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EFFECT OF RADIATION ON AN UNSTEADY MHD MIXED CONVECTIVE FLOW PAST AN ACCELERATED VERTICAL POROUS PLATE WITH SUCTION AND CHEMICAL REACTION

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Abstract— **The paper deals with an unsteady mixed convective MHD flow of a viscous incompressible electrically conducting fluid past an accelerated infinite vertical porous flat plate with suction in presence of radiation and heat generation/absorption. The governing boundary layer equations have been transformed into a two-point boundary value problem in similarity variables and the resultant problem is solved numerically by a fourth order Runge-Kutta method along with shooting technique. The effects of various governing parameters on the velocity field, temperature field, concentration field, skin friction, Nusselt number and Sherwood number are computed and discussed in detailed.**

Index terms- **Radiation, unsteady, MHD, mixed convection, Chemical reaction, Porous plate and suction.**

I. INTRODUCTION

The concept of a boundary layer is one of the most important ideas in understanding transport processes. The essentials of the boundary-layer theory had been presented in 1904 by Prandtl in a paper that revolutionized fluid mechanics. Free convection is caused by the temperature difference of the fluid at different locations and forced convection is the flow of heat due to the cause of some external applied forces. The combination of free convection and forced convection is called as mixed convection. Mixed convection flows, has many important applications in the fields of science and engineering. The majority of treatments of this problem are limited to cases in which the flow is directed vertically upward (assisting flow), while the situation when the flow is directed downward (opposing flow). It appears that separation in mixed convection flow was first discussed by Merkin [1], who examined the effect of opposing buoyancy forces on the boundary layer flow on a semi-infinite vertical flat plate at uniform temperature in a uniform free stream. This problem was studied further by Wilks [2] and Hunt and Wilks [3], who also considered the case of uniform flow over a semi-infinite flat plate heated at a constant heat flux rate.

Chen and Mucoglu [4] have investigated the effects of mixed convection over a vertical slender cylinder due to the thermal diffusion with the prescribed wall temperature Ridha [5], Merkin and Mahmood [6] and Wilks and Bramley [7] have studied the mixed convection boundary layer flow over an impermeable vertical flat plate. In such cases, the mixed convection flows are characterized by the buoyancy parameter λ which depends on the flow configuration and the surface heating conditions, where $\lambda > 0$ for assisting flow and $\lambda < 0$ for opposing flow. When the buoyancy effects are negligible, i.e., when $\lambda = 0$, the problem corresponds to forced convection flow past a flat surface. Recently, HosseinTamim et al. [8] studied the mixed convection boundary-layer flow of a nanofluid near stagnation-point on a vertical plate with effects of buoyancy assisting and opposing flows.

Several investigators have studied different dimensions of the boundary-layer flow of electrically conducting fluid and heat transfer due to stretching sheet in the presence of a transverse magnetic field. Accordingly, Ishak [9] studied unsteady laminar magnetohydrodynamic flow and heat transfer due to continuously stretching plate immersed in an electrically conducting fluid. The result shows that the heat transfer rate at the surface increases with an increase in unsteadiness parameter *A* and Prandtl number Pr, but decreases with an increase in magnetic parameter *M* values. Furthermore, Ishak et al. [10] investigated the solution to the unsteady mixed convection boundary-layer flow and heat transfer due to a stretching vertical surface. They discussed the effects of unsteadiness parameter, buoyancy parameter and Prandtl number on the flow field and heat transfer characteristics. Further, they indicated that the heat transfer rate at the surface increases with an increase in unsteadiness parameter, buoyancy parameter and Prandtl number. Chandran et al. [11] studied the unsteady hydromagnetic free convection flow with heat flux and accelerated boundary motion. Choudhury and Das [12] investigated the magnetohydrodynamic boundary layer flow of a non-Newtonian fluid past a flat plate. Sharma and Pareek [13] have discussed the steady free convection MHD flow past a vertical porous moving surface. Das and Mitra [14] studied the unsteady mixed convective MHD flow and mass transfer past an accelerated infinite vertical porous plate with suction. Gangadhar and Bhaskar Reddy [15] has analyzed by chemically reacting MHD boundary layer flow of heat and mass transfer over a moving vertical plate in a porous medium with suction.

