get

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}=-\frac{1}{\rho}\frac{\partial p}{\partial x}$$

Hence equation (2) becomes

$$\frac{\partial u}{\partial t}-\frac{\partial U}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=U\frac{\partial U}{\partial x}+\nu\frac{\partial^2 u}{\partial y^2}+g\beta(T-T_\infty)\cos\alpha +g\beta^*(C-C_\infty)\cos\alpha-\frac{\sigma B_0^2(u-U)}{\rho}-\frac{\nu}{K}(u-U) \tag{5}$$

By using the Rosseland approximation, we have the radiative heat flux, $\mathrm{q_r}=-\dfrac{4\sigma^*}{3\mathrm{K_0}}\dfrac{\partial \mathrm{T}^4}{\partial \mathrm{y}}$ where σ^* is the Stefan-Boltzman constant, $\mathrm{K_0}$ is the Rosseland mean absorption coefficient. Assuming that, the difference in temperature within the flow are such that T^4 can be expressed as a linear combination of the temperatures. We expand T^4 in Taylors series about T_∞ as follows:

$$T^4=T_\infty^4+4T_\infty^3(T-T_\infty)+6T_\infty^2(T-T_\infty)^2+\ldots\ldots\ldots$$

and neglecting the higher order terms beyond the first degree in $(T-T_\infty)$; we have $T^4\approx -3T_\infty^4+4T_\infty^3 T$. Therefore $q_r=-\dfrac{16\sigma^*}{3K_0}T_\infty^3\dfrac{\partial T}{\partial y}$ .So the equation (3) becomes

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\kappa}{\rho c_p}\frac{\partial^2 T}{\partial y^2}+\frac{16\sigma^*}{3K_0}T_\infty^3\frac{\partial^2 T}{\partial^2 y} \tag{6}$$

According to Arunachalam and Rajappa [15] and Chaim [16], the thermal conductivity is taken of the form $\kappa=\kappa^*(1+\varepsilon\theta)$, where u and v are the velocity components along x and y directions, T, T_w and T_∞ are the fluid temperature, the stretching sheet temperature and the free stream temperature respectively while C , C_w and C_∞ are the corresponding concentrations, κ is the variable thermal conductivity of the fluid, κ^* is the thermal conductivity of the fluid, K is the permeability of the porous medium, C_p specific heat with constant pressure, α is the angle of inclination , γ is the constant, μ is the coefficient of viscosity, ν is the kinematic viscosity , ε is the perturbation, σ is the electrical conductivity, ρ is the fluid density, β is the thermal expansion coefficient, β^* is the concentration expansion coefficient, B_0 is the magnetic field intensity, U is the free steam velocity, g is the acceleration due to gravity, D_m is the coefficient of mass diffusivity, T_m is the mean fluid temperature, K_T is the thermal diffusion ratio respectively. The above equations are subject to the following boundary conditions:

$$\begin{gathered} u=u_w,\ v=0,\ T=T_w, C=C_w \quad at \quad y=0 \\ u=U, T=T_\infty, C=C_\infty \quad as \quad y\to\infty \end{gathered} \tag{7}$$

The velocity of the sheet $u_w(x,t)$, the surface temperature of the sheet $T_w(x,t)$, concentration $C_w(x,t)$, and the transverse magnetic field strength $B(t)$ are respectively defined as follows:

$$u_w = \frac{ax}{\sqrt{1\text{-}\gamma t}}, T_w - T_\infty = \frac{bx}{\sqrt{1\text{-}\gamma t}}, C_w - C_\infty = \frac{cx}{\sqrt{1\text{-}\gamma t}},$$
$$B(t) = \frac{B_0}{\sqrt{1\text{-}\gamma t}}$$

where, a is the stretching rate and b, c are positive constant with dimension (time)-1. We introduce the steam function $\psi(x,y)$ as defined by $u = \frac{\partial \psi}{\partial y}$ and $v = -\frac{\partial \psi}{\partial x}$.

