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Numerical Solution of MHD Mixed Convective Boundary Layer Flow of a Nanofluid through a Porous Medium due to an Exponentially Stretching Sheet with Magnetic Field Effect

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Abstract

In this paper, Magnetohydrodynamic - MHD boundary layer flow of a nanofluid is explored over an exponentially stretching sheet. Using similarity transformations, the governing boundary layer equations are reduced to ordinary differential equations. Hence obtained equations are solved numerically using the implicit finite difference method such as Keller Box technique. The heat transfer characteristics and flow field for the effects of the governing parameters were computed and discussed. The numerical patterns for various governing parameters like wall skin friction coefficient, the velocity, mass transfer coefficient, heat and temperature, concentration profiles are computed, discussed for its graphical characteristics. A comparison is made with prior published work and the results are found to be in excellent agreement.

Keywords: MHD, Nanofluid, Stretching Sheet, Keller Box, Heat transfer,Thermal Radiation.

INTRODUCTION

Magnetohydrodynamics - MHD boundary layer flow study on a continuous stretching sheet caught profound attention during the last few decades. This can be attributed to the numerous applications of MHD flow in industrial manufacturing processes such like aerodynamic extrusion of glass fiber, liquid firm, plastic sheets and paper production, polymer extrusion and drawing of plastic films, metal, and metal spinning.

Harris et.al [1] studied the transient free convection near the lower stagnation point of a cylindrical surface subjected to a sudden change in surface temperature. Numerical study of unsteady MHD oblique stagnation point flow with heat transfer over an oscillating flat plate was studied by Tariq Javed et.al [2]. Umer Farooq and Hang Xu [3] discussed the free convection nanofluid flow in the stagnation-point region of a three-dimensional body. Alsaedi et.al[4] analysed the effects of heat generation/absorption on stagnation point flow of nanofluid over a surface with convective boundary conditions. Stagnation Point Flow of a Nanofluid toward an Exponentially Stretching Sheet with Nonuniform Heat Generation/Absorption was presented by Malvandi et.al [5]. Domairry and Ziabakhsh [6] solved the solution of boundary layer flow and heat transfer of an electrically conducting micropolar fluid in a non-Darcian porous medium. Singh [7] presented the heat source and radiation effects on magneto-convection flow of a viscoelastic fluid past a stretching sheet: analysis with Kummer's functions. Magyari and Keller[8] investigated the heat and mass transfer in the boundary layers on an exponentially stretching continuous surface. Kuznetsov and Nield[9] investigated on Natural convective boundary layer flow of a nanofluid past a vertical plate. Khan and Pop [10] studied the boundary-layer flow of a nanofluid past a stretching sheet. MHD mixed convective boundary layer flow of a nanofluid through a porous medium due to an exponentially stretching sheet was investigated by Ferdows et.al [11]. Siva Kumar Reddy et.al [12] solved a HAM solution on MHD flow of Nano-fluid through Saturated Porous medium with Hall effects. Kiran Kumar and Varma[13] investigated on MHD boundary layer flow of nanofluid through a porous medium over a stretching sheet with variable wall thickness: using cattaneo–christov heat flux model. Numerical solution of the boundary layer flow over an exponentially stretching sheet with thermal radiation was given by Bidin and Nazar[14]. Mahatha et.al [15] investigated on Stagnation point nanofluid flow along a stretching sheet with non-uniform heat generation/absorption and Newtonian heating. Transpiration effect on stagnation-point flow of a Carreau nanofluid in the presence of thermophoresis and Brownian motion was studied by Sulochana et.al [16]. Yasin Abdela et.al [17] discussed on Sagnation point flow of nan fluid over a linear stretching surface with the effect of non-uniform heat source/sink. Shankar Goud et.al[18] have showed the study of Hall current and radiation effects on MHD free convective flow past an inclined parabolic accelerated Plate with variable temperature in a Porous medium. Influence of heat source/sink on a Maxwell fluid over a stretching surface with convective boundary condition in the presence of nanoparticles was given by Ramesh and Gireesha [19]. Kai-Long Hsiao [20] presented on conjugate heat transfer for mixed convection and maxwell fluid on a stagnation point. MHD flow past a vertical oscillating plate with radiation and chemical reaction in porous medium- finite difference method was presented by Shankar Goud[21]. Influence of non-uniform heat source/sink on MHD nanofluid flow past a slendering stretching sheet with slip effects was invested by Ramana Reddy et.al [22]. Hayat et.al [23] have studied on Stagnation-point flow of Maxwell fluid with magnetic field and radiation effects. Nadeem et.al [24] investigated on MHD stagnation flow of a micropolar fluid through a porous medium. Bal Reddy et.al [25] investigated an implicit finite difference solution of radiation effects on MHD fluid flow of a nanofluid past an exponential stretching sheet embedded in a porous medium. Alsaedi [26] studied the effects of heat generation/absorption on stagnation point flow of nanofluid over a surface with convective boundary condition. Ferdowsnet.al [27] investigated on MHD mixed convective boundary layer flow of a nanofluid through a porous medium due to an exponentially stretching sheet. MHD boundary layer flow of nanofluid over a continuously moving stretching surface have studied by Haroon Rasheed[28]. Malik et.al[29] discussed the boundary layer flow of hyperbolic tangent fluid over a vertical exponentially stretching cylinder.Abdul Rehman and Naveed Sheikh[30] investigated on the boundary layer stagnation point flow of micropolar fluid over an exponentially stretching sheet. Partha et.al [31] have analysed the effect of viscous dissipation on the mixed convection of heat transfer from an exponential stretching surface. Natural convective boundary-layer flow of a nanofluid past a vertical plate was studied by Kuznetsov and Nield[32].