During its manufacturing process a stretched sheet interacts with the ambient fluid thermally and mechanically. Both the kinematics of stretching and the simultaneous heating or cooling during such processes has a decisive influence on the quality of the final products (Magyari& Keller [16]). Xu[17] studied the free convective heat transfer characteristics in an electrically conducting fluid near an isothermal sheet with internal heat generation or absorption. Khan [18] studied the effect of heat transfer on a viscoelastic fluid flow over a stretching sheet with heat source/sink, suction/blowing and radiation. Pal and Talukdar[19] studied the unsteady MHD heat and mass transfer along with heat source past a vertical permeable plate using a perturbation analysis, where the unsteadiness is caused by the time dependent surface temperature and concentration. Dash and Das [20] analyzed the effect of hall current on MHD flow along an accelerated porous flat plate with mass transfer and internal heat generation. Elbashbeshy and Aldawody [21] analyzed heat transfer over an unsteady stretching surface with variable heat flux in the presence of a heat source or sink. The numerical results reveal that the momentum boundary layer thickness decreases with an increase in unsteadiness parameter. However, an increase in the unsteadiness parameter increases the skin friction coefficient and the local Nusselt number. Their study indicated that an increase in the heat source or sink parameter leads to an increase in the surface temperature and thus a decrease in the local Nusselt number. Samad and Mohebujjaman [22] studied a steady state two dimensional MHD heat and mass transfer free convection flow along a vertical stretching sheet in the presence of a magnetic field with heat generation. They discussed the influences of buoyancy, heat source, Prandtl number and magnetic parameter on the velocity, temperature and concentration profile. Zheng et al. [23] analyzed unsteady boundary layer flow and heat transfer over a permeable surface with heat source or sink analytically using homotopy analysis method. Their result shows that both the velocity and thermal boundary layer thickness decreases as unsteadiness and heat source or sink parameter increases. Ali et al. [24] studied the Hall effects on steady MHD boundary layer flow and heat transfer due to stretching plate in the presence of heat source or sink. Recently, Ibrahim and Shanker [25] studied anunsteady MHD boundary-layer flow and heat transfer due to stretching sheet in the presence of heat source or sink by quasi-linearization technique.

Radiation plays a vital role when convection is relatively small and this cannot be neglected. Raptis[26] explained the effect of radiation in free convection flow, Irfan et.al.[27] analyzed the heat transfer by radiation in annulus. Thermophoresis is a phenomenon which causes small particles to be driven away from hot surface and towards a cold one. Small particles suspended in a gas with temperature gradient experiences a force in a direction opposite to the temperature gradient. It has an application in removing small particles from gas streams in determining the exhaust gas particle trajectories from combustion devices. It also been shown that thermal-diffusion is dominant in mass transfer mechanism in the modified chemical vapor deposition process used in the fabrication of optical fiber. Recently, Nagaradhika [28] studied the Non-Darcian convective heat and mass transfer through a porous medium in a vertical channel through radiation and thermo-diffusion effect.

The study reported herein considers an unsteady mixed convective MHD flow of a viscous incompressible electrically conducting fluid past an accelerated infinite vertical porous flat plate with suction in presence of radiation and heat generation/absorption. The governing boundary layer equations have been transformed into a two-point boundary value problem in similarity variables and the resultant problem is solved numerically by a fourth order Runge-Kutta method along with shooting technique. The flow phenomenon has been characterized with the help of flow parameters and the effects of these parameters on the velocity field, temperature field, and skin friction, Nusselt number and Sherwood number have been analyzed and the results are presented graphically and discussed quantitatively with the help of graphs and tables. This type of problem has some relevance in geophysical, astrophysical and cosmically studies.