To convert the governing equations into a set of similarity equations, we introduce the following similarity transformation:

$$\psi = x\sqrt{\frac{a\nu}{1\text{-}\gamma t}}\, f(\eta), \eta = \sqrt{\frac{a}{\nu(1\text{-}\gamma t)}}\, y,\ \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty},$$
$$\varphi(\eta) = \frac{C - C_\infty}{C_w - C_\infty}$$

From the above transformations, the non-dimensional, nonlinear and coupled ordinary differential equations are obtained as follows:

$$f''' + ff'' - f'^2 - A\left(f' + \frac{1}{2}f''\right) - (M+N)f' + Gr\theta\ \cos\alpha + Gm\varphi\cos\alpha + \frac{1}{2}A\lambda + \lambda^2 = 0 \tag{8}$$

$$(1 + R\Pr + \varepsilon\theta)\theta'' + \Pr f\theta' - \frac{1}{2}\Pr A\eta\theta' = 0 \tag{9}$$

$$\varphi'' + Scf\varphi' - \frac{1}{2}ASc\eta\varphi' - S_0\theta'' = 0 \tag{10}$$

The transform boundary conditions:

$$\begin{aligned} &f = 0\ \ f' = 1, \theta = \varphi = 1\ at\ \eta = 0, \\ &f' = \lambda, \theta = \varphi = 0\ \ as\ \eta \to \infty \end{aligned} \tag{11}$$

Where f', θ and φ are the dimensionless velocity, temperature and concentration respectively, η is the similarity variable, the prime denotes differentiation with respect to η. Also

$$M = \frac{\sigma B_0^2(1-\gamma t)}{\rho a}, N = \frac{\nu(1-\gamma t)}{Ka}, A = \frac{\gamma}{a},$$
$$\lambda = \frac{b\sqrt{(1-\gamma t)}}{a}, Gr = \frac{g\beta(T_w - T_\infty)(1-\gamma t)^2}{a^2 x},$$
$$Gm = \frac{g\beta^*(C_w - C_\infty)(1-\gamma t)^2}{a^2 x}, \Pr = \frac{\mu c_p}{\kappa^*},$$
$$Sc = \frac{\nu}{D_m}, R = \frac{16\sigma^* T_\infty^3}{3K_0}\ and\ S_0 = \frac{K_T(T_w - T_\infty)}{T_m(C_w - C_\infty)}$$

are the Magnetic parameter, porosity parameter, unsteadiness parameter, stretching ratio, Grashof number, modified Grashof number, Prandtl number, Schmidt number, Radiation parameter and Soret number respectively. The important physical quantities of this problem are skin friction coefficient C_f and the local Nusselt number Nu which are proportional to rate of velocity and rate of temperature respectively.

3. Methodology

The governing concentration boundary layer Eq. (4), momentum boundary layer Eq. (5) and thermal boundary layer Eq. (6) with the boundary conditions (7) are transformed into a system of first order ordinary differential equations which are then solved numerically by using Runge-Kutta fourth-fifth order method along with shooting iteration technique. First of all, the coupled ordinary differential Eq. (8) – Eq. (10) are third order in f and second order in θ and φ which have been reduced to a system of seven simultaneous ordinary differential equations for seven unknowns. For the purpose of numerically solve this system of equations using Runge-Kutta method, the solution requires seven initial conditions but two initial conditions in f, one initial condition in each of θ and φ are known. However, the values of f', θ and φ are known at $\eta \to \infty$. These end conditions are utilized to produce unknown initial conditions at $\eta \to 0$ by using shooting technique. The most important step of this scheme is to choose the appropriate finite value of η_∞. Thus to estimate the value of η_∞, we start with some initial guess value and solve the boundary value problem consisting of Eq. (8)– Eq.(10) to obtain $f''(0), \theta'(0)$ and $\varphi'(0)$. The solution process is repeated with another larger value of η_∞ until two successive values of $f''(0), \theta'(0)$ and $\varphi'(0)$ differ only after desired significant digit. The last value η_∞ is taken as the finite value of the limit for the particular set of physical parameters for determining velocity, temperature and concentration, respectively, are