Current paper focuses on the problem of MHD mixed convective boundary layer of a nanofluid flow over an exponentially stretching sheet. The nonlinear coupled ordinary differential equations are obtained from the governing equations. The transformed equations are dependent on dimensionless inertia parameter(∇), Thermophoresis parameter (Nt), magnetic parameter (R), viscosity ratio parameter$(\wedge)$, Eckert number(Ec), Brownian motion parameter (Nb), the combined porous and Mass convective parameter(λ_{M}), Lewis number$((Le)$, thermal convective parameter (λ_T) and Prandtl number (Pr) Hence obtained nonlinear coupled ordinary differential equations are numerically computed using implcit finite difference technique which is known as Temperature, velocity and concentration distributions are analysed graphically for effects of mass transfer rate, the surface heat and skin-friction coefficient at the sheet.

MATHEMATICAL FORMULATION

In this study, assume a steady two-dimensional flow of an electrically conducting nanofluid which is incompressible, viscous due to a stretching sheet. The sheet is of uniform temperature, placed in a quiescent ambient where the species concentration is raised to $T_w \geq T_\infty$ and $C_w^* \geq C_\infty^*$. This is maintained a constant further, where T_w, C_w^* refer to the temperature and species concentration at the wall while T_∞ and C_∞^*

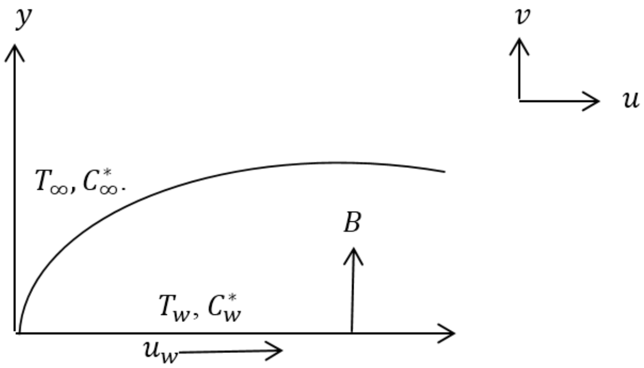

Fig 1: Schematic diagram of physical problems

correspond to temperature and species concentration far away from the plate. Along the stretching sheet, assume the *x*-axis along the direction of the motion and *y*-axis perpendicular to the motion. Also, assume a varying magnetic field $B(x)$ normal to the sheet neglecting the induced magnetic field, which can be justified for MHD flow at small values of magnetic Reynolds number. Figure 1 describes the physical configuration along with the coordinate system. The MHD free convective nanofluid flows for mass and heat transfer are as follows for the above considerations with usual boundary layer approximation

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y} = \bar{\upsilon}\frac{\partial^2 u}{\partial y^2}-\left(\frac{\upsilon}{K}+\frac{\sigma B_0^2}{\rho}\right)u+g\beta(T^*-T_\infty^*) + g\beta^*(C^*-C_\infty^*)-c^*\varepsilon^2u^2 \qquad \ldots(2)$$

$$u\frac{\partial T^*}{\partial x}+v\frac{\partial T^*}{\partial y} = \alpha\frac{\partial^2 T^*}{\partial y^2} + \frac{(\rho C)_p}{(\rho C)_f}\left\{D_B\frac{\partial T^*}{\partial y}\frac{\partial C^*}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T^*}{\partial y}\right)^2\right\}+\frac{\bar{\upsilon}}{c_p}\left(\frac{\partial u}{\partial y}\right)^2 \qquad \ldots(3)$$

$$u\frac{\partial C^*}{\partial x}+v\frac{\partial C^*}{\partial y} = D_B\frac{\partial^2 C^*}{\partial y^2}+\frac{D_T}{T_\infty}\frac{\partial^2 C^*}{\partial y^2} \qquad \ldots(4)$$

The appropriate boundary condition for this model is given by

$$\begin{aligned} &u=U_w=u_o e^{\left(\frac{x}{L}\right)}, v=0, T^*=T_w^*=T_\infty^*+T_0 e^{\left(\frac{x}{2L}\right)}, \\ &C^*=C_w^*=C_\infty^*+C_0 e^{\left(\frac{x}{2L}\right)}, \qquad \text{at } y\to 0 \qquad \ldots(5) \\ &u\to 0, \quad T^*\to T_\infty^* \quad C^*\to C_\infty^* \qquad \text{as } y\to\infty \end{aligned}$$

To obtain the similarity solutions, it is assumed that the magnetic field ($B(x)$) and variable thermal condutivity(K) can be taken as of the form $B(x) = B_0 e^{\left(\frac{x}{2L}\right)}$, $K = k_0 e^{\left(\frac{x}{2L}\right)}$. And also Equation (1) satisfies by defining the stream functions as

$$u = \frac{\partial \psi}{\partial y},\ v = -\frac{\partial \psi}{\partial x} \quad \ldots (6)$$

In order to gets a similarity solution to equations (1)-(4) with the boundary conditions equation (5), the following non-dimensional variables are used:

$$\psi = \sqrt{2\upsilon L u_0}\, f(\eta)\, e^{x/2L},\ T^* = T^*_\infty + (T^*_w - T^*_\infty)\theta(\eta),$$
$$C^* = C^*_\infty + (C^*_w - C^*_\infty)C(\eta)\quad \eta = y\sqrt{\left(\frac{u_0}{2\upsilon L}\right)}\, e^{x/2L},$$
$$u = \frac{\partial \psi}{\partial y} = u_o e^{\left(\frac{x}{L}\right)} f',\ v = -\frac{\partial \psi}{\partial x} = \sqrt{\left(\frac{u_0}{2\upsilon L}\right)}\, e^{x/2L}\left(f + \eta f'\right) \quad \ldots (7)$$

