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COMBINED HEAT AND MASS TRANSFER IN MHD FREE CONVECTION FROM A WEDGE WITH OHMIC HEATING AND VISCOUS DISSIPATION IN THE PRESENCE OF SUCTION OR INJECTION*

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Abstract – The problem of combined heat and mass transfer of an electrically conducting fluid in MHD natural convection adjacent to a vertical surface is analyzed, taking into account the effects of Ohmic heating in the presence of suction or injection. An approximate numerical solution for the steady laminar boundary-layer flow over a wall of the wedge in the presence of species concentration and mass diffusion has been obtained by solving the governing equations using the numerical technique. The fluid is assumed to be viscous and incompressible. Numerical calculations are carried out for different values of dimensionless parameters and an analysis of the results obtained shows that the flow field is influenced appreciably by the magnetic effect, the buoyancy ratio between species and thermal diffusion and suction/injection at the wall surface. Effects of these major parameters on transport behaviors are investigated methodically and typical results are illustrated to reveal the tendency of the solutions. Representative results are presented for the velocity, temperature, and concentration distributions, as well as the local skin-friction coefficient and skin friction.

Keywords – Buoyancy ratio, Ohmic heating, Boussinesq fluid, MHD boundary layer flow and suction/injection at the wall of the wedge

1. INTRODUCTION

Simultaneous heat and mass transfer from different geometrics embedded in porous media has many engineering and geophysical applications such as geothermal reservoirs, drying of porous solids, thermal insulation, enhanced oil recovery, packed-bed catalytic reactors, cooling of nuclear reactors, and under ground energy transport. A very significant area of research in radiative heat transfer at present is the numerical simulation of combined radiation and convection/conduction transport processes. The effort has arisen largely due to the need to optimize industrial systems such as furnaces, ovens and boilers, and the interest in our environment and in no conventional energy sources such as the use of salt-gradient solar ponds for energy collection and storage. In particular, natural convection induced by the simultaneous action of buoyancy forces resulting from thermal and mass diffusion is of considerable interest in nature and in many industrial applications such as geophysics, oceanography, drying processes, solidification of binary alloy and chemical engineering. Frequently the transformations proceed in a moving fluid, a situation encountered in a number of technological fields. In previous investigations, Chambre and Acrivos [1], analyzed catalytic surface reactions in hydrodynamic flows. The paper was concerned with its counterpart, namely, an investigation of a certain special class of homogeneous volume reactions in flow

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systems. Chambre et al. [2] had studied the diffusion of a chemically reactive species in a laminar boundary layer flow. Acrivos [3] analyzed the laminar forced convection mass transfer with homogeneous chemical reaction. A unified boundary layer analysis was applied to the problem of a steady state mass transfer of a chemical species, diffusing from a surface and reacting isothermally in a linear fluid stream.

In these types of problems, the well-known Falkner-Skan transformation is used to reduce boundary-layer equations into ordinary differential equations for similar flows. It can also be used for non-similar flows for convenience in numerical work because it reduces, even if it does not eliminate, dependence on the x-coordinate. The solutions of the Falkner-Skan equations are sometimes referred to as wedge-flow solutions with only two of the wedge flows being common in practice. The dimensionless parameter, β_1 plays an important role in such types of problems because it denotes the shape factor of the velocity profiles. It has been shown [4] that when $\beta_1 < 0$ (increasing pressure), the velocity profiles have a point of inflexion, whereas when $\beta_1 > 0$ (decreasing pressure), there is no point of inflexion. This fact is of great importance in the analysis of the stability of laminar flows with a pressure gradient.

Yih [5] presented an analysis of the forced convection boundary layer flow over a wedge with uniform suction/blowing, whereas Watanabe [6] investigated the behavior of the boundary layer over a wedge with suction or injection in forced flow. Recently, MHD laminar boundary layer flow over a wedge with suction or injection had been discussed by Kafoussias and Nanousis [7], and Kumari [8] discussed the effect of large blowing rates on the steady laminar incompressible electrically conducting fluid over an infinite wedge with a magnetic field applied parallel to the wedge. Anjali Devi and Kandasamy [9] have studied the effects of heat and mass transfer on nonlinear boundary layer flow over a wedge with suction or injection. The effect of an induced magnetic field is included in the analysis. Chamkha and Khaled [10] investigated the problem of coupled heat and mass transfer by MHD free convection from an inclined plate in the presence of internal heat generation or absorption. For the problem of coupled heat and mass transfer in MHD free convection, the effects of viscous dissipation and Ohmic heating with a chemical reaction are not studied in the above investigation. However, it is more realistic to include these effects to explore the impact of the magnetic field on the thermal transport in the buoyancy layer. With this awareness, the effect of Ohmic heating on the MHD free convection heat transfer has been examined for a Newtonian fluid [11] and for a micro polar fluid [12]. Kuo Bor-Lih [13] studied the effect of heat transfer analysis for the Fakner-Skan wedge flow by the differential transformation method. Cheng and Lin [14] analyzed the non-similarity solution and correlation of transient heat transfer in laminar boundary layer flow over a wedge. Pantokratoras [15] discussed the Falkner–Skan flow with a constant wall temperature and variable viscosity. These effects on combined heat and mass transfer in MHD free convection flow past a wedge in the presence of suction or injection have not yet been studied. This study is therefore initiated to investigate the problem of MHD natural convection flow over a wedge, taking into consideration the effects of viscous dissipation and Ohmic heating.

