Analysis of MHD Flow on Exponentially Stretching Sheet with Slip Conditions

Preeti Kaushik

Assistant Professor, Department of Applied Sciences and Humanities, Ajay Kumar Garg Engineering College, Ghaziabad

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ABSTRACT

This work examines radiative heat transfer and magnetohydrodynamic (MHD) boundary layer flow with second-order slip condition. The fluid flow in the direction of an exponentially stretched sheet is taken into consideration. Thermal conductivity and the impact of the magnetic field are considered. By using similarity transformation, the nonlinear mathematical expression of the flow that is acquired is converted into ordinary differential equations. Numerical solutions are found for the linked higher order nonlinear ordinary differential equations. Analysis is done on the velocity and temperature profile solution in relation to the first and second order slip parameters. Graphs for several relevant metrics are used to explain the flow's features. As the Prandtl number rises, the rate of heat transmission falls, but the radiation parameter increases.

Keywords: Exponentially stretching sheet, MHD flow, Second order slip condition, Heat transfer, Finite difference method.

INTRODUCTION

An exponentially stretched sheet plays an important role in boundary layer fluid flow problems, this phenomenon has developed interest in several researchers. The exponentially expanding sheet idea has been used in several industrial engineering and technological applications, including the manufacturing of polymer extrusion, electric heaters, and stretching of metal, where the flow dynamics are influenced by the sheet's deformation. The primary benefit of MHD flow is that it makes cooling rate estimate possible. Gas turbines, various aviation systems, and several space spacecraft are produced using the energy equation of a viscous fluid over an exponentially stretched sheet in conjunction with the magnetohydrodynamic flow principle. Crane et al. [1] originally looked at the distance-dependent velocity of the boundary layer flow toward the linear stretching sheet issue. Ibrahim et al. [2] developed the new concept for solving stagnation point flow problem across the stretching sheet. Irfan et al. [3] used the application of exponential stretching sheet for solving two dimensional incompressible flow. Ishak et al. [4] proposed the fluid flow of nanofluid due chemical reaction with effect of porous medium. Majeed et al. [5] investigated suction and injection impact on the velocity of Casson fluid flow. Nandeppanavar et al. [6] provided the numerical solution of nanofluid flow towards exponentially stretching surface. Ene et al. [7] analyzed influences of the heat generation and absorption on the 2D viscous flow of nanofluid. Kumar et al. [8] proposed the unsteady flow of MHD nanofluid due to exponentially extending surface. Bhattacharyya et al. [9,10] explored the condition of velocity slip applied on the carreau nanofluid with porous medium effects. Aurangzaib et al. [11] examined the Newtonian heating condition on the nanofluid over a stretched surface. Bhattacharyya et al. [12] presented consequences of the velocity slip conditions on the Casson fluid flow. Mukhopadhyay et al. [13] provided the Brownian motion and Thermophoresis parameters influences on the flow passing through vertical sheet. Waini et al. [14] investigated the properties of various variable impacting the flow over an exponential sheet. Nadeem et al. [15] developed the scheme to solve the issue of viscous fluid model in the presence of porous media. Reddy et al. [16] studied the incompressible fluid flow with chemical reaction impact across the stretching surface. Mabood et al. [17] MHD flow of Non-Newtonian fluid with thermal radiation. Nandeppanavar et al. [18] provided the solution of Maxwell fluid flow issue with velocity slip condition. Bhattacharyya et al. [19,20,21] explored several problems related to fluid flow using analytical and numerical methods. Mandal et al. [22] analyzed the radiative heat transfer in nanofluid due to heat source and sink effect. Mabood et al. [23] determined the characteristics of nanofluid with over a nonlinear stretching sheet. Ghosh et al. [24] implemented the advanced finite element method to get the solution of nanofluid problem. Adegbie et al. [25] examined the joule heating effect on the heat transfer on Maxwell fluid flow. Sheikholeslami et al. [26] inspected the homogeneous-heterogeneous effect on velocity distribution of nanofluid flow. Afterwards, several researchers [27,28,29,30,31] presented the work on nano fluid flow past an exponentially extended sheet. Zeeshan et al. [32] studied the axisymmetric flow of casson fluid with the condition of Brownian motion and Thermophoresis effect. Xun et al. [33] illustrated the consequences of viscous dissipation on MHD flow.

The purpose of this investigation is to examine the effect of second order slip on MHD flow over an exponentially stretching sheet. The effect of first and second order slip, magnetic parameter, radiation parameter explored in this study. The study offers important insights into the boundary layer flow problems in a porous medium. The mathematical equations are solved numerically by bvp4c through Matlab. The fluid velocity and temperature profile for pertinent parameters are presented graphically. The results validate with the previously published work and found to be in good agreement.