Using the above non-dimensional and similarity variables, eqns.(2)-(4) transformed into to the following nondimensional, nonlinear, and coupled ordinary differential equations as of the form:

$$\wedge f''' + ff'' - 2f'\left(f'(\Delta+1) + R\right) + 2(\lambda_T\theta + \lambda_M C) = 0 \quad (8)$$

$$\frac{1}{\Pr}\theta'' - \left(f'\theta - f\theta' - \wedge Ec\left(f'\right)^2 - Nb\theta' C' - Nt\theta'^2\right) = 0 \quad \ldots (9)$$

$$C'' + Le\left(fC' - f'\phi\right) + \frac{Nt}{Nb}C'' = 0 \quad \ldots (10)$$

The boundary conditions (8) and (4) becomes in the following form:

$$\begin{aligned} &f = 0, f' = 1,\ \theta = 1, C = 1 && at\ \eta \to 0 \\ &f' \to 0,\quad \theta \to 0,\ C \to 0 && as\ \eta \to \infty \end{aligned} \quad \ldots (11)$$

Here prime denote the differentiation with respect to η the non- dimensional physical parameters are defined as

$$\lambda_T = \frac{Gr}{Re_x^2} = \frac{g\beta\left(T_w - T_\infty\right)}{u_w^2},$$
$$\lambda_M = \frac{Gm}{Re_x^2} = \frac{g\beta\left(C^*_w - C^*_\infty\right)}{u_w^2},$$
$$R = \left(\frac{v}{k_0 u_0} + \frac{\sigma B_0^2 L}{\rho u_0}\right), \nabla = c^*\varepsilon^2 L,$$

$$\Pr = \frac{\upsilon}{\alpha}, Ec = \frac{u_0^2}{T_0 c_p}, Nb = \left(\frac{(\rho c)_p D_B\left(C^*_w - C^*_\infty\right)}{\upsilon(\rho c)_f}\right),$$
$$Nt = \left(\frac{(\rho c)_p D_T\left(T_w - T_\infty\right)}{\upsilon T_\infty(\rho c)_f}\right), Le = \frac{\upsilon}{D_B}, \wedge = \left(\frac{\bar{\upsilon}}{v}\right),$$

The quantities of physical meaning for this model are the skin friction, Nusselt number and the Sherwood numbers, which are calculated respectively, defines as is given by

$$C_f = -f''(0)\Big/\sqrt{2\,Re_x} \quad \ldots (12)$$

$$Nu = -\left(\sqrt{Re_x}\right)\theta'(0) \quad \ldots (13)$$

$$Sh = -\left(\sqrt{Re_x}\right)C'(0) \quad \ldots (14)$$

Where $Re_x = \frac{U_w x}{\upsilon}$ is the local Reynolds number.

SOLUTION OF THE PROBLEM

The system of nonlinear ordinary differential equations (8)-(10) with the boundary conditions (11) are solved numerically by using of Keller box method in combination with the Newton's linearization techniques with the MATLAB. In this method the following few steps are involved to complete Numerical solutions:

- In the first step reduce the transformed differential equations (8) – (10) are written into system of first order ordinary differential equations. In this case we introduce the new independent variables p, q, t, n, and the equations (8)-(10) and (11) reduces to the following way
-
$$\left.\begin{aligned} &f' = p,\ p' = q,\ \theta' = t,\ C' = n \\ &\wedge q' + fq - 2p\left(p(\Delta+1) + R\right) + 2(\lambda_T\theta + \lambda_M C) = 0, \\ &\frac{1}{\Pr}t' - \left(p\theta - ft - \wedge Ec\left(p\right)^2 - Nb\left(tn\right) - \left(t^2\right)Nt\right) = 0 \\ &n' + Le(fn - pC) + \left(\frac{Nt}{Nb}\right)t' = 0 \end{aligned}\right\} \quad \ldots (15)$$

  In order to new dependent variable the boundary conditions (11) becomes

$$\begin{aligned} &f = 0\ p = 1, \theta = 0, C = 1 && at\ \ \eta \to 0 \\ &p \to 0,\quad \theta \to 0,\ C \to 0 && as\ \eta \to \infty \end{aligned} \quad \ldots (16)$$

- In the second step write the finite differences for the first order equations.
- Step three linearize the algebraic equations, using the Newton's method,

  Example: $f_j^{(i+1)} = f_j^{(i)} + \delta f_j^{(i)}$.

- Fourth step write them in matrix form and solve the linear system by the block tri-diagonal elimination technique consists of variables or constants.