Since no attempt has been made to analyze the combined heat and mass transfer in MHD free convection from a wedge with Ohmic heating and viscous dissipation in the presence of suction or injection, we have investigated it in this article. The similarity transformation has been utilized to convert the governing partial differential equations into ordinary differential equations and then the numerical solution of the problem is drawn using the Runge Kutta Gill method, [16]. Numerical calculations up to the third level of truncation were carried out for different values of dimensionless parameters of the problem under consideration for the purpose of illustrating the results graphically. Examination of such flow models reveals the influence of the chemical reaction, Ohmic heating and buoyancy ratio on velocity, temperature and concentration profiles. The analysis of the results obtained shows that the flow field is influenced appreciably by the presence of the magnetic effect and buoyancy ratio in the presence of suction or injection at the wall of the wedge.

2. MATHEMATICAL ANALYSIS

Two dimensional MHD laminar boundary layer flow of an incompressible, viscous, electrically conducting double diffusive and Boussinesq fluid over a wall of the wedge with suction or injection is considered. X-axis is taken parallel to the wedge and y-axis is taken normal to it as cited in Fig. 1. A uniform transverse magnetic field of strength B_O is applied parallel to the y-axis. The fluid properties are assumed to be constant in a limited temperature range. The Soret and Dufour effects are neglected as the concentration of diffusing species is very small in comparison to other chemical species and the concentration of species far from the wall, C_∞, is infinitesimally small [17]. The physical properties μ,D and α are constant throughout the fluid. In writing the following equations, the governing boundary layer equations of momentum, energy and diffusion for the flow under Boussinesq's approximation, [13] and [14], are

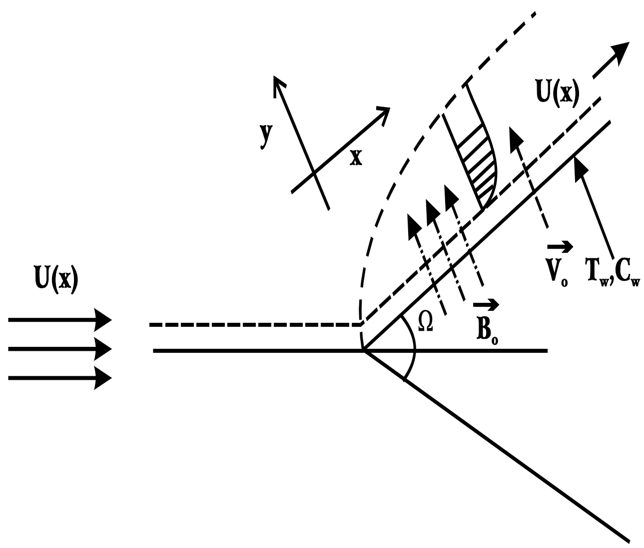

Fig. 1. Flow analysis along the wall of the wedge

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}+U\frac{dU}{dx}-\frac{\sigma B_0{}^2}{\rho}(u-U)+g\beta(T-T_\infty)+g\beta^*(C-C\infty) \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{\mu}{\rho c_p}[\frac{\partial u}{\partial y}]^2+\frac{\sigma B_0{}^2}{\rho c_p}u^2 \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial u}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-k_1 C \tag{4}$$

where

u ,v-Velocity components in x and y direction

U-Flow velocity of the fluid away from the wedge

g-Acceleration due to gravity

β-Coefficient of volume expansion

T-Temperature of the fluid

T_w-Temperature of the wall

T_∞-Temperature of the fluid far away from the wall
β*-Coefficient of expansion with concentration
C-Species concentration of the fluid
C_∞-Species concentration of the fluid away from the wall
ρ-Density of the fluid
σ-Electric conductivity of the fluid
α-Thermal diffusivity.
The boundary conditions are,

$$u = 0,\ v = v_0,\ C = C_w, T = T_w \text{ at } y = 0 \tag{5}$$

$$u = U(x),\ C = C_\infty,\ T = T_\infty \text{ as } y \to \infty \tag{6}$$

Following the lines of Bansal [18], the following change of variables are introduced

$$\psi(x,y)=\sqrt{\frac{2U\nu x}{1+m}}\, f(x,\eta) \tag{7}$$

$$\eta(x,y)= y\sqrt{\frac{(1+m)U}{2\nu x}} \tag{8}$$

Under this consideration, the potential flow velocity can be written as

$$U(x)=\sqrt{g\beta x(T-T_\infty)}\ ,\ \beta_1 = \frac{2m}{1+m} \tag{9}$$

where c is a constant and β_1 is the Hartree pressure gradient parameter that corresponds to $\beta_1 = \frac{\Omega}{\pi}$ for a total angle Ω of the wedge.
The velocity components are given by

$$u = \frac{\partial \psi}{\partial y} \text{ and } v = -\frac{\partial \psi}{\partial x} \tag{10}$$