Mathematical Formulation

We are considering two-dimensional magnetohydrodynamic fluid flow towards an exponentially stretching sheet. The stretching sheet is taken along x axis at $y = 0$. A strong magnetic field of strength B_0 applied, where B_0 is constant and it is applied normal to the x axis. The induced magnetic field is not considered because of the low value of the Reynolds number. Here it is considered that thermal conductivity varies linear with temperature. $u_w = -Ce^{x/L}$is velocity at boundary , where C is constant, $v = v_w = v_0 e^{x/2L}$ is a special kind of velocity, where $v_0$is a constant, $v_0$is considered as velocity suction for $v(x) > 0$,when $v(x) < 0$, v_0 is the velocity blowing, $T = T_w = T_\infty + T_0 e^{x/2L} + N\frac{\partial T}{\partial y}$ is fluid temperature. T_w is fluid temperature at wall, T_∞ is ambient temperature, , T_0 is reference temperature, N is thermal slip coefficient. The governing equations of continuity, momentum, and energy for boundary layer flow problems are represented as.

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

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

$$\rho c_p\left[u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right] = k_0\frac{\partial^2 T}{\partial y^2} - \frac{\partial q_r}{\partial y} \qquad (3)$$

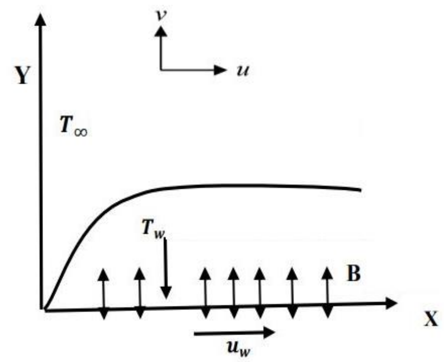

Figure 1 Physical model of the flow

where u and v are fluid velocity components along x and y axis respectively. ν is kinematic viscosity, k is permeability for Porous medium, ρ is fluid density, σ is chemical reaction rate constant, c_p is specific heat, T is fluid temperature, $k_f$is thermal conductivity, q_r is radiative heat flux, $B = B_0 e^{x/2L}$ is magnetic field where B_0 is magnetic field constant.

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The corresponding boundary conditions are:

$$u_w = -Ce^{x/L} \quad (4)$$

$$u_{slip} = \frac{2}{3}\left(\frac{3-\alpha l^3}{\alpha} - \frac{2}{3}\frac{1-l^2}{k_n}\right)\lambda\frac{\partial u}{\partial y} - \frac{1}{4}\left(l^4 + \frac{2}{k_n^2}(1-l^2)\right)\lambda^2\frac{\partial^2 u}{\partial y^2} = a_1\frac{\partial u}{\partial y} + a_2\frac{\partial^2 u}{\partial y^2} \quad (5)$$

$$u = u_w + u_{slip} = -Ce^{x/L} + a_1\frac{\partial u}{\partial y} + a_2\frac{\partial^2 u}{\partial y^2} \quad (6)$$

$$v = v_w = v_0 e^{x/2L}, T = T_w = T_\infty + T_0 e^{x/2L} + N\frac{\partial T}{\partial y} \quad \text{at } y = 0 \quad (7)$$

$$u \to 0,\ T \to T_\infty \text{at } y \to \infty \quad (8)$$

k_n is Knudsen number,α is momentum adaptation coefficient, λ is molecular mean free path. $l = \min\left[\frac{1}{k_n}, 1\right]$, L is characteristic length. a_1 and a_2 are constant.

Similarity Transformation

Taking similarity transformation by using stream function $\psi(x, y)$

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

The stream function uniformly satisfies Eq. (1), and Eq. (2) reduced to

$$\frac{\partial \psi}{\partial y}.\frac{\partial^2 \psi}{\partial y \partial x} - \frac{\partial \psi}{\partial x}\frac{\partial^2 \psi}{\partial y^2} - \nu\frac{\partial^3 \psi}{\partial y^3} - \frac{\sigma B^2}{\rho}\frac{\partial \psi}{\partial y} \quad (10)$$

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

Therefore Eq. (3) becomes

$$\rho c_p\left[u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right] = k_0\frac{\partial^2 T}{\partial y^2} - \frac{16\sigma T_\infty^3}{3k^*}\frac{\partial^2 T}{\partial y^2} \quad (11)$$