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For example:

$$\begin{bmatrix} [A_1][C_1] & & & & \\ [B_2][A_2][C_1] & & & & \\ & \dots & & & \\ & & \dots & & \\ & & [B_{i-1}][A_{j-2}][C_{i-1}] & & \\ & & & [B_j][A_j] \end{bmatrix} \begin{bmatrix} [\delta_1] \\ [\delta_2] \\ \dots \\ \dots \\ [\delta_{j-1}] \\ [\delta_j] \end{bmatrix} = \begin{bmatrix} [r_1] \\ [r_2] \\ \dots \\ \dots \\ [r_{j-1}] \\ [r_j] \end{bmatrix},$$

i.e, $[A][\delta] = [r]$

- To get the correctness of this method the appropriate initial guesses theories have been chosen. The following initial guesses are selected with the assistance of boundary conditions

$$f(\eta) = 1 - e^{-\eta},\ \theta(\eta) = e^{-\eta}, \phi(\eta) = e^{-\eta}.$$

RESULTS AND DISCUSSIONS

The system of nonlinear ordinary differential equations are coupled both heat and mass transfer; it is evident that analytical solution is not possible. In this manner, calculations have been carried out based on numerical technique which is known as Keller Box method However; the numerical outcomes are presented for some representative values of these governing parameters. In order to see the physical insight, the numerical values of velocity, temperature, and concentration with the boundary layer have been computed for different parameters. So as to examination the exactness of the numerical outcomes as the outcomes for the decreased Nusselt number for various estimations of Prandtl number and Eckert number Ec, the present outcomes compared with Ferdows et.al[11]. Comparison with the current outcomes demonstrates a positive assention, as presented in Table 1. In the present study, for numerical computation we have considered the non-dimensional parameter values such as $\lambda_T = 5.0, \lambda_M = 2.0, R = 4.0, \nabla = 1.0, Ec = 0.2, Pr = 1.0, Le = 5.0,$ $Nt = 0.1, Nb = 0.1$ and $\wedge = 1.5$. These values are kept as common in the entire study except the varied values as shown in respective figures and tables.

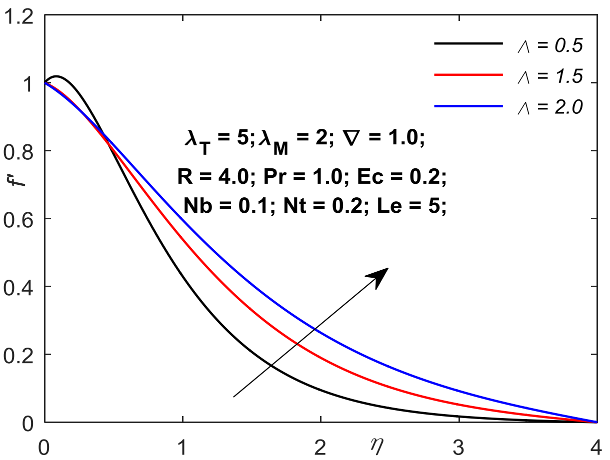

Fig. 2: Velocity profiles for various values of ∧.

Figure 2 depict the influence of the non-dimensional parameter such as viscosity ratio (∧), on the dimensionless velocity distribution for different values of ∧. Then for above case it is evident that increasing the values of ∧ the velocity profiles increase.

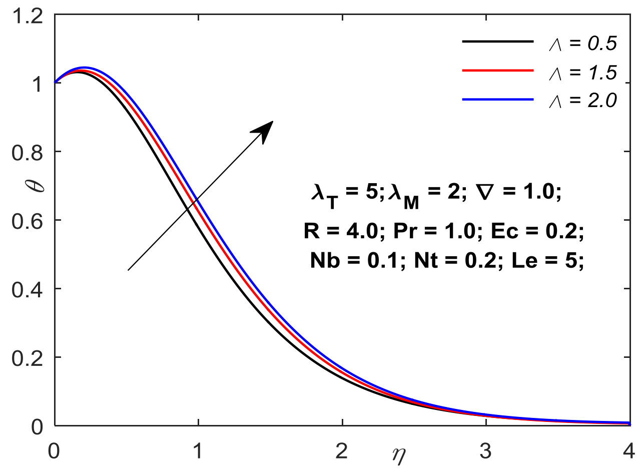

Fig. 3: Temperature profiles for various values of ∧.

The effect of the viscosity ratio (∧) on the dimensionless temperature distribution is exposed in figure 3. It is observed that the thermal boundary layer rises as ∧ is increased due to the fluid temperature to reduce at every point other than the wall.

Figure 4 displays the consequences of viscosity ratio (∧) on the concentration distribution. It pragamtic that the concentration boundary layer increases as ∧ is increases.

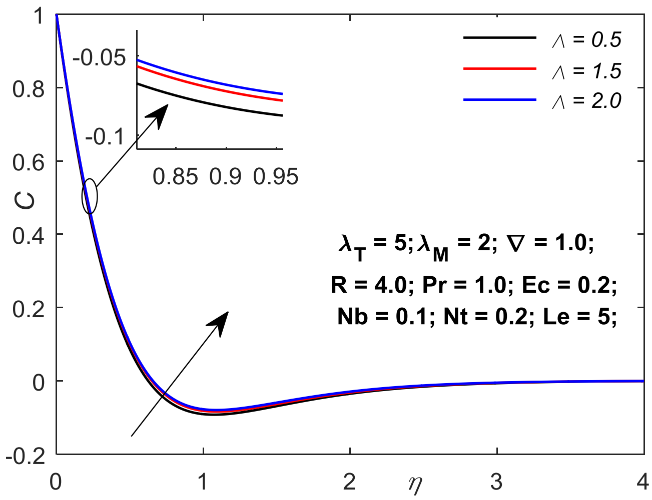

Fig. 4: Concentration profiles for various values of ∧.

