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Radiation an Mass Transfer Effects on MHD Boundary Layer Flow due to an Exponentially Stretching Sheet with Heat Source

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Abstract*— This paper focuses on the study of the heat and mass transfer effects on MHD boundary layer flow of a viscous incompressible and radiating fluid over an exponentially stretching sheet. The initial governing boundary layer equations are transformed to a system of ordinary differential equations, which are then solved numerically by a fourth order Runge-Kutta method along with shooting technique. A parametric study is conducted and so that Numerical results are obtained for the velocity, temperature and concentration as well as the skin-friction coefficient, the local Nusselt number and local Sherwood number for different values of the material parameters, namely, the magnetic parameter, heat source parameter, radiation parameter, Schmidt number and Prandtl number, and discussed in detail.

Index Terms—**Heat and Mass Transfer, Heat source, MHD, Radiation, Stretching sheet.**

I. INTRODUCTION

The boundary layer flow on a continuous stretching sheet has attracted considerable attention during the last few decades due to its numerous applications in industrial manufacturing processes such as hot rolling, wire drawing, glass-fiber and paper production, drawing of plastic films, metal and polymer extrusion and metal spinning. 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 [1]). Crane [2] was the first to consider the boundary layer flow caused by a stretching sheet which moves with a velocity varying linearly with the distance from a fixed point. The heat transfer aspect of this problem was investigated by Carragher and Crane [3], under the conditions when the temperature difference between the surface and the ambient fluid is proportional to a power of the distance from a fixed point. Magyari and Keller [1] investigated the steady boundary layers on an exponentially stretching continuous surface with an exponential temperature distribution. Partha et al. [4] studied the effect of viscous dissipation on the mixed convection heat transfer from an exponentially stretching surface. Coupled heat and mass transfer finds applications in a variety of engineering applications, such as the migration of moisture through the air contained in fibrous insulation and grain storage installations, filtration, chemical catalytic reactors and processes, spreading of chemical pollutants in plants and diffusion of medicine in blood veins. Free convection flow of an incompressible viscous fluid past an infinite or semi-infinite vertical plate has been studied since long because of its technological importance. Callahan and Marner [5] solved the problem of transient free convection with mass transfer on an isothermal vertical plate using an explicit finite difference scheme. Subhashini et al. [6] studied the effect of Mass Transfer on the flow past a vertical porous plate. Unsteady free convective flow on taking into account the mass transfer phenomenon past an infinite vertical porous plate with constant suction was studied by Soundalgekar and Wavre [7]. Soundalgekar [8] studied the effects of mass transfer and free convection currents on the flow past an impulsively started vertical plate. In these studies the magnetohydrodynamic phenomena is ignored. However in **metallurgical** transport systems, by drawing plates in an electrically conducting fluid subjected to a transverse magnetic field, the rate of cooling can be controlled and the final desired characteristics can be further refined. Magneto hydrodynamic flow has applications in meteorology, solar physics, cosmic fluid dynamics, astrophysics, geophysics and in the motion of earth's core. Shanker and Kishan [9] presented the effect of mass transfer on the MHD flow past an impulsively started infinite vertical plate. Bhaskara Reddy and Bathaiah [10, 11] analyze the Magnetohydrodynamic free convection laminar flow of an incompressible Viscoelastic fluid. Later, he was studied the MHD combined free and forced convection flow through two parallel porous walls. Elabashbeshy [12] studied heat and mass transfer along a vertical plate in the presence of magnetic field. Gangadhar and Bhaskar Reddy [13] analyzed the problem of chemically reacting MHD boundary layer flow of heat and mass transfer over a moving vertical plate in a porous medium with suction. The heat source/sink effects in thermal convection, are significant where there may exist a high temperature differences between the surface (e.g. space craft body) and the ambient fluid. Heat generation is also important in the context of exothermic or endothermic chemical reactions. Sparrow and Cess [14] provided one of the earliest studies using a similarity approach for stagnation point flow with heat source/sink which vary in time. Pop and Soundalgekar [15] studied unsteady free convection flow past an infinite plate with constant suction and heat source. Much later