It can be easily verified that the continuity equation (1) is identically satisfied and introduce the non-dimensional form, [14] of temperature and the concentration as

$$\theta= \frac{T-T\infty}{T_w - T_\infty} \tag{11}$$

$$\phi= \frac{C-C_\infty}{C_w - C_\infty} \tag{12}$$

$$Gr_1= \frac{\nu g\beta(T-T_\infty)}{U^3} \text{ (Grashof number)} \tag{13}$$

$$Gc_1= \frac{\nu g\beta^*(T-T_\infty)}{U^3} \text{(Modified Grashof number)} \tag{14}$$

$$N= \frac{\beta^*(C_w - C_\infty)}{\beta(T_w - T_\infty)} \text{(Buoyancy ratio)} \tag{15}$$

$$Pr= \frac{\mu\, c_p}{K} \text{ (Prandtl number)} \tag{16}$$

$$Sc=\frac{\nu}{D} \text{ (Schmidt number)} \tag{17}$$

$$Ec=\frac{c^2}{c_p(T-T_\infty)(K^2)^{\frac{2m}{1+m}}} \text{ (Eckert number)} \tag{18}$$

$$M^2=\frac{\sigma B_0{}^2}{\rho\, c\, k^2} \text{ (magnetic parameter)} \tag{10}$$

$$S=-v_0\sqrt{\frac{(1+m)x}{2\nu U}} \text{ (suction or injection parameter)} \tag{20}$$

Now the equations (2) to (4)

$$\frac{\partial^3 f}{\partial\eta^3}=-f\frac{\partial^2 f}{\partial\eta^2}-\frac{2m}{1+m}(1-(\frac{\partial f}{\partial\eta})^2-\frac{2}{1+m}\frac{N\phi+\theta}{1+N}\sin\frac{\Omega}{2}+\frac{2x}{1+m}(\frac{\partial f}{\partial\eta}\frac{\partial^2 f}{\partial x\partial\eta}-\frac{\partial f}{\partial x}\frac{\partial^2 f}{\partial\eta^2}) + \frac{\sigma B_0{}^2}{\rho U}(\frac{\partial f}{\partial\eta}-1) \tag{21}$$

$$\frac{\partial^2\theta}{\partial\eta^2}=-\Pr\frac{\partial\theta}{\partial\eta}+\frac{2\Pr}{1+m}\theta\frac{\partial f}{\partial\eta}+\Pr\frac{2x}{1+m}(\frac{\partial f}{\partial\eta}\frac{\partial\theta}{\partial x}-\frac{\partial f}{\partial x}\frac{\partial\theta}{\partial\eta})-\Pr Ec(\frac{\partial^2 f}{\partial\eta^2})^2 - \frac{\sigma B_0{}^2}{\rho U}\frac{U^2}{c_p(T-T_\infty)(\frac{\partial f}{\partial\eta})^2} \tag{22}$$

$$\frac{\partial^2\phi}{\partial\eta^2}=-Sc\, f\frac{\partial\phi}{\partial\eta}+\frac{2\,Sc\,x}{1+m}\gamma\,\phi+\frac{2\,Sc}{1+m}\phi\frac{\partial f}{\partial\eta}+\frac{2xSc}{1+m}(\frac{\partial f}{\partial\eta}\frac{\partial\phi}{\partial x}-\frac{\partial f}{\partial x}\frac{\partial\phi}{\partial\eta}) \tag{23}$$

The boundary conditions can be written as

$$\eta=0:\ \frac{\partial f}{\partial\eta}=0,\ \frac{f}{2}(1+\frac{x}{U}\frac{dU}{dx})+x\frac{\partial f}{\partial x}=-v_0\sqrt{\frac{(1+m)x}{2\nu U}},\ \theta=1,\ \phi=1$$

$$\eta\to\infty:\ \frac{\partial f}{\partial\eta}=1,\ \theta=0,\ \phi=0 \tag{24}$$

where v_0 is the velocity of suction if $v_0 < 0$ and injection if $v_0 > 0$ and $Gr=Gr_1+Gc_1$
The equations (21) to (23) and boundary conditions (24) can be written a