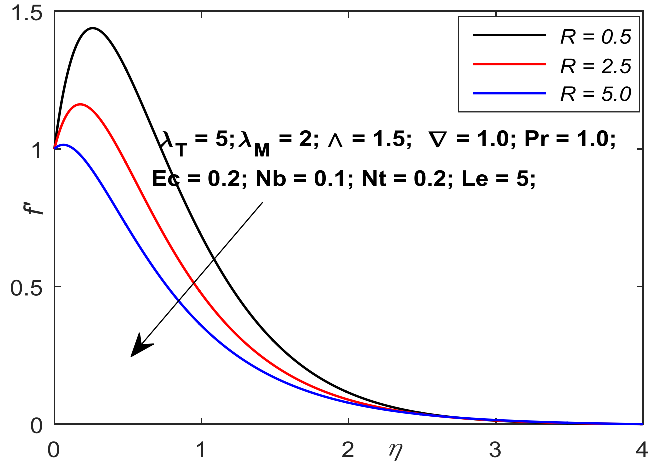

Fig. 5: Velocity profiles for various values of R.

Figure 5 shows the results of magnetic parameter (R) on the dimensionless velocity profiles. It is observed that the velocity reduces suddenly near the exponential stretching sheet as R is increased.

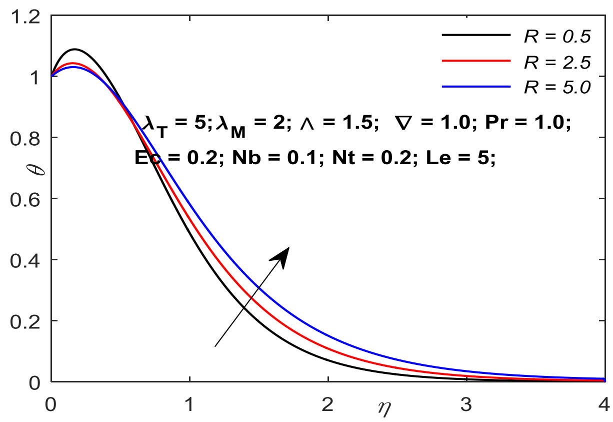

Fig. 6: Temperature profiles for various values of R.

Figure 6 signifies the temperature profiles outlines for various values of magnetic parameter (R). It is ascertained that the thermal boundary layer increases as R is increased.

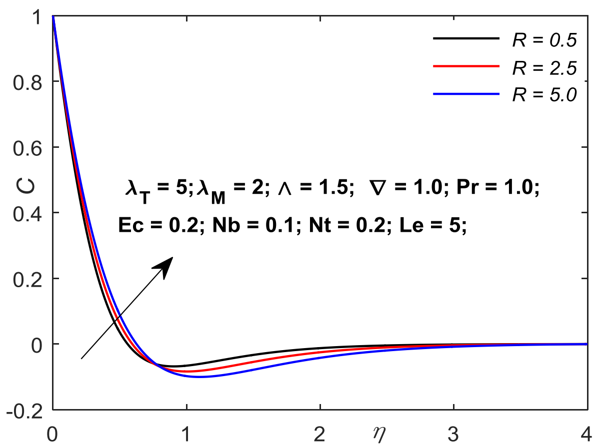

Fig. 7: Concentration profiles for various values of R.

Figure 7 represent the the concentration distribution for different values of magnetic parameter(R). It shows that the enhancement in the value of R improves the concentration profiles.

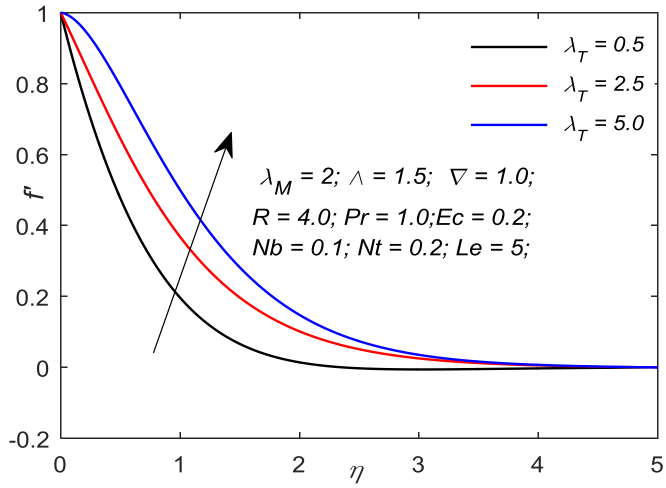

Fig. 8: Velocity profiles for various values of λ_T .

Figure 8 depict the effect of the dimensionless governing parameter on velocity profiles for different values of thermal convective parameter (λ_T), It observed that the velocity rises with an increasing the values of λ_T .

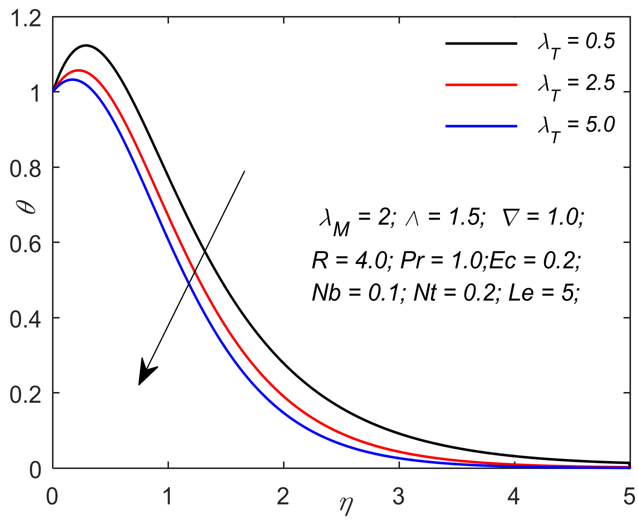

Fig. 9: Temperature profiles for various values of λ_T .