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Takhar et al. [16] presented one of the most robust studies of thermal and concentration boundary layers with MHD effects for the case of a point sink. Takhar et al. [17] extended this analysis to examine combined variable lateral mass flux (wall injection/suction), heat source effects and hall current effects on double-diffusive boundary layers under strong magnetic fields. Sahoo et al. [18] studied magnetohydrodynamic unsteady free convection flow past an infinite vertical plate with constant suction and heat sink. Recently, Bhaskar Reddy et al [19] analyzed the radiation and mass transfer effects on MHD flow over a stretching surface with heat generation and suction/ injection. In the context of space technology and in the processes involving high temperatures, the effects of radiation are of vital importance. Recent developments in hypersonic flights, missile re-entry, rocket combustion chambers, power plants for inter planetary flight and gas cooled nuclear reactors, have focused attention on thermal radiation as a mode of energy transfer, and emphasized the need for improved understanding of radiative transfer in these processes. The interaction of radiation with laminar free convection heat transfer from a vertical plate was investigated by Cess [20] for an absorbing, emitting fluid in the optically thick region, using the singular perturbation technique. Arpaci [21] considered a similar problem in both the optically thin and optically thick regions and used the approximate integral technique and first-order profiles to solve the energy equation. Raptis [22] analyzed the thermal radiation and free convection flow through a porous medium bounded by a vertical infinite porous plate by using a regular perturbation technique. Ishak [23] studied the MHD boundary layer flow due to an exponentially stretching sheet with radiation effect. The unsteady flow past a moving plate in the presence of free convection and radiation were presented by Mansour [24]. Sajid and Hayat [25] investigated the radiation effects on the mixed convection flow over an exponentially stretching sheet, and solved the problem analytically using the homotopy analysis method. The numerical solution for the same problem was then given by Bidin and Nazar [26]. Recently, Poornima and Bhaskar Reddy [27] presented an analysis of the radiation effects on MHD free convective boundary layer flow of nanofluids over a nonlinear stretching sheet. However, the interaction of radiation with mass transfer due to a stretching sheet has received little attention. Hence, the aim of the present study is to analyze the effect of thermal radiation and mass transfer on the steady magnetohydrodynamic (MHD) boundary layer flow due to an exponentially stretching sheet in the presence of heat source or sink. The governing boundary layer equations have been transformed to 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 fluid velocity, temperature, concentration, skin friction, Nusselt number and Sherwood number are shown in figures and discussed in detail.

II. MATHEMATICAL ANALYSIS

A steady two dimensional flow of an incompressible viscous, electrically conducting and radiating fluid past an exponentially stretching sheet is considered. The sheet is placed in a quiescent ambient fluid of uniform surface temperature and concentration T_∞ and C_∞.

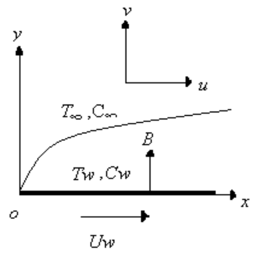

Fig. A: Physical modal and coordinate system

The x-axis is taken along the plate and y-axis normal to it. A variable magnetic field of strength B(x) is applied transversely and the induced magnetic field is assumed to be neglected, which is justified for MHD flow with small magnetic Reynolds number. Hall effects and Joule heating are also negligible. 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

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\upsilon\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B(x)}{\rho}u \qquad (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2}-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial y}+\frac{Q_0}{\rho c_p}(T-T_\infty) \qquad (3)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2} \qquad (4)$$

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

$$u=U_w=U_0e^{x/L}, v=0, T=T_w=T_\infty+T_0e^{x/2L}$$
$$C=C_w=C_\infty+C_0e^{x/2L} \quad at \;\; y=0$$
$$u\to 0, T\to T_\infty, C\to C_\infty \;\; \text{as} \;\; y\to\infty \qquad (5)$$

where u and v are the velocity components along the x and y axes, respectively, T - the temperature of the fluid and C - the fluid concentration in the boundary layer, υ - the kinematic viscosity, ρ - the fluid density, C_p - the specific heat, $B(x)$ - the magnetic field of constant strength, q_r - the radiative heat flux, L - the reference length, U_0 - the reference velocity, T_0 - the reference temperature, C_0 - the reference concentration, T_w - the temperature uniform of the sheet, C_w - the concentration uniform of the sheet, D -