$f(\eta), \theta(\eta)$ and $\varphi(\eta)$ in the boundary layer. After getting all the initial conditions we solve this system of simultaneous equations using fourth order Runge-Kutta integration scheme. The effects of the flow parameters on the velocity, temperature and species concentration, are computed, discussed and have been graphically represented in figures and also the shearing stress and rate of heat transfer shown in table for various value of different parameters. Now defining new variables by the equations

$$y_1 = f, y_2 = f', y_3 = f'', y_4 = \theta, y_5 = \theta', y_6 = \varphi,$$
$$y_7 = \varphi'$$

The higher order differential Eq. (8), Eq. (9), Eq.(10) and boundary conditions (11) may be transformed to seven equivalent first order differential equations and boundary conditions are as follows:

$$dy_1 = y_2, dy_2 = y_3, dy_3 = -y_1 y_3 + y_1^2 + (M+N)y_2 +$$
$$A\left(y_2 + \frac{1}{2}y_3\right) - \frac{A\lambda}{2} - \lambda^2 - Gr\cos\alpha\, y_4 - Gm\cos\alpha\, y_6,$$
$$dy_4 = y_5, dy_5 = \frac{-\Pr y_1 y_5}{1 + R\Pr + \varepsilon y_4} + \frac{\Pr A\eta\, y_5}{2(1 + R\Pr + \varepsilon y_4)},$$
$$dy_6 = y_7, dy_7 = -Sc\, y_1 y_7 + \frac{1}{2}ScA\eta\, y_7 + \frac{S_0 \Pr y_1 y_5}{1 + R\Pr + \varepsilon y_4}$$
$$-\frac{S_0 \Pr A\eta\, y_5}{2(1 + R\Pr + \varepsilon y_4)}$$

And the boundary conditions are

$$y_1 = 0, y_2 = 1, y_4 = 1, y_6 = 1 \quad at\ \eta = 0$$
$$y_2 = \lambda, y_4 = 0, y_6 = 0 \quad as \quad \eta \to \infty$$

4. Results and discussion

Numerical calculation for distribution of the velocity, temperature and concentration profiles across the boundary layer for different values of the parameters are carried out. For the purpose of our simulation we have chosen $\lambda = 0.1$, $M = 1.0$, $N = 0.6$, $A = 1.0$, $Gr = -0.2$, $Gm = -0.2$, $Sc = 0.22$, $Pr = 1.0$, $S0 = 0.2$, $\varepsilon = 1.0$, $R = 0.5$ and $\alpha = 60^o$ while the parameters are varied over range as shown in the figures. Fig.1 clearly demonstrates that the primary velocity starts from maximum value at the surface and then decreasing until it reaches to the minimum value at the end of the boundary layer for all the values *M*. It is interesting to note that the effect of magnetic field is more prominent at the point of peak value, because the presence of *M* in an electrically conducting fluid introduces a force like Lorentz force which acts against the flow if the magnetic field is applied in the normal direction as in the present problem. As a result velocity profile is decreased. Similar effect is also observed in Fig.2 and Fig.4 with increasing values of *N* and *A* and reverse trend arise for λ is shown in Fig.3 but there is no effect of *R* and ε which are shown in Fig.5 and Fig.6. Fig.7 – Fig.12 show the temperature profile obtained by the numerical simulations for various values of entering parameters. The temperature is decreased for the increasing effect of *M* and *N* but opposite effect arises for the values of λ, *R* and ε. From Fig.10 it is observed that the thermal boundary layer is increased up to certain values of η and then decreased for increasing values of A whereas the reverse trend is observed for the increasing values of *A*, *R* and ε in concentration profiles which are shown in Fig.16-Fig.18. Also, Fig.13 - Fig.18 show the concentration profiles obtained by the numerical simulation for various values of entering non-dimensional parameters. From Fig.13, and Fig.14, it is observed that the concentration profile decreases for the effect of *M* and *N* but reverse effect arises for the increasing values of λ [Fig.15]. Further the numerical solutions for the skin friction [$f''(0)$] and local Nusselt number [$-\theta'(0)$] have been compared with those of Pop et al. [12], Mahapatra and Gupta [13] and Sharma and Singh [14] when $M = 0$, $Gr = 0$, $Gm = 0$, $N = 0$, $A = 0$, $\alpha = 0$ and consider the Prandtl number $Pr = 0.05$, $R = 0.2$, $K = 2.0$, $\varepsilon = 1.0$. These results are given in Table1 and it is observed that the agreement between the present results and those of Pop et al. [12], Mahapatra and Gupta [13] and Sharma and Singh [14] are familiar.