The effect of the temperature distribution for various values of the thermal convective parameter (λ_T) as shown in figure 9.It is clear that thermal convective parameter increasing the thermal boundary layer reduces.

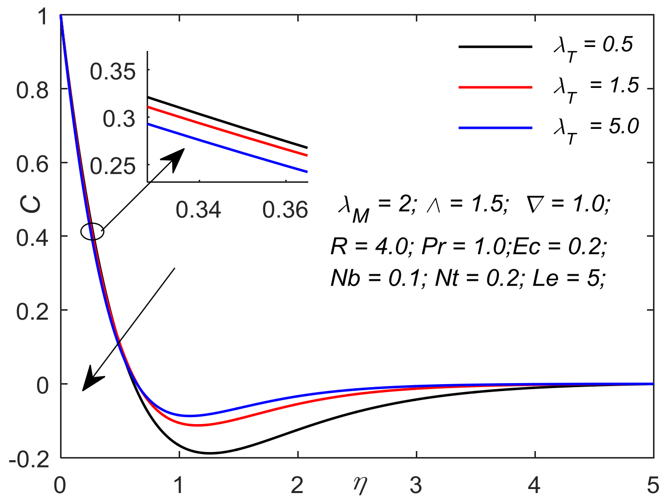

Fig. 10: Concentration profiles for various values of λ_T .

Figure 10 represent the concentration distribution for dissimilar values of thermal convective parameter(λ_T). It is seen that the increasing consequence of λ_T is to decrease concentration profiles as concentration species is dispersed away.

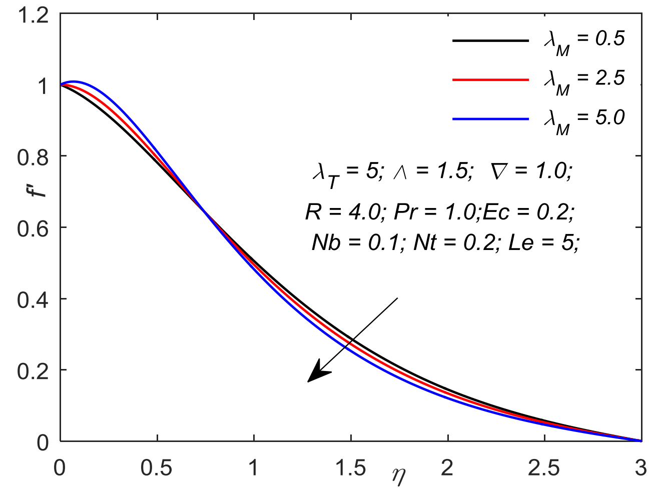

Fig. 11: Velocity profiles for various values of λ_M .

Figure 11 portrays the velocity outlines for various values of mass convective parameter λ_M . It shows that the velocity decreases with an increasing λ_M .

Figure 12 represent the dimensionless temperature profiles for distinct values of mass convective parameter λ_M . It is seen that the thermal boundary layer increases as λ_M is increased.

Table 1: Comparison for the reduced Nusselt number $-\theta'(0)$ for the absence physical parameter values

Pr	$Ec = 0.0, K = 0.0$		$Ec = 0.2, K = 0.0$		$Ec = 0.9, K = 0.0$	
	Ferdows et.al [11]	Present study	Ferdows et.al [11	Present study	Ferdows et.al [11	Present study
1	0.9550	0.9554	0.8629	0.8632	0.5392	0.5396
2	1.4719	1.4723	0.3062	0.3066	0.7250	0.7254
3	1.8701	1.8705	1.6890	1.6893	0.8309	0.8313

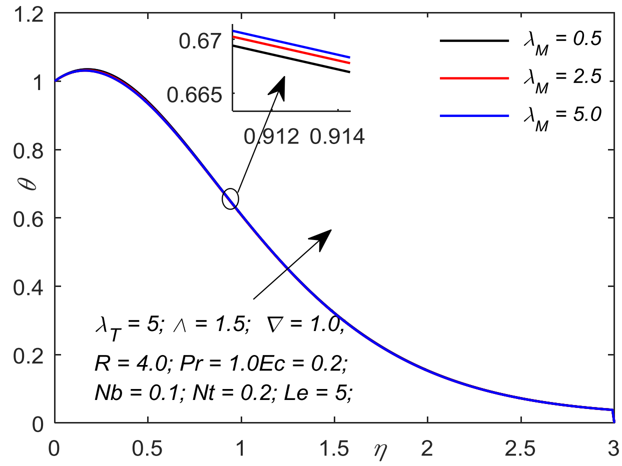

Fig. 12: Temperature profiles for various values of λ_M .

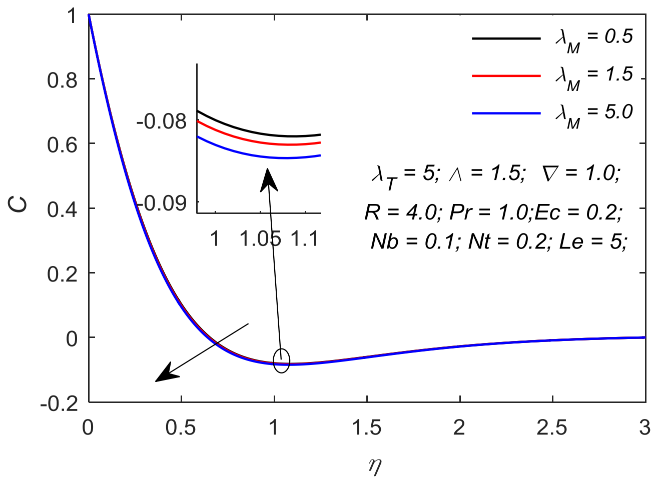

Fig. 13: Concentration profiles for various values of λ_M .