$$\frac{\partial^3 f}{\partial\eta^3}+(f+\frac{1-m}{1+m}\xi\frac{\partial f}{\partial\xi})\frac{\partial^2 f}{\partial\eta^2}-\frac{1-m}{1+m}\xi\frac{\partial^2 f}{\partial\xi\,\partial\eta}\frac{\partial f}{\partial\eta}-\frac{2}{1+m}M^2\xi^2(\frac{\partial f}{\partial\eta}-1) +\frac{2m}{1+m}(1-(\frac{\partial f}{\partial\eta})^2+\frac{2}{1+m}\frac{N\phi+\theta}{1+N}\sin\frac{\Omega}{2}=0 \tag{25}$$

$$\frac{\partial^2\theta}{\partial\eta^2}+\Pr(f+\frac{1-m}{1+m}\xi\frac{\partial f}{\partial\xi})\frac{\partial\theta}{\partial\eta}+\Pr Ec(\frac{\partial^2 f}{\partial\eta^2})^2+\Pr\frac{2}{1+m}M^2 Ec\,\xi^{\frac{2(1+m)}{1-m}}(\frac{\partial f}{\partial\eta})^2 -\frac{2\Pr}{1+m}\theta\frac{\partial f}{\partial\eta}-\frac{1-m}{1+m}\xi\frac{\partial\theta}{\partial\xi}\frac{\partial f}{\partial\eta}=0 \tag{26}$$

$$\frac{\partial^2\phi}{\partial\eta^2}+Sc\ f\ \frac{\partial\phi}{\partial\eta}-\frac{2Sc}{1+m}\xi^2\gamma\ \phi+Sc\frac{1+m}{1-m}(\frac{\partial\phi}{\partial\eta}\xi\frac{\partial f}{\partial\xi}-\frac{\partial f}{\partial\eta}\xi\frac{\partial\phi}{\partial\xi})-\frac{2Sc}{1+m}\phi\frac{\partial f}{\partial\eta}=0 \qquad (27)$$

$$\eta=0:\ \frac{\partial f}{\partial\eta}=0,\frac{(1+m)f}{2}+\frac{1-m}{2}\xi\frac{\partial f}{\partial\xi}=S,\theta=1,\phi=1$$

$$\eta\ \rightarrow\ \infty:\ \frac{\partial f}{\partial\eta}=1,\theta=0,\phi=0 \qquad (28)$$

where S is the suction parameter if S > 0 and injection if S<0 and $\xi = k\,x^{\frac{1-m}{2}}$ [7] is the dimensionless distance along the wedge ($\xi > 0$).

In this system of equations f (ξ,η) is the dimensionless stream function; $\theta(\xi,\eta)$ the dimensionless temperature; $\phi(\xi,\eta)$ the dimensionless concentration; Pr, the Prandtl number, Re_x, Reynolds number etc. which are defined in (10) to (20). The parameter ξ indicates the dimensionless distance along the wedge ($\xi > 0$). It is obvious that to retain the ξ–derivative terms, it is necessary to employ a numerical scheme suitable for partial differential equations for the solution. In addition, owing to the coupling between the adjacent stream wise location through the ξ–derivatives, a locally autonomous solution at any given stream wise location cannot be obtained. In such a case, an implicit marching numerical solution scheme is usually applied proceeding the solution in the ξ–direction, i.e., calculating unknown profiles at $\xi_{\iota+1}$ when the same profiles at ξ_ι are known. The process starts at $\xi = 0$ and the solution proceeds from ξ_ι to $\xi_{\iota+1}$, however, such a procedure is time consuming

Yet, when the terms involving $\frac{\partial f}{\partial\xi},\frac{\partial\theta}{\partial\xi}\ and\ \frac{\partial\phi}{\partial\xi}$ and their η derivatives are deleted, the resulting system of equations resembles, in effect, a system of ordinary differential equations for the functions f, θ and ϕ with ξ as a parameter and the computational task is simplified. Furthermore, a locally autonomous solution for any given ξ can be obtained because the stream wise coupling is severed. So, following the lines of [9], R. K. Gill [16] and the Shooting numerical solution scheme are utilized for obtaining the solution of the problem. Now, due to the above mentioned factors, the equations (25) to (27) are changed to

$$f'''+f\ f''+\frac{2m}{1+m}(1-f'^2)+\frac{2}{1+m}\frac{N\phi+\theta}{1+N}\sin\frac{\Omega}{2}-\frac{2}{1+m}M^2\xi^2(f'-1)=0 \qquad (29)$$

$$\theta''+\Pr\ f\theta'-\frac{2\Pr}{1+m}f'\theta+\Pr\ Ec\ f''^2+\frac{2\Pr}{1+m}M^2Ec\xi^{\frac{2(1+m)}{1-m}}f'^2=0 \qquad (30)$$

$$\phi''+Sc\ f\ \phi'-\frac{2Sc}{1+m}f'\phi-\frac{2\ Sc}{1+m}\xi^2\gamma\ \phi=0 \qquad (31)$$

with boundary conditions

$$\eta=0:\ f(0)=\frac{2}{1+m}S,\ f'(0)=0,\theta(0)=1,\phi(0)=1$$

$$\eta\ \rightarrow\ \infty:\ f'(\infty)=1,\theta(\infty)=0,\phi(\infty)=0 \qquad (32)$$

Equations (29) to (31) with boundary conditions (32) are integrated using the R. K. Gill method, [16]. The effects of chemical reaction, and heat and mass transfer are studied for different values of suction/injection at the wall of the wedge and the strength of the applied magnetic field. In the following section, the results are discussed in detail.