4. Conclusions

Following are the conclusions made from above analysis:

- The magnitude of velocity decreases with increasing magnetic parameter causing of Lorentz force and similar effect is observed for porosity and unsteadiness parameter but reverse trend arise for stretching parameter.

- The temperature and concentration boundary layer are decreased for the effect of magnetic and porosity parameter and increased for stretching parameter.

- For the effect of Radiation and perturbation parameter, the temperature is increased but concentration decreased up to a certain value of η and then increased.

- For the effect of unsteadiness parameter, the temperature is increased up to a certain value of η and then decreased but opposite result is observed in concentration.

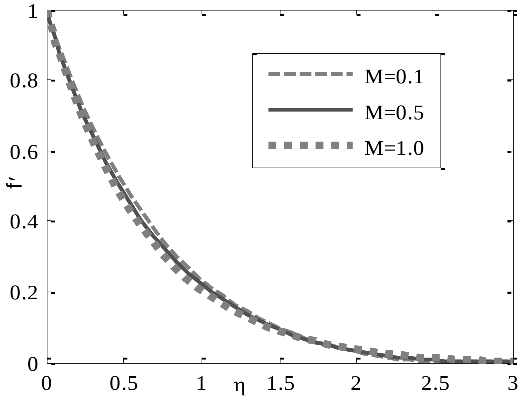

Fig.1 Velocity profile for various values of M

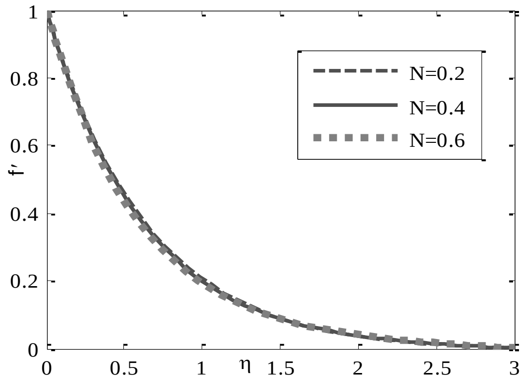

Fig.2 Velocity profile for various values of N

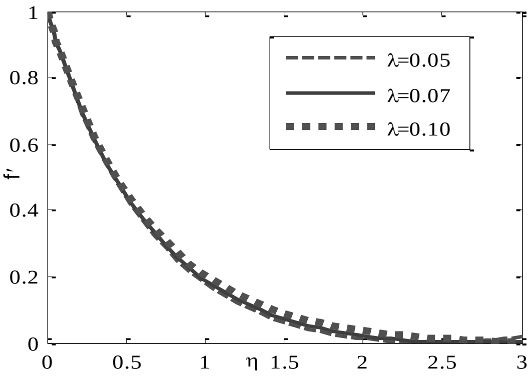

Fig.3 Velocity profile for various values of λ

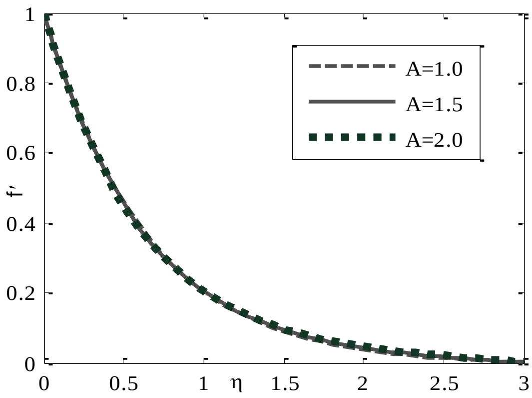

Fig.4 Velocity profile for various values of A

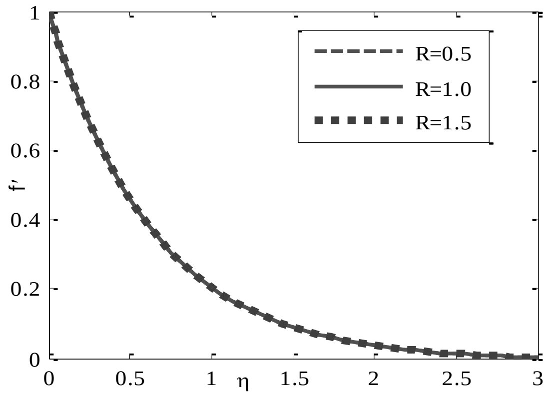

Fig.5 Velocity profile for various values of R

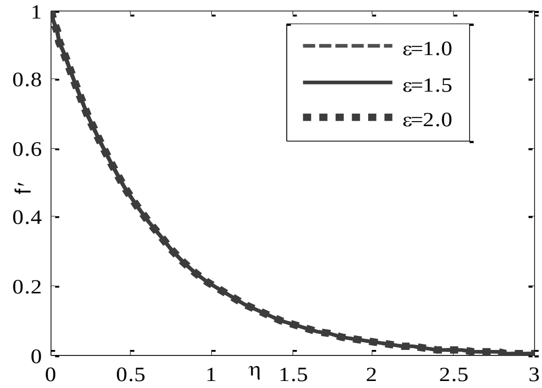

Fig.6 Velocity profile for various values of ε

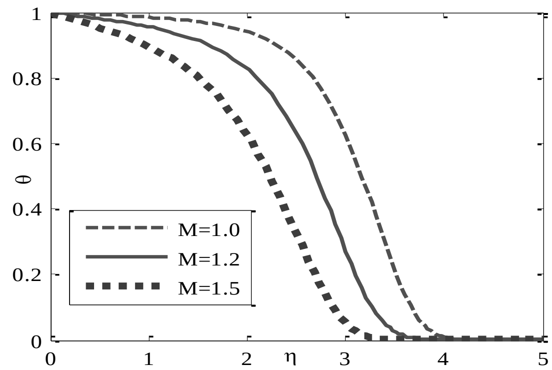

Fig.7 Temperature profile for various values of M

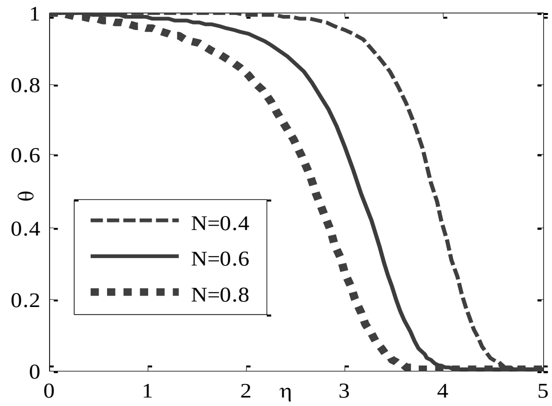

Fig.8 Temperature profile for various values of N