II. MATHEMATICAL ANALYSIS

An unsteady mixed convective mass transfer flow of a viscous incompressible electrically conducting and radiating fluid past an accelerating vertical infinite porous flat plate in presence of a transverse magnetic field B_0 is considered. The induced magnetic field is neglected, which is justified for MHD flow at small magnetic Reynolds number. Let the x-axis be directed upward along the plate and the y-axis normal to the plate. Let u and v be the velocity components along x- and y-axes respectively. It is assumed that the plate is accelerating with a velocity $u = Ut$ in its own plane at time $t \geq 0$. The level of concentration of foreign mass is assumed to be low, so that the Soret and Dufour effects are negligible. Under these assumptions along with the Boussinesq and boundary layer approximations, the system of equations, which models the flow is given by.

Continuity equation

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

Momentum equation

$$\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial y} = \upsilon\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2}{\rho}u + g\beta(T - T_\infty) + g\beta^*(C - C_\infty) \tag{2}$$

Energy equation

$$\rho C_p\left(\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial y}\right)=k\frac{\partial^2 T}{\partial y^2}-\frac{\partial q_r}{\partial y}+q(T-T_\infty) \quad (3)$$

Species equation

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

The boundary conditions for the velocity, temperature and concentration fields are

$$u=Ut, T=T_w, C=C_w \text{ at } y=0$$
$$u\to 0, T\to T_\infty, C\to C_\infty \text{ as } y\to\infty \text{ for } t\to\infty \quad (5)$$

where, v is the kinematic viscosity, k is the thermal conductivity, $\beta$is the volumetric coefficient of expansion for heat transfer, β^* is the volumetric coefficient of expansion for mass transfer, $\rho$is the density, σ is the electrical conductivity of the fluid, q is the heat generation/absorption coefficient, g is the acceleration due to gravity, q_r is the radiative heat flux, T is the temperature, $T_\infty$is the temperature of the fluid far away from the plate, C is the concentration, $C_\infty$is the concentration of the fluid far away from the plate and D is the molecular diffusivity.

By using the Rosseland approximation, the radiative heat flux q_r is given by

$$q_r=-\frac{4\sigma^*}{3K'}\frac{\partial T^4}{\partial y} \quad (6)$$

where σ^* is the Stefan-Boltzmann constant and K' - the mean absorption coefficient. It should be noted that by using the Rosseland approximation, the present analysis is limited to optically thick fluids. If temperature differences within the flow are sufficiently small, then equation (6) can be linearized by expanding T^4 into the Taylor series about T_∞, which after neglecting higher order terms takes the form

$$T^4 \cong 4T_\infty{}^3 T-3T_\infty{}^4 \quad (7)$$

In view of the equations (6) and (7), the equation (3) reduces to

$$\rho C_p\left(\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial y}\right)=k\left(1+\frac{16\sigma^* T_\infty^3}{3kK'}\right)\frac{\partial^2 T}{\partial y^2}+q(T-T_\infty) \quad (8)$$

In order to transform equations (2), (8) and (4) into a set of ordinary differential equations, the following similarity transformations and dimensionless variables are introduced.

$$\eta=\frac{y}{2\sqrt{\upsilon t}}, u=Utf(\eta), Gr=4g\beta\frac{T_w-T_\infty}{U}, Gc=4g\beta^*\frac{C_w-C_\infty}{U}, \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty}$$
$$\phi(\eta)=\frac{C-C_\infty}{C_w-C_\infty}, M=\frac{\sigma B_0^2}{\rho}\frac{\upsilon}{v^2}, \Pr=\frac{\upsilon}{k}, q=\frac{Q}{t}, Sc=\frac{\upsilon}{D}, R=\frac{4\sigma^* T_\infty^3}{K'k} \quad (9)$$

where $f(\eta)$ is the dimensionless stream function, θ - the dimensionless temperature, ϕ - the dimensionless concentration, η - the similarity variable, M - the magnetic parameter, Pr- the Prandtl number, Sc - the Schmidt number and R- the radiation parameter.