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the coefficient of mass diffusivity and k - the thermal conductivity of the fluid. By using the Rosseland approximation (Brewster [28]), the radiative heat flux q_r is given by

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

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 the equation (7) can be linearized by expanding T^4 into the Taylor series about T_∞, which after neglecting higher order terms takes the form

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4 \qquad (7)$$

In view of the equations (7) and (8), the equation (4) reduces to

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \left(\frac{k}{\rho c_p} + \frac{16\sigma^* T_\infty^3}{3\rho c_p K'}\right)\frac{\partial^2 T}{\partial y^2} + \frac{Q_0}{\rho c_p}(T - T_\infty) \qquad (8)$$

To obtain similarity solutions. It is assumed that the magnetic field B(x) is of the form

$$B(x) = B_0 e^{x/2L}$$

where B_0 is the constant magnetic field.

The continuity equation (1) is satisfied by the Cauchy Riemann equations

$$u = \frac{\partial \psi}{\partial y} \quad and \quad v = -\frac{\partial \psi}{\partial x} \qquad (9)$$

where $\psi(x, y)$ is the stream function.

In order to transform the equations (2), (4) and (8) into a set of ordinary differential equations, the following similarity transformations and dimensionless variables are introduced (Sajid and Hayat [25]).

$$\psi(x,y) = \sqrt{2\upsilon U_0 L}e^{x/2L} f(\eta), \eta = \left(\frac{U_0}{2\upsilon L}\right)^{1/2} e^{x/2L} y$$

$$u = U_0 e^{x/L} f'(\eta), v = -\left(\frac{\nu U_0}{2L}\right)^{1/2} e^{x/2L}\left(f(\eta) + \eta f'(\eta)\right)$$

$$T = T_\infty + T_0 e^{x/2L}\theta(\eta), Q = \frac{Q_0}{\rho c_p}, C = C_\infty + C_0 e^{x/2L}\phi(\eta)$$

$$M = \frac{2\sigma B_0^2 L}{\rho U_0}, \Pr = \frac{\rho\upsilon c_p}{k}, Sc = \frac{\upsilon}{D}, R = \frac{4\sigma^* T_\infty^3}{K'k} \qquad (10)$$

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, Q - the heat source or sink parameter, Sc- the Schmidt number and R- the radiation parameter.

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

$$f''' + ff'' - f'^2 + Mf' = 0 \qquad (11)$$

$$\left(1 + \frac{4}{3}R\right)\theta'' + \Pr f\theta' - \Pr f'\theta + \Pr Q\theta = 0 \qquad (12)$$

$$\phi'' + Scf\phi' - Scf'\phi = 0 \qquad (13)$$

The transformed boundary conditions can be written as

$$f = 0, f' = 1, \theta = 1, \phi = 1 \quad \text{at} \quad \eta = 0$$

$$f' = \theta = \phi = 0 \quad as \quad \eta \to \infty \qquad (14)$$

The main physical quantities of interest are the skin friction coefficient $f''(0)$, the local Nusselt number $-\theta'(0)$and the Sherwood number $-\phi'(0)$ which represent the wall shear stress, the heat transfer rate and mass transfer rate at the surface, respectively. Our task is to investigate how the values of $f''(0)$, $-\theta'(0)$and $-\phi'(0)$ vary with the radiation parameter R, magnetic parameter M and Prandtl number Pr.

III. NUMERICAL ANALYSIS

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.*[29]). 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

In order to get a clear insight of the physical problem, the velocity, temperature and concentration have been discussed by assigning numerical values to the governing parameters encountered in the problem. The effects of various parameters on the velocity are depicted in Fig. 1. The effects of various parameters on the temperature are depicted in Figs. 2-5. The effects of various parameters on the concentration are depicted in Figs. 6-7. Fig. 1 shows the dimensionless velocity for different values of the magnetic parameter (M). It is seen that, as expected, the velocity decreases with an increase of magnetic parameter. The magnetic parameter is found to retard the velocity at all points of the flow field. It is because that the application of transverse magnetic field will result in a resistive type force (Lorentz force) similar to drag force which tends to resist the fluid flow and thus reducing its velocity. Also, the boundary layer thickness decreases with an increase in the magnetic parameter. The effect of the magnetic parameter