Using stream function Eq. (11) becomes

$$\rho c_p\left[\frac{\partial \psi}{\partial y}\frac{\partial T}{\partial x} - \frac{\partial \psi}{\partial x}\frac{\partial T}{\partial y}\right] = k_0\frac{\partial^2 T}{\partial y^2} - \frac{16\sigma T_\infty^3}{3k^*}\frac{\partial^2 T}{\partial y^2} \quad (12)$$

Where

$$\psi = \sqrt{2\nu LC}.\mathrm{f}(\eta)e^{x/2L} \quad \eta = y\sqrt{\frac{C}{2\nu L}}e^{x/2L}, \theta = \frac{T - T_\infty}{T_w - T_\infty} \quad (13)$$

For the similarity solution permeability is assumed to have the following form

$$k(x) = 2k_0 e^{-x/L} \quad (14)$$

Where k_0 is reference permeability

The Thermal conductivity of the fluid varies linearly with temperature

$$k_f = k_\infty(1 + \epsilon\theta) \quad (15)$$

Where ϵ is thermal conductivity variation parameter. Using similarity transformation and boundary layer approximation Eqs. (10) and (12) become

$$f''' + ff'' - 2f'^2 - \frac{f'}{K} - Mf' = 0 \qquad (16)$$

$$\left(1+\frac{4}{3}R\right)\theta'' + \Pr(f\,\theta' - f'\,\theta) = 0 \qquad (17)$$

With boundary conditions

$$f'(0) = 1 + \gamma f''(0) + \delta f'''(0), f(0) = S, \theta(0) = 1 + \alpha^*\theta'(0) \quad as\ \eta = 0 \qquad (18)$$

$$f'(\eta) \to 0\,, \theta(\eta) \to 0 as\, \eta \to \infty \qquad (19)$$

Where $M = \frac{2\sigma B_0^2 L}{\rho C}$ is magnetic parameter,$R = \frac{4\sigma T_\infty^3 L}{kk^*}$ is radiation parameter, $Pr = \frac{\rho C_p}{k_\infty}$ prandtl number, $\gamma = a_1\sqrt{\frac{C}{2vL}}e^{x/2L}$ is first order slip parameter and $\delta = \left(\frac{C}{2vL}e^{x/L}\right)$ is second order slip parameter. $\alpha^* = N\sqrt{\frac{C}{2vL}}e^{x/2L}$ is thermal slip parameter.

Numerical Solution

The highly nonlinear system of ordinary differential equations (16) to (17) with the corresponding boundary conditions (18) and (19) are solved numerically using MATLAB bvp4c software. The software is using finite difference method to solve the boundary value problems. The transformed equations converted into initial value problem by taking the following transformation.

$$f' = z\,,\ z' = p, \quad p' = Mz + \frac{z}{K} + 2z^2 - fp \ \ \theta' = q \quad q' = -\frac{pr(fq - z\theta)}{\left(1+\frac{4}{3}R\right)} \qquad (20)$$

and the transformed dimensionless boundary conditions becomes

$$f(0) = S,(0) = 1 + \gamma p(0) + \delta p'(0), \theta(0) = 1 + \alpha q(0) \qquad (21)$$

$$z(\infty) = 0, \theta(\infty) = 0. \qquad (22)$$

Finite value for boundary condition $\eta \to \infty$, i.e. η_{max} taken as 40. The step size is taken as $\nabla\eta = 0.01$, with the tolerance limit up to 10^{-5}. Trial values of $f''(0), \theta'(0)$ were adjusted to get a better approximation to satisfy the corresponding boundary condition

RESULTS AND DISCUSSION

An analysis of a two-dimensional flow have been figured. Various physical quantities of interest like skin friction, Nusselt number functions are being calculated mathematically and the outcomes are traced out for the same in terms graphs. Some important quantities are presented in tabular form. The variations in velocity and temperature through the pertinent quantities are clear explained in the study. The solution of modified equations (16) to (17) together with boundary conditions (18) to (19) are acquired numerically. Graphs for many relevant inputs have been created to depict the fluid boundary layer flow and temperature distribution. In the whole inquiry, the non-dimensional numbers $\gamma = 0, \delta = -1, M = 0.2, R = 0.7, Pr = 0.5, \alpha = -2$ are taken commonly