3. RESULTS AND DISCUSSION

In order to obtain a better insight of the physical problem, numerical results are displayed with the help of graphical illustrations.

In the absence of mass transfer and chemical reaction, the results could have been compared with that of the previous work of Kafoussias and Nanousis [7], if their equations were correct. It is found that the term $+(\sigma Bo^2 / \rho)\ U$ was missing in their equation of motion and hence an exact comparison is not possible. However the trends of the velocity profiles and temperature distributions are similar in the absence of mass transfer and chemical reaction.

Figure 2 represents the dimensionless velocity profiles for different values of suction parameter (S>0). In the presence of a uniform magnetic field, it is clear that the velocity increases and the dimensionless temperature $\theta(\eta)$ and concentration $\phi(\eta)$ of the fluid decrease with the increase of suction and these are shown in Figs. 2, 3 and 4 respectively.

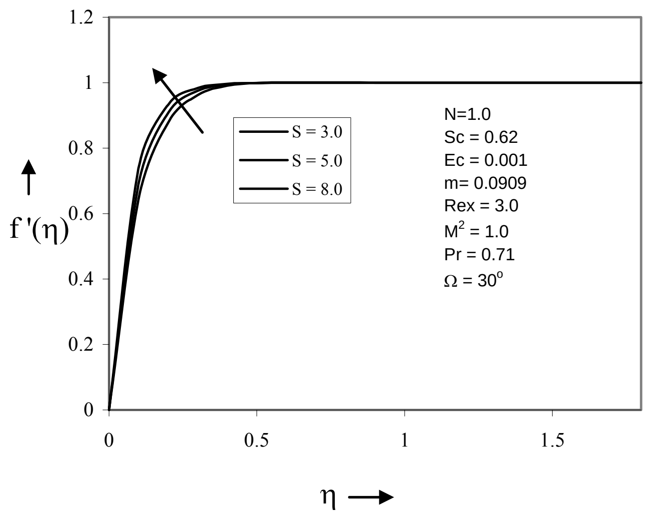

Fig. 2. Effects of suction over the velocity profiles

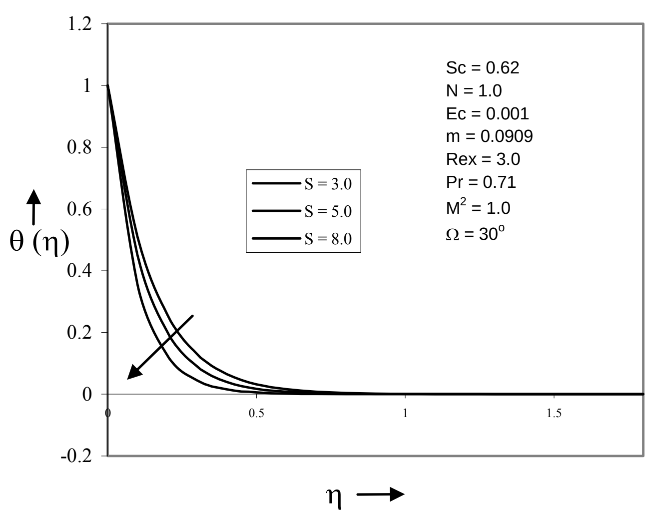

Fig. 3. Effects of suction over the temperature profiles

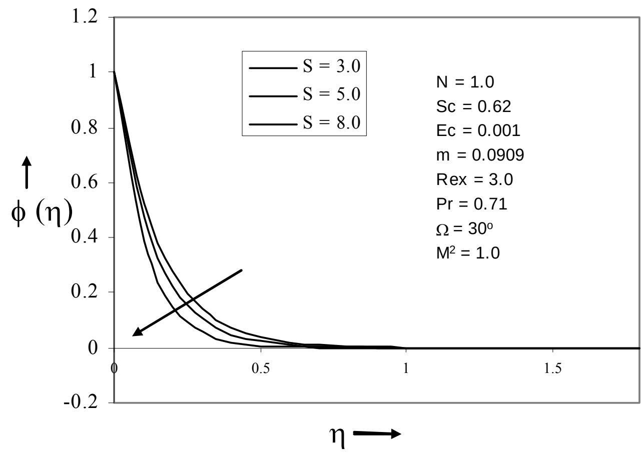

Fig. 4. Influence of suction over the concentration profiles

The dimensionless velocity profiles for different values of the strength of the magnetic field are plotted in Fig. 5. In the case of uniform suction, it is clear that the velocity and the temperature of the fluid increase and the concentration of the fluid decreases with the increase of strength of the applied magnetic field and these are displayed through Figs. 5, 6 and 7 respectively.