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(*M*) on the temperature is illustrated in Fig.2. It is observed that as the magnetic parameter increases, the temperature increases. Fig. 3 depicts the variation of the thermal boundary layer for the different the Prandtl number (*Pr*). It is noticed that the thermal boundary layer thickness decreases with an increase in the Prandtl number. Fig.4 illustrates the effect of the radiation parameter (*R*) on the temperature. It is noticed that as the radiation parameter increases, the temperature decreases. Fig.5 illustrates the effect of the heat source parameter (*Q*) on the temperature. It is noticed that as the heat source parameter increases, the temperature increases. The effect of the magnetic parameter (*M*) on the concentration field is illustrated in Fig.6. As the magnetic parameter increases the concentration is found to be increasing. The effect of the Schmidt number *(Sc)* on the concentration field is illustrated in Fig. 7. It is noticed that the concentration boundary layer thickness decreases with an increase in the Schmidt number. Figs. 8 and 9 show the variation of the Nusselt number for the different magnetic parameter, radiation parameter, heat source/sink parameter and Prandtl number. It is observed that the Nusselt number increases with an increase in the radiation parameter or the Magnetic parameter or the Prandtl number and decreases with an increase in the heat source/sink parameter. In Table 1, the present results are compared with those of Magyari and kellar [1], Ei-Aziz [30], Bidin and Zazar [26] and Anvar Ishak [23] found that there is a perfect agreement.

V. CONCLUSION

In the present paper, a steady magnetohydrodynamic (MHD) boundary layer flow due to an exponentially stretching sheet with radiation by taking mass transfer and heat source/ sink into account, are analyzed. 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. The results are summarized as follows

- The momentum boundary layer thickness decreases, while both thermal and concentration boundary layer thicknesses increase with an increase in the magnetic field intensity.
- The radiation reduces temperature.
- The Schmidt number reduces the concentration.
- The magnetic field, radiation and Prandtl number enhances the heat transfer rate.