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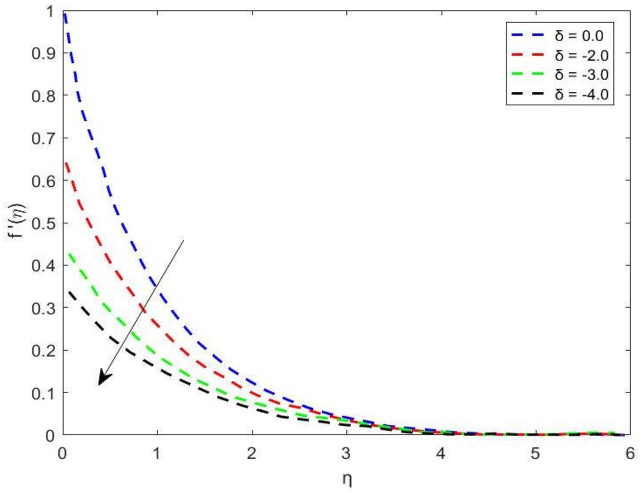

Figure 2 Variation of $f'(\eta)$ for the different values of δ for $\gamma = 0, M = 0.2, R = 0.7, Pr = 0.5, \alpha = -2$

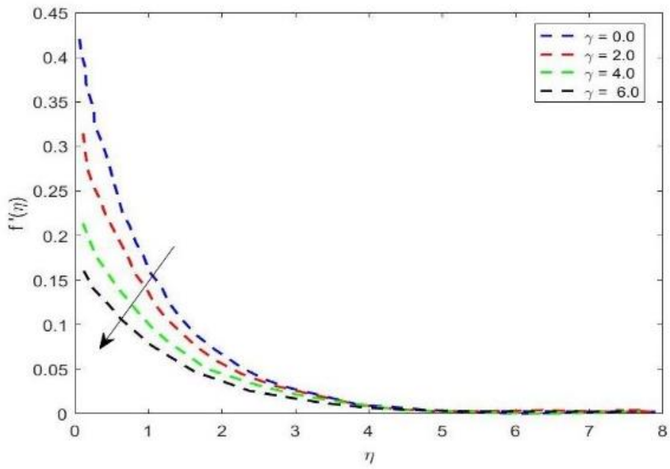

Figure 3 Variation of $f'(\eta)$ for the different values of γ for $\delta = -1, M = 0.2, R = 0.7, Pr = 0.5, \alpha = -2$

The consequence of second-order slip parameter δ on velocity profile $f'(\eta)$ elluciated in **Figure 2.** The intriguing outcome seen that velocity is dropping down, when the value of δ boost up. To see the performance of velocity function $f'(\eta)$ for variety of γ values is highlighted in **Figure 3.** The findings further explain that $f'(\eta)$ degrades, as γ enhances. The resistance to fluid flow increases as a result of the first order slip parameter (γ) which results in a decrease in the velocity rofile $f'(\eta)$.

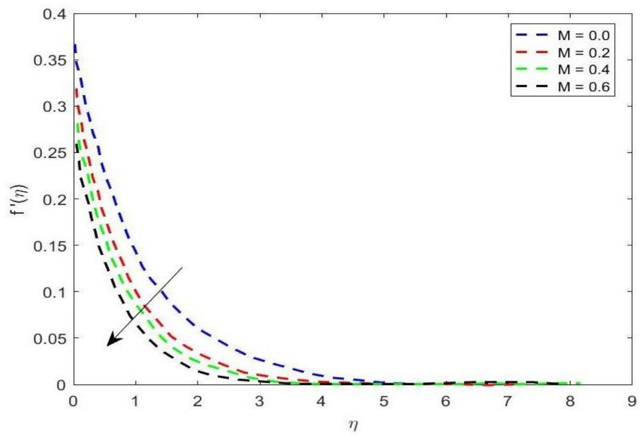

Figure 4 Variation of $f'(\eta)$ for the different values of M for values $\gamma = 0, \delta = -1, R = 0.7, Pr = 0.5, \alpha = -2$

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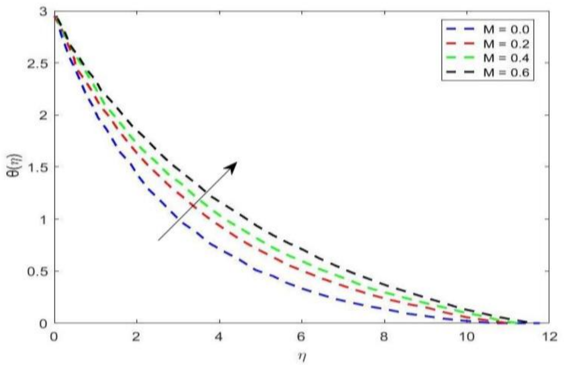

Figure 5 Variation of $\theta(\eta)$ for the different values of M for $\gamma = 0,\ \delta = -1, R = 0.7, Pr = 0.5, \alpha = -2.$