Figure 8 represents the dimensionless velocity profiles for different buoyancy ratios. Due to the uniform magnetic field and suction, it is clear that the velocity of the fluid is uniform, but slightly decreases with the increase in buoyancy ratio.

Figure 9 demonstrates the dimensionless temperature profiles for different values of the buoyancy ratio. In the presence of a uniform magnetic field with uniform suction, it is seen that the temperature of the fluid decreases with increase in buoyancy ratio.

The concentration of the fluid increases with an increase in the buoyancy ratio and this is shown through Fig. 10.

Figure 11 represents the dimensionless velocity profiles for different values of injection parameter ($S<0$). In the presence of a uniform magnetic field, it is clear that the velocity and the dimensionless temperature $\theta(\eta)$ of the fluid increase with an increase in injection and these are shown in the Figs. 11 and 12 respectively.

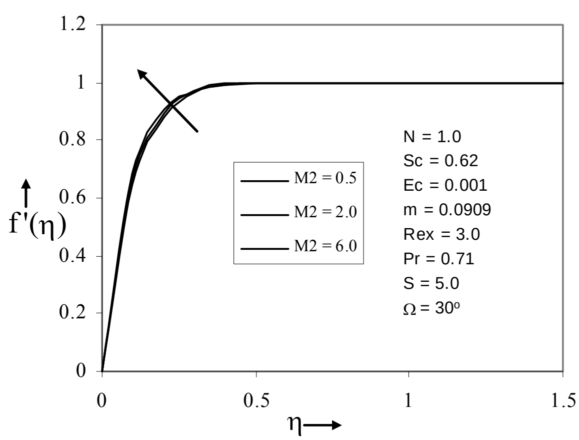

Fig. 5. Influence of magnetic field over the velocity profiles

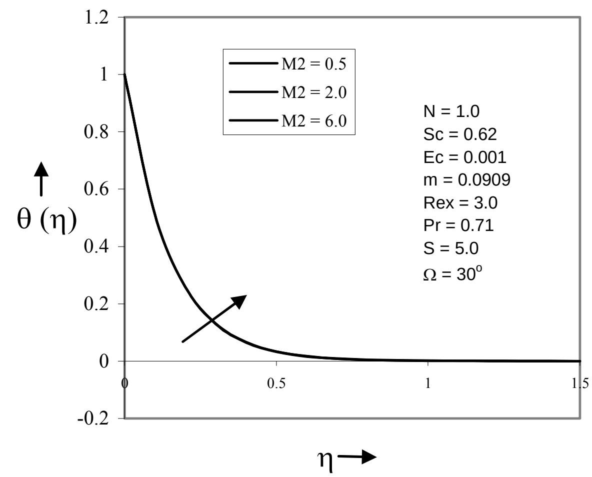

Fig. 6. Effects of magnetic field over the temperature profiles

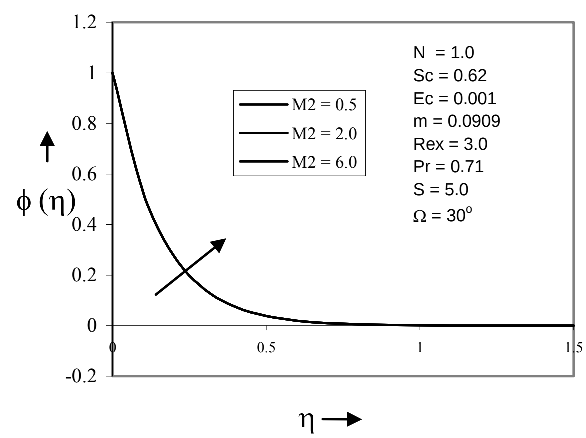

Fig. 7. Effects of magnetic field over the concentration profiles

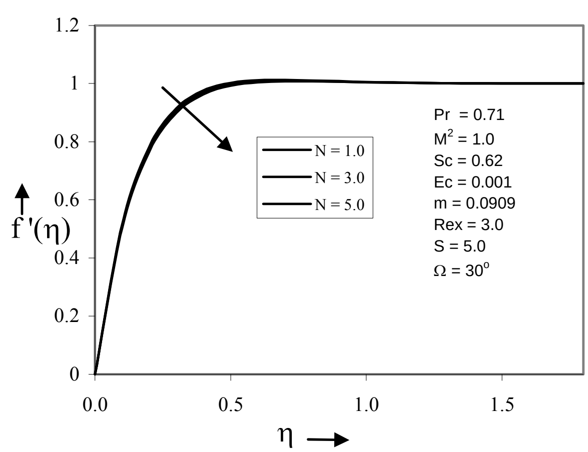

Fig. 8. Influence of buoyancy ratio over the velocity profiles

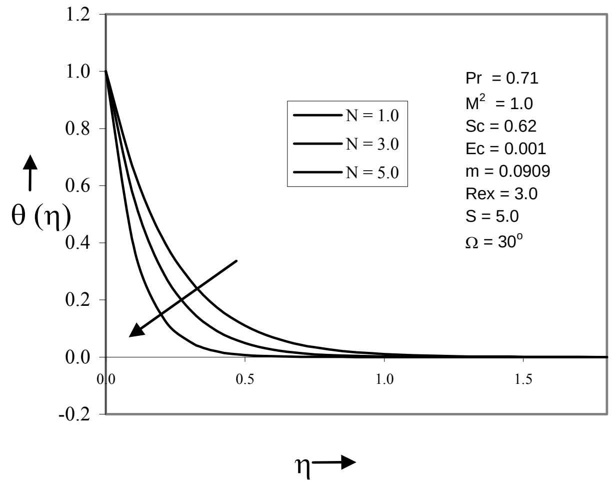

Fig. 9. Buoyancy ratio over the temperature profiles

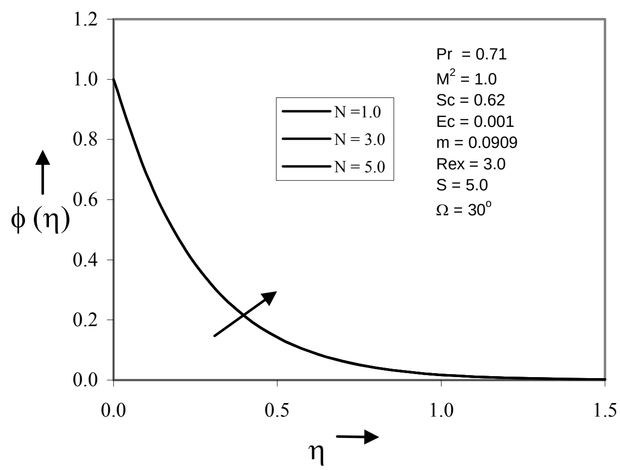

Fig. 10. Effects of buoyancy ratio over the concentration profiles

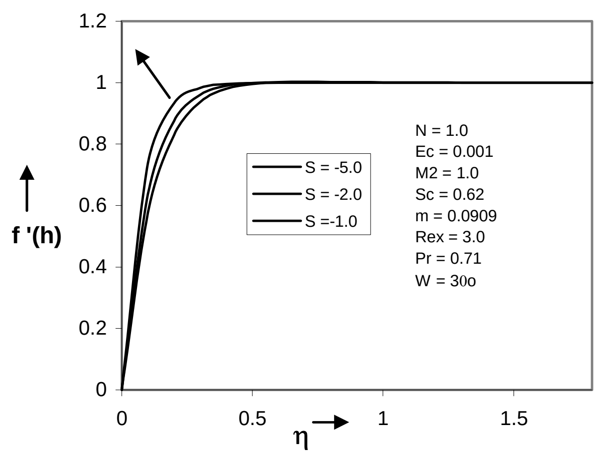

Fig. 11. Effects of injection over the velocity profiles

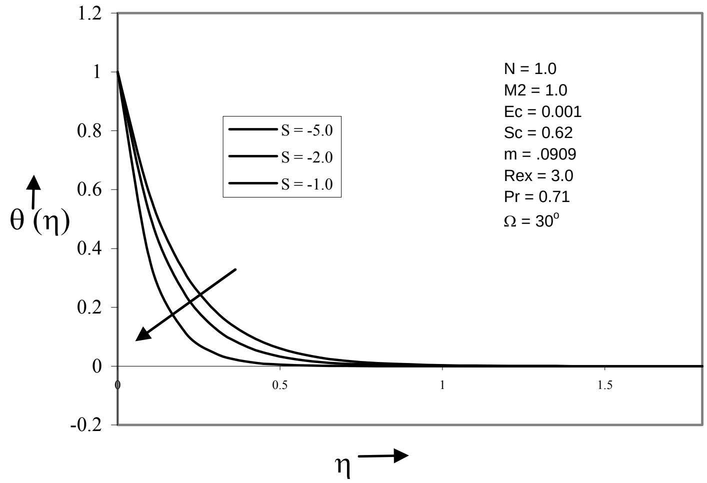

Fig. 12. Effects of injection over the temperature profiles