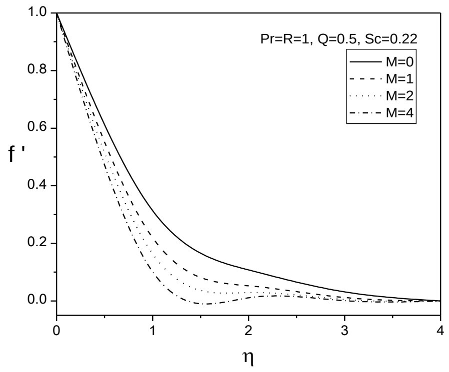

Fig.1 Velocity for different values of *M*

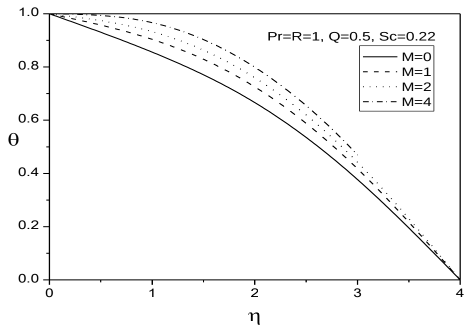

Fig.2 Temperature for different values of *M*

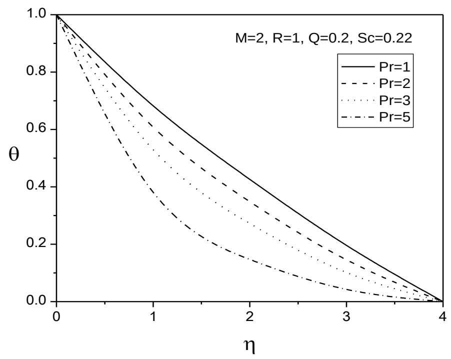

Fig.3 Temperature for different values of *Pr*

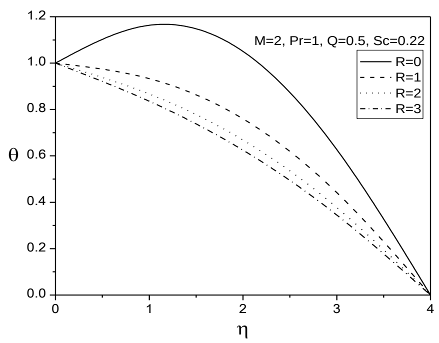

Fig.4 Temperature for different values of *R*

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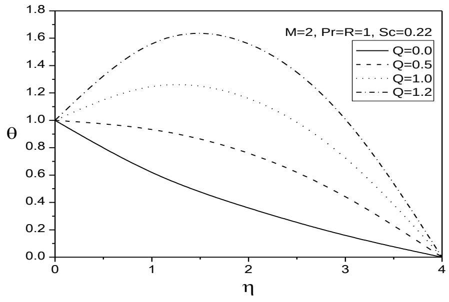

Fig.5 Temperature for different values of *Q*

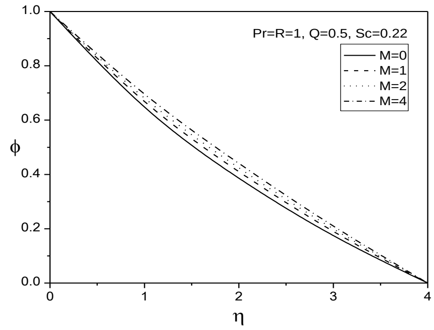

Fig.6 Concentration for different values of *M*

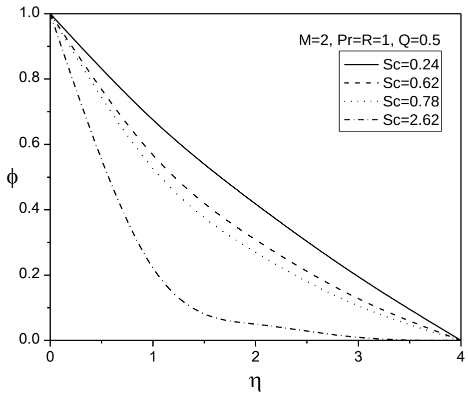

Fig.7 Concentration for different values of *Sc*

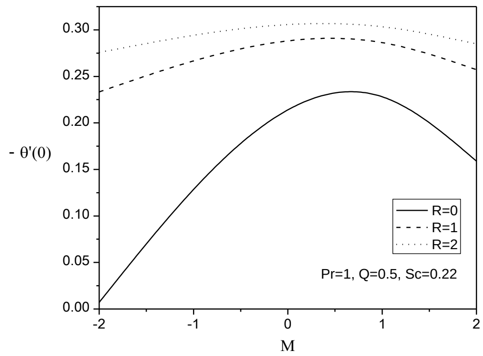

Fig.8 Variation of the Nusselt number for different *R*

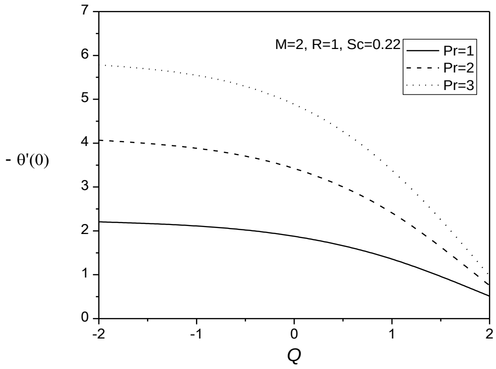

Fig.9 Variation of the Nusselt number for different *Pr*

Table 1 Numerical values of $\theta'(0)$ at the sheet for different values of R, M and *Pr* when *Q=0* and *Sc*=0, Comparison of the present results with that of Magyari and Kellar [1], El-Aziz [30], Bidin and Nazar [26] and Anuar Ishak [23]

R	M	Pr	Present Results	Magyari and Kellar [1]	El-Aziz [30]	Bidin and Nazar [26]	Anuar Ishak [23]
0	0	1	-0.957433	-0.954782	-0.954785	-0.9548	-0.9548
		2	-1.47898			-1.4714	-1.4715
		3	-1.86443	-1.869075	-1.869074	-1.8691	-1.8691
		5	-2.500615	-2.500135	-2.500132		-2.5001
		10	-3.60024	-3.660379	-0.3660372		-3.6604
	1	1	-0.861390				-0.8611
1	0		-0.563196			-0.5315	-0.5312
	1		-0.450533				-0.4505

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