Following Hasimoto [29], Das et al. [14] and Singh and Soundalgekar [30], we choose

$$v=-a\left(\frac{\upsilon}{t}\right)^{1/2} \quad (10)$$

where$a > 0$ is the suction parameter.

In view of equations (9) and (10), the equations (2), (4) and (8) transform into

$$f''+2(\eta+a)f'-4(1+a^2M)f+Gr\theta+Gc\phi=0 \quad (11)$$

$$\left(1+\frac{4}{3R}\right)\theta''+2(\eta+a)\Pr\theta'+\Pr Q\theta=0 \quad (12)$$

$$\phi''+2(\eta+a)Sc\phi'=0 \quad (13)$$

The transformed boundary conditions are

$$f=1, \theta=1, \phi=1 \text{ at } \eta=0$$
$$f=\theta=\phi=0. \text{ as } \eta\to\infty \quad (14)$$

The main physical quantities of interest are the skin friction coefficient, the local Nusselt number and the Sherwood number which represent the wall shear stress, the heat transfer rate and mass transfer rate at the surface, respectively.

The skin friction at the wall is given by

$$\tau=\rho\upsilon\left(\frac{\partial u}{\partial y}\right)_{y=0}=-\rho U\frac{\sqrt{\upsilon t}}{2}f'(0) \quad (15)$$

In non-dimensional form, we get

$$\tau'=-\frac{2\tau}{\rho U\sqrt{\upsilon t}}=-f'(0) \quad (16)$$

The non-dimensional local heat flux in terms of Nusselt number (Nu) at the plate is given by

$$Nu=\frac{2q_w\sqrt{\upsilon t}}{k(T_w-T_\infty)}=-\theta'(0) \quad (17)$$

The non-dimensional local Sherwood number (Sh) at the plate is given by

$$Sh=\frac{2\sqrt{\upsilon t}}{D(C_w-C_\infty)}=-\phi'(0) \quad (18)$$

III. METHOD OF SOLUTION

The set of coupled non-linear governing boundary layer equations (11) - (13) together with the boundary conditions (14) are solved numerically by using Runge-Kutta fourth order technique along with shooting method. First of all, higher order non-linear differential Equations (11) - (13) are converted into simultaneous linear differential equations of first order and they are further transformed into initial value problem by applying the shooting technique (Jain *et al*.[31]). The resultant initial value problem is solved by employing Runge-Kutta fourth order technique. The step size $\Delta\eta$ =0.05 is used to obtain the numerical solution with five decimal place accuracy as the criterion of convergence. From the process of numerical computation, the skin-friction coefficient, the Nusselt number and the Sherwood number, which are respectively proportional to $f'(0), -\theta'(0)$ and $-\phi'(0)$, are also sorted out and their numerical values are presented in a tabular form.

IV. RESULTS AND DISCUSSION

The problem of an unsteady mixed convective mass transfer MHD flow past an accelerated infinite vertical porous flat plate with suction, radiation and heat source/sink has been formulated. The effects of the flow parameters such as magnetic parameter (*M*), suction parameter (*a*), Grashof number for heat and mass transfer (*Gr*, *Gc*), Schmidt number (*Sc*), radiation parameter (*R*), heat source/sink parameter (Q) and Prandtl number (*Pr*) on the velocity, temperature and concentration profiles of the flow field are presented with the help of velocity profiles (Figs.1-5), temperature profiles (Figs.6-9) and concentration profiles (Figs.10, 11). The non-dimensional skin friction at the wall and Nusselt number and Sherwood number profiles (Figs. 12-14) are discussed in detailed. The detailed discussed are omitted here for brevity. Velocity of the flow field varies to an appreciable extent with the variation of the flow parameters. In Table 1, the present results are compared with those of Das and Mitra [14] who used finite difference method, and found a perfect agreement in the results.

V. CONCLUSIONS

The above study brings out the following inferences of physical interest on the velocity, temperature and the concentration as well as skin-friction, Nusselt number and concentration distribution of the flow field.