4. CONCLUSIONS

In this paper, the combined heat and mass transfer of an electrically conducting fluid in MHD natural convection adjacent to a wedge surface is analyzed, taking into account the effects of Ohmic heating in the presence of suction or injection. The governing equations are approximated to a system of non-linear ordinary differential equations by similarity transformation. Numerical calculations are carried out for various values of the dimensionless parameters of the problem. Comparisons with previously published works are performed and excellent agreement between the results is obtained. The results are presented graphically and the conclusion is drawn that the flow field and other quantities of physical interest are significantly influenced by these parameters. We conclude the following from the results and discussions:

*In the presence of heat source and uniform suction at the wall, it is interesting to note that the fluid flow along the wall of the wedge accelerates the fluid motion and the temperature of the fluid. The concentration of the fluid is uniform, but slightly decreases with the increase of strength of the magnetic field. All these facts clearly depict the combined effects of the heat source and the strength of the magnetic effect at the wall of the wedge

*In the presence of a uniform magnetic field, the velocity of the fluid increases and the temperature and concentration of the fluid decrease with the increase of suction at the wall of the wedge, whereas the velocity of the fluid increases and the temperature of the fluid decreases with an increase of injection at the wall of the wedge. All these facts clearly depict the combined effects of mass diffusion and the strength of the magnetic effect at the wall of the wedge surface.