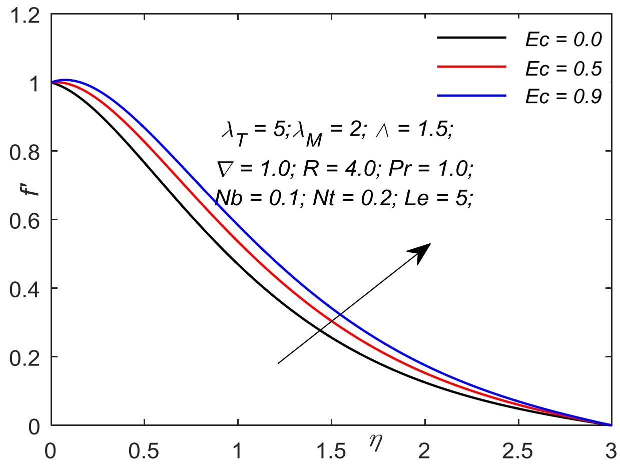

Fig. 14: Velocity profiles for various values of Ec .

Figure 13 displays the consequences of mass convective parameter λ_M on the concentration distribution. It is pragmatic that the concentration boundary layer reduces as λ_M is increased.

Figure 14 represent the dimensionless velocity profiles for changed values of Eckert number(Ec). It is observer that the velocity increases with an increasing the values of Eckert number(Ec).

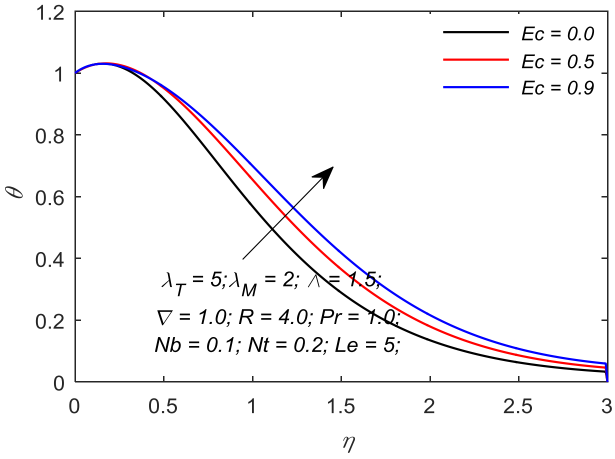

Fig. 15: Temperature profiles for various values of Ec .

Figure 15 displays the non-dimensional temperature distribution for different values of Eckert number(Ec). It is noticed that a rise within the Eckert number results increased in thermal boundary layer.

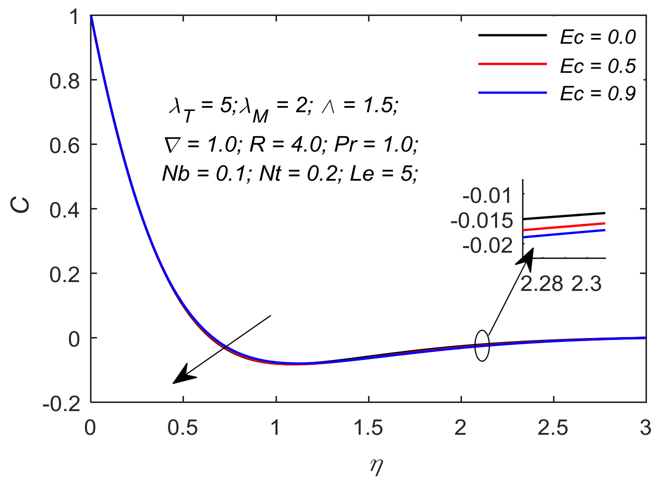

Fig. 16: Concentration profiles for various values of Ec .

Figure 16 shows the characteristics of non-dimensional concentration distribution for different values of Eckert number(Ec). It is illustrate that a rise within the Eckert number results in reduction of the concentration boundary layer.

Since the physical importance of the problem, the skin-friction coefficient the Nusselt number at the sheet and the Sherwood number at the sheet are plotted against Brownian motion parameter(Nb) and illustrated in Figures 17–20.

Figure 17 represent the skin-friction coefficient $-f''(0)$ plotted for the various values of magnetic parameter R. It is confirmed that there is a decrease in skin-friction coefficient as R increases.

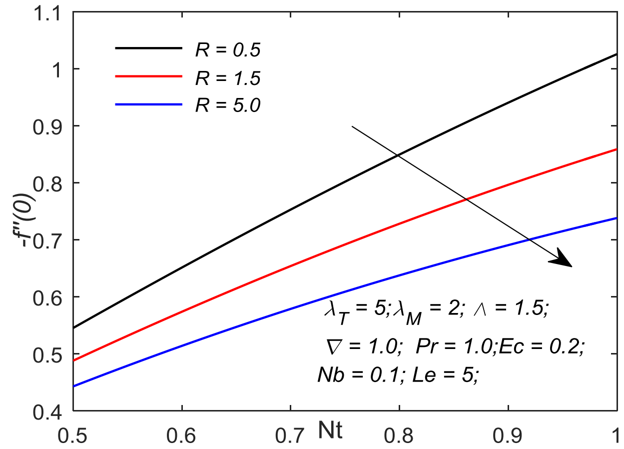

Fig. 17: Effect of R on skin-friction coefficient.