- Greater suction leads to a faster reduction in the velocity of the flow field.
- The magnetic parameter retards the velocity of the flow field at all points.
- The Grashof numbers for heat transfer and mass transfer have accelerating effect on the velocity of the flow field at all points.
- The radiation parameter leads to a faster reduction in the velocity of the flow field.
- At any point in the flow field, the cooling of the plate is faster as the suction parameter, radiation parameter and Prandtl number become larger. Thus greater suction/ radiation/ Prandtl number leads to faster cooling of the plate.
- The heat source/sink enhances the temperature field.
- Heavier diffusing species has a significant decrease in the concentration boundary layer of the flow field. The Schmidt number and the suction parameter have a retarding effect on the concentration distribution of the flow field.
- The effect of suction parameter is to enhance the skin friction, Nusselt number and Sherwood number at the wall.

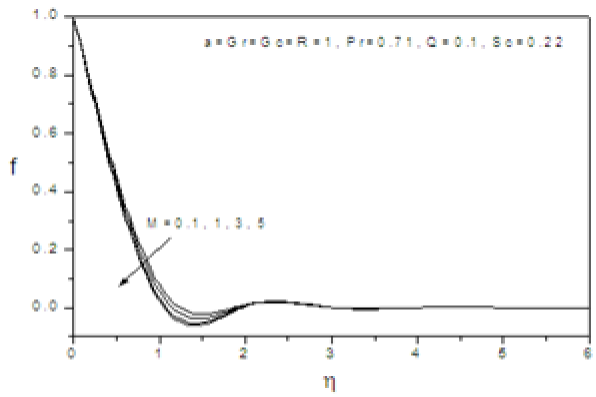


Fig.1 Velocity for different values of *M*

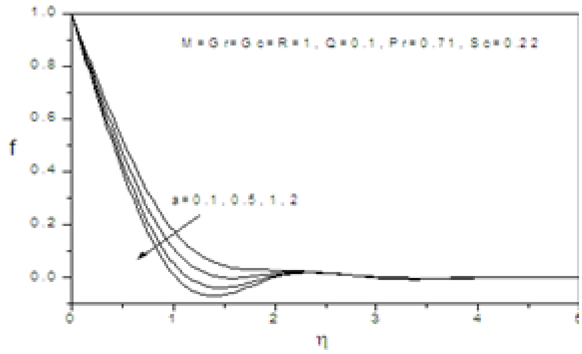


Fig.2 Velocity for different values of *a*

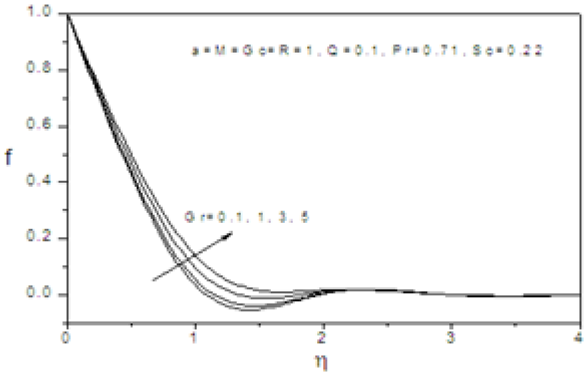


Fig.3 Temperature for different values of *Gr*

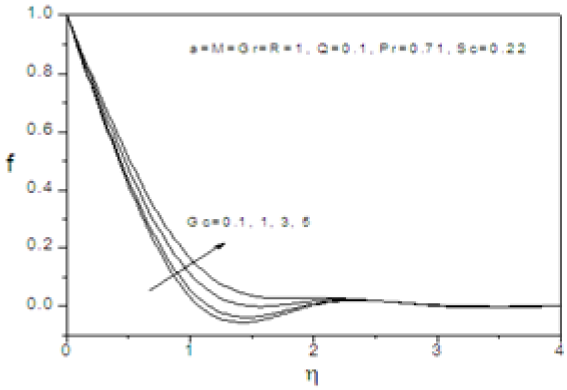


Fig.4 Temperature for different values of *Gc*

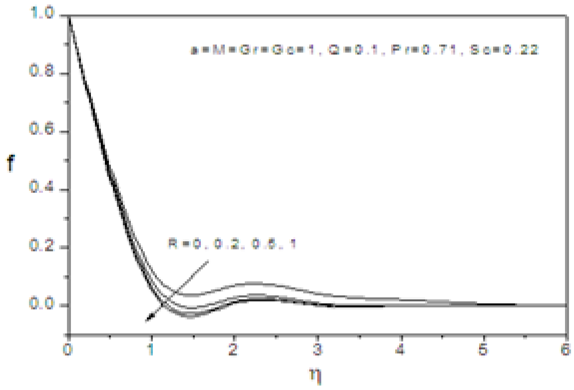


Fig.5 Velocity for different values of *R*

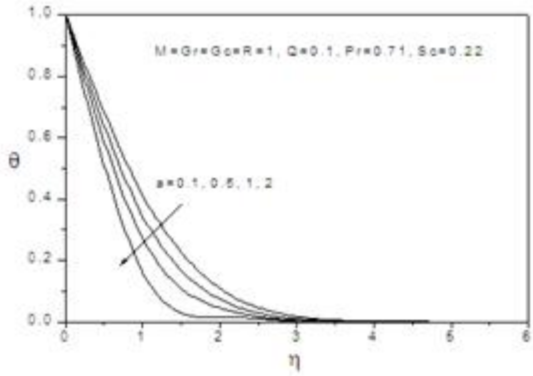
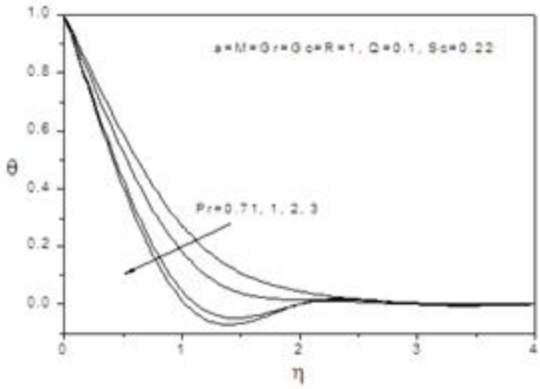