The velocity distribution $f'(\eta)$ owing to variations in the magnetic parameter (M) is portrays in **Figure 4.** It is noticed that, the upshot of escalating magnetic parameter M is seen in terms of declining behavior of velocity profile $f'(\eta)$. For the hydrodynamic flow condition M is considered to be zero while for the hydro-magnetic flow, M is considered to be nonzero. It is clearly revealed in the graph that velocity flow field diminishes as higher values of M. Resistance is caused by a resistive force that is produced as a result of a physical magnetic field. Because of this resistance, the fluid moves more slowly. With respect to changing magnetic parameter values M. The variation in the strength of the temperature field is seen in **Figure 5**. It is evidence in the graph For rising amount **of $\boldsymbol{M}$**.

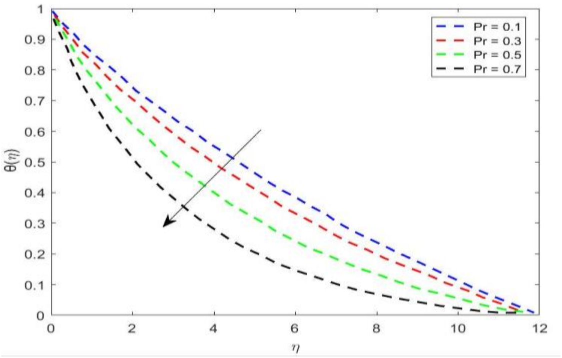

Figure 6 Variation of $\theta(\eta)$ for the different values of Pr for $\gamma = 0, \delta = -1,\ M = 0.2,\ R = 0.7, \alpha = -2$

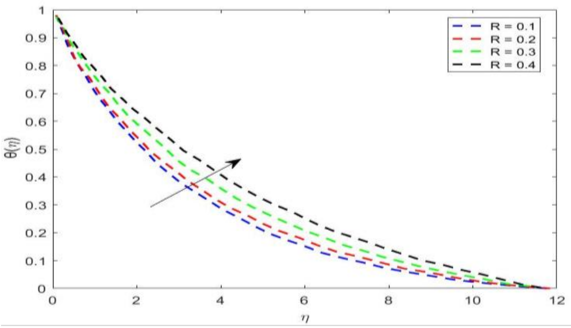

Figure 7 Variation of $\theta(\eta)$ for the different values of R for $\gamma = 0, \delta = -1,\ M = 0.2,\ Pr = 0.5, \alpha = -2$

Figure 6 demonstrate the effect of Prandtl number (Pr) on temperature profile $\theta(\eta)$. The graph elucidate that temperature profile $\theta(\eta)$ gradually decreases with the increasing value of Prandtl number (Pr).It is due to the property of Prandtl number that momentum diffusivity is higher than thermal diffusivity for large vale of Pr. **Figure7** shows that the impact of Radiation parameter (R) on temperature profile $\theta(\eta)$. Graph elaborate that temperature profile $\theta(\eta)$ enhances against the Radiation parameter (R). Due to the phenomenon of electromagnetic radiation, Thermal energy generates in the fluid flow because of radiation parameter. That causes to increase in the temperature profile.

Concluding Remark

In this study, we investigated the impact of second-order velocity slip condition on the two-dimensional flow of the fluid towards an exponentially stretching sheet. The effect of pertinent parameters on the velocity profile and temperature profile has been investigated.

The major findings are summarized as follows:

- In comparison to the second-order slip parameter $(\delta = -2)$, Velocity profile $f'(\eta)$ is a decreasing function for second-order slip parameter $(\delta = -4)$. This is due to an enhancement in resistance of fluid flow, which results in a decrement in the velocity profile $f'(\eta)$.
- Velocity profile $f'(\eta)$ is maximum for the first order slip parameter $(\gamma = 0)$ while it is lower for the first order slip parameter $(\gamma = 6)$. This shows a significant decrement in the velocity profile.
- Velocity profile $f'(\eta)$ is higher for the low magnetic parameter $(M = 0)$ but it is lower for high magnetic parameter $(M = 0.6)$.This reduction in velocity profile occurs because of resistive force generated by magnetic field.
- Temperature profile $\theta(\eta)$ is lesser for magnetic parameter $(M = 0)$, but for magnetic parameter $(M = 0.6)$, it displays a higher value of temperature profile $\theta(\eta)$. The increasing variation was observed in temperature profile for the magnetic parameter.
- Temperature profile $\theta(\eta)$ is maximum for Prandtl number $(Pr = 0.1)$ but it decreases for Prandtl number $(Pr = 0.7)$.The opposite behavior observed in Temperature profile against the Radiation parameter.

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