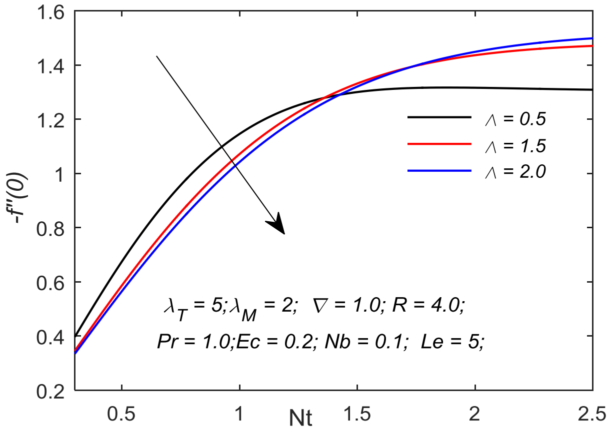

Fig. 18: Effect of $\wedge$ on skin-friction coefficient.

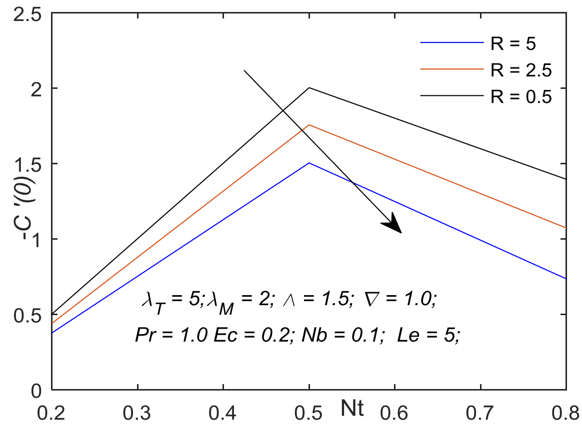

Figure 21: Effect of R on mass transfer rate.

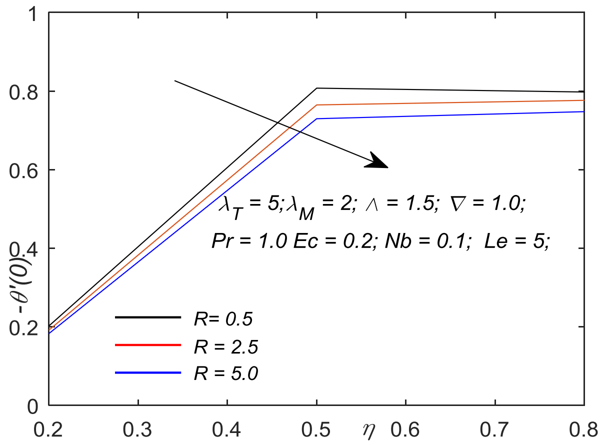

Fig 19: Effect of R on heat transfer rate.

Figure 18 demonstrates the skin-friction coefficient $-f''(0)$ depict for the dissimilar values of viscosity ratio parameter($\wedge$). It is shown that there is a decrease in skin-friction coefficient with an increase of ratio parameter($\wedge$) increases.

Figure 19 exhibits the Nusselt number $-\theta'(0)$ plotted for the various values of magnetic parameter(R). It is noticed that an increasing the magnetic parameter there is a decrease in Nusselt number.

Figure 21 displays the Sherwood number $-C'(0)$ depicted for the distinct values of viscosity ratio parameter($\wedge$) and is verified that there is a decrease in Sherwood number with viscosity ratio parameter($\wedge$) increases.

CONCLUSIONS

In this paper, the effects of radiation on steady MHD mixed convection boundary layer flow of a nanofluid over an exponentially stretching sheet are analysed. For various governing parameters, the effects on fluid flow are numerically computed and analysed graphically. Among the graphs, the effects of Nusselt number, skin-friction coefficient and Sherwood number with the exponential sheet along with the temperature, concentration and velocity effects.

The current study can be concluded with the following:

- On increasing viscous ratio parameter, concentration boundary layer, momentum, thermal boundary layer thickness increases. Alternatively, increase in viscous ratio parameter leads to decrease in skin friction coefficient.
- Near the exponential stretching sheet, concentration boundary layer increases steeply along with thermal boundary layer with an increase in Magnetic parameter and porous together. Alternative behaviour is observed with surface heat transfer rate and skinfriction coefficient and mass transfer rate.
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- On higher values of Eckert number, concentration boundary layer is found to decrease gradually while thermal boundary layer and momentum are observed to decrease.

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Nomenclature	
(u,v)	Velocity components in (x,y) direction
μ	Dynamic viscosity
υ	Kinematic viscosity
$\bar{\upsilon}$	Reference kinematic viscosity
σ	Electrical conductivity
T & C	Temperature & concentration in boundary layer
$c^*\varepsilon^2$	Inertia parameter
ρ	Density of the fluid
K	Variable thermal conductivity
α	Thermal diffusivity
C_p	Specific heat at constant pressure
D_B	Bronian diffusion coefficient thermophoretic
D_T	Thermophoretic diffusion coefficient
L	Characteristic length of the plate
u_0 & B_0	Reference velocity &constant magnetic field
T_0 & C_0	Reference of the temperature & concentration
R	Combined porous and magnetic parameter
$\wedge$	Viscosity ratio parameter
λ_T	Thermal convective parameter
λ_M	Mass convective parameter
Pr	Prandtl number
Ec	Eckert number
Nb	Brownian motion parameter
Nt	Thermophoresis parameter