Fig.6 Temperature for different values of *a*



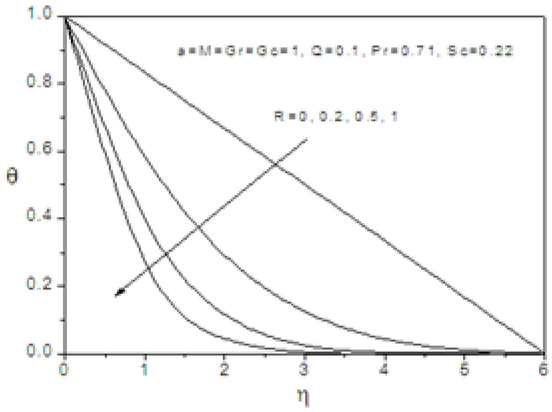


Fig.8 Temperature for different values of *R*

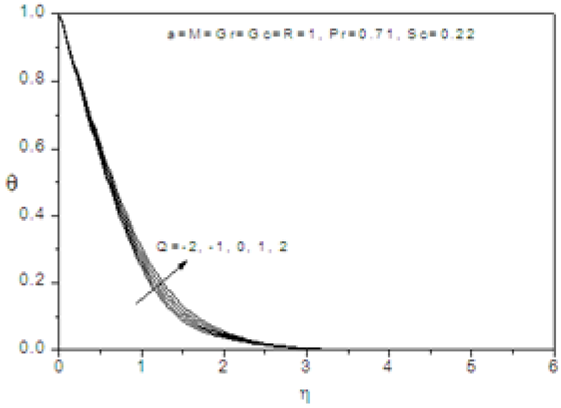


Fig.9 Temperature for different values of *Q*

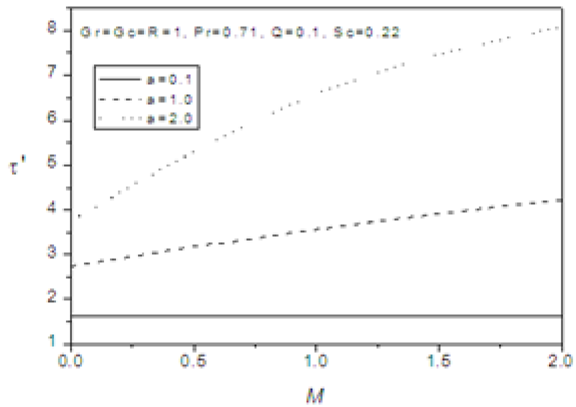


Fig.12 Variation of the skin friction for different *a* with *M*

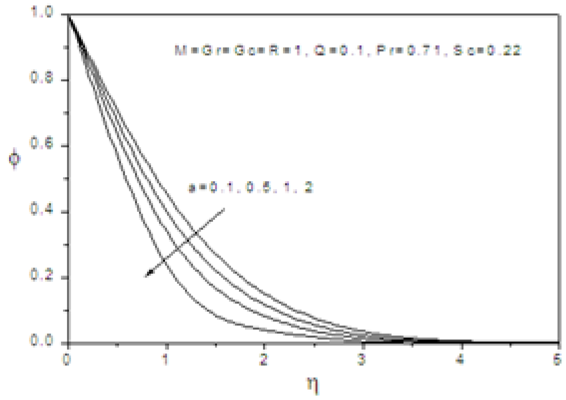


Fig.10 Concentration for different values of *a*

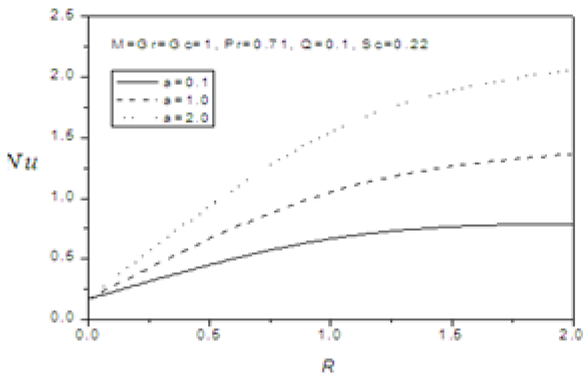


Fig.13 Variation of the Nusselt number for different *a* with *R*

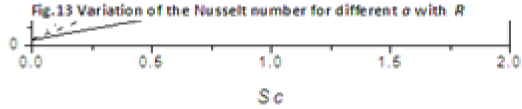


Fig.14 Variation of the Sherwood number for different *a* with *Sc*

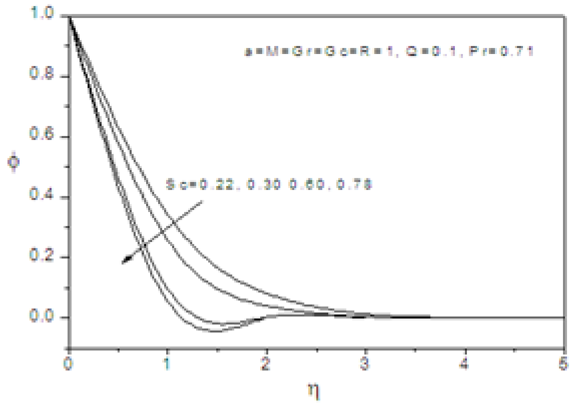


Fig.11 Concentration for different values of *Sc*

Table 1: Numerical values of Nu at the sheet for different values of *a* when *Pr=0.71*, *Gr=Gc=1*, *R=Sc=0.*Comparison of present results with thosethat of Das and Mitra [14].

a	Das and Mitra [14]	Present results
0.1	1.04299514	1.04300
1	2.00275564	2.00276
2	3.23732738	3.23733

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