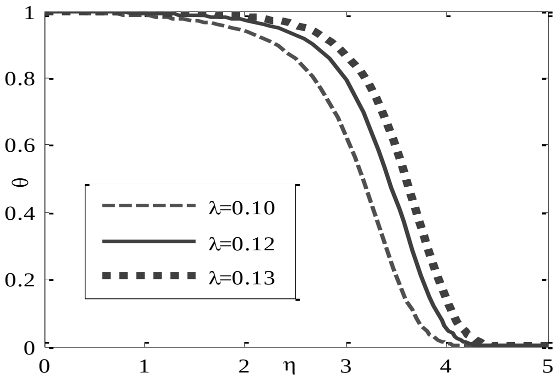

Fig.9 Temperature profile for various values of λ

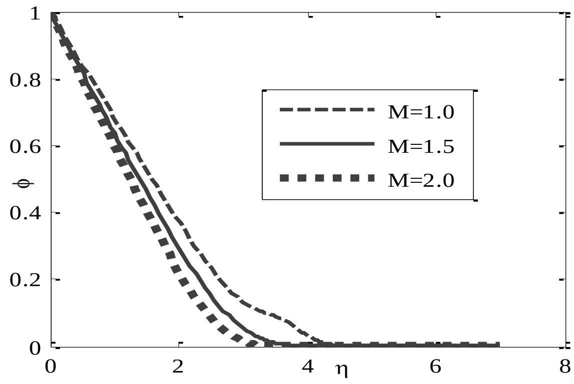

Fig.13 Concentration profile for various values of M

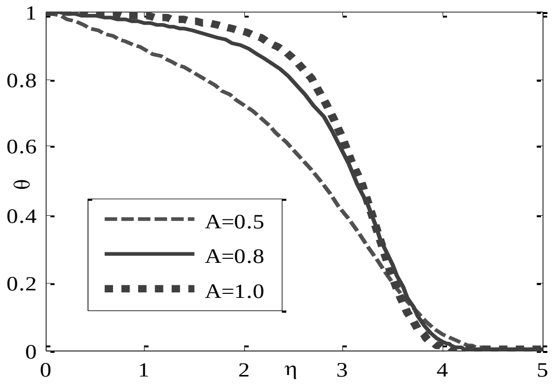

Fig.10 Temperature profile for various values of A

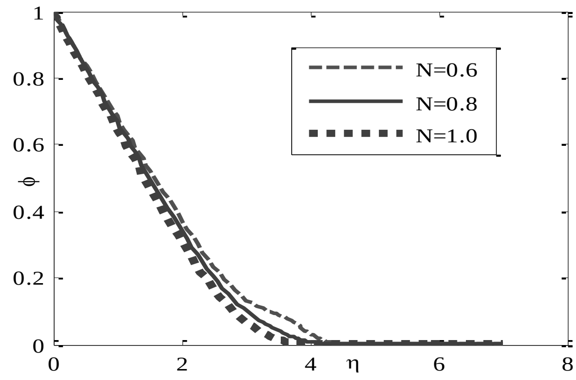

Fig.14 Concentration profile for various values of N

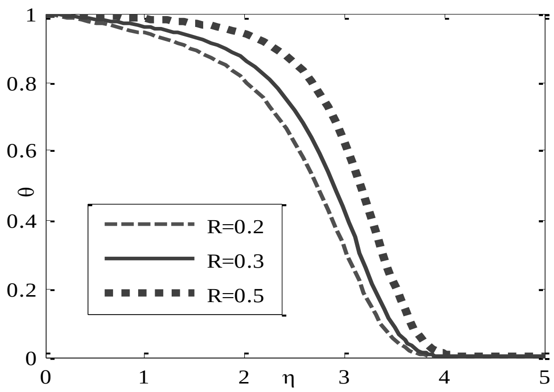

Fig.11 Temperature profile for various values of R

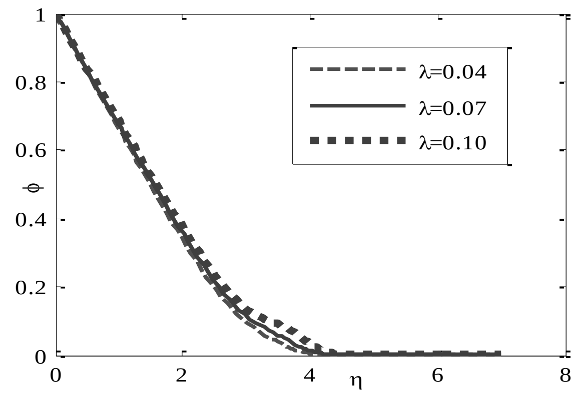

Fig.15 Concentration profile for various values of λ

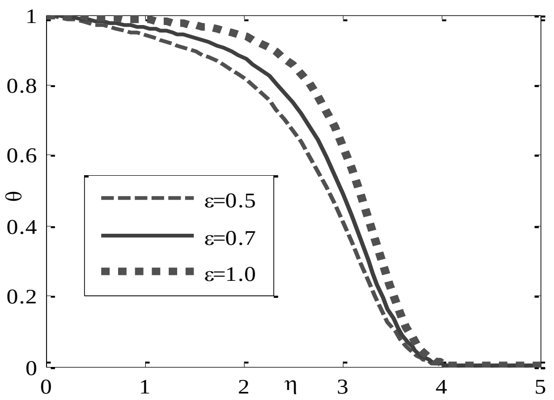

Fig.12 Temperature profile for various values of ε

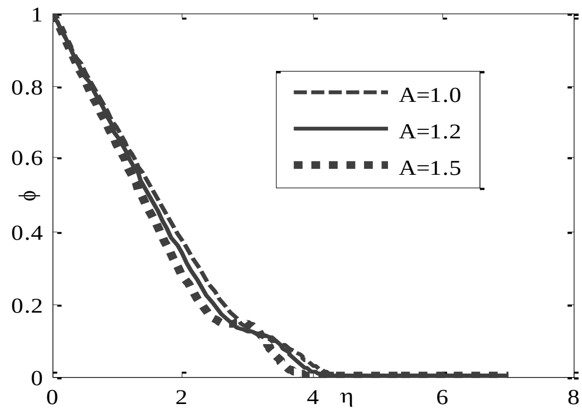

Fig.16 Concentration profile for various values of A