*Due to the uniform magnetic field at the wall of the wedge, the velocity and the temperature of the fluid decrease and the concentration of the fluid increases with the increase in the buoyancy ration. All these facts clearly depict the combined effects of Ohmic heating and the buoyancy ratio between species and thermal diffusion at the wall of the surface.

*It is interesting to note that the comparison of velocity profiles shows that the velocity increases near the plate and thereafter remains uniform in all the cases.

*In the case of suction, it is clear that the temperature of the fluid decreases near the plate and thereafter becomes uniform for the increasing heat source.

It is hoped that the present investigation of the study of physics of flow over a wedge can be utilized as the basis for many scientific and engineering applications and for studying more complex vertical problems involving the flow of electrically conducting fluids. The findings may be useful for the study of movement of oil or gas and water through the reservoir of an oil or gas field, in the migration of underground water, and in filtration and water purification processes. The results of the problem are also of great interest in geophysics in the study of interaction of the geomagnetic field with the fluid in the geothermal region.

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REFERENCES

1. Chambre, P. L. & Acrivos, J. D. (1956), Analysis of catalytic surface reactions in hydrodynamic flows. *Journal of applied physics*, *27*, 1322-1331.
2. Chambre, P. L. & Acrivos, A. (1957). Diffusion of a chemically reactive species in a laminar boundary layer flow. *Indian Engng .Chem*, *49*, 1025-1032.
3. Acrivos, A. (1960). Analysis of the laminar forced convection mass transfer with homogeneous chemical reaction. *Amer. Inst. Chem. Engrs., 6*, 410-418.
4. Schlichting, H. (1979). *Boundary value theory*. Mc Graw Hill Inc, 164.
5. Yih, K. A. (1998).Uniform suction/blowing effect on force convection about wedge. *Acta Mech., 128*, 173-181.
6. Watanabe,T.(1990). Thermal boundary layer over a wedge with uniform suction or injection in forced flow. *Acta Mechanica, 83*, 119-126.
7. Kafoussias, N. G. & Nanousis, N. D. (1997). Magnetohydrodynamic laminar boundary layer flow over a wedge with suction or injection. *Canadian Journal of Physics, 75*, 733-745.
8. Kumari, M. (1998). Effect of large blowing rates on the steady laminar incompressible electrically conducting fluid over an infinite wedge with a magnetic field applied parallel to the wedge. *International Journal of Engng. Sci.*, *36*, 299-308.
9. Anjali Devi, S. P. & Kandasamy, R. (2001). Effects of heat and mass transfer on MHD laminar boundary layer flow over a wedge with suction or injection. *Journal of Energy Heat and Mass Transfer, 23*, 167-175.
10. Chamkha, A. J. & Khaled, A. R. A. (2001). Similarity solutions for hydro magnetic simultaneous heat and mass transfer. *Heat Mass Transfer, 37*, 117-124.
11. Hossain, M. A. (1992). Viscous and Joule heating effects on MHD free convection flow with variable plate temperature. *International journal of heat and mass transfer, 35*, 3485-3492.
12. Hakiem, M. A. E. L., Mohammadeian, A. A., Kaheir, S. M. M. E. L. & Gorla, R. S. R. (1999). Joule heating effects on Magnetohydrodynamic free convection flow of a micro polar fluid. *International Communications Heat Mass Transfer, 26*, 219-227.
13. Kuo, Bor-Lih. (2005). Heat transfer analysis for the Falkner-Skan wedge flow by the differential transformation method. *International Journal of Heat Mass Transfer, 48*, 5036-5046.
14. Cheng, W. T. & Lin, H. T. (2002). Non-similarity solution and correlation of transient heat transfer in laminar boundary layer flow over a wedge. *International Journal of Engineering Science, 40*, 531-540.
15. Pantokratoras, A. (2006). The Falkner-Skan flow with constant wall temperature and variable viscosity. *International Journal of Thermal Sciences, 45*, 378-389.
16. Gill, S. (1951). *Proceeding of Cambridge Philosophical Society* (96-123).
17. Bird, B. R., Warren, E., Stewart, E. & Lightfoot, N. (1992). *Transport phenomena*. New York, John Wiley and sons.
18. Bansal, J. L. (1986). *Boundary value problem: Vol. 6*. Oxford and IBM publishing company.