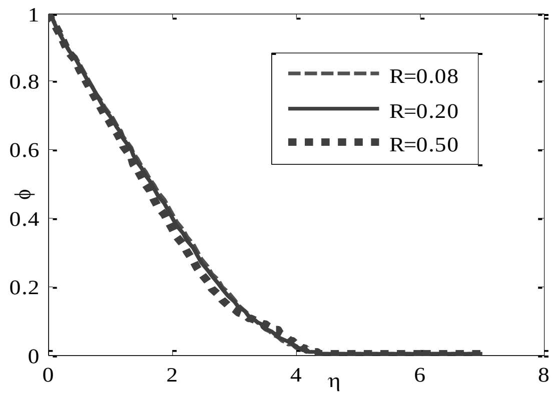

Fig.17 Concentration profile for various values of R

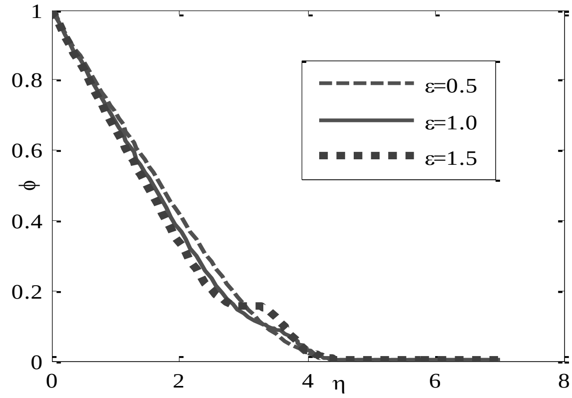

Fig.18 Concentration profile for various values of ε

Table 1 Comparison of the skin friction [$f''(0)$] and local Nusselt number [$-\theta(0)$]

λ	Pop et al.[12]		Mahapatra and Gupta[13]		Sharma and Singh [14]		Present results	
	$f''(0)$	$-\theta(0)$	$f''(0)$	$-\theta(0)$	$f''(0)$	$-\theta(0)$	$f''(0)$	$-\theta(0)$
0.1	-0.9694	0.081	-0.9694	0.081	-0.969386	0.081245	-0.97017	0.081005
0.2	-0.9181	-	-0.9181	-	-0.9181069	-	-0.91886	-
0.5	-0.6673	0.135	-0.6673	0.136	-0.667263	0.135571	-0.667909	0.135331
2.0	2.0174	0.241	2.0175	0.241	2.01749079	0.241025	2.00317	0.2410321

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