Heat Source/Sink and Chemical Reaction Effects on MHD and Heat Transfer Flow of Radiative Nanofluid Over a Porous Exponentially Stretching Sheet with Viscous Dissipation and Ohmic Heating

M. Thiagarajan, M. Dinesh Kumar

Abstract: This paper presents an investigation of the hydromagnetic boundary layer flow of a nanofluid and heat transfer past a porous exponentially stretching sheet with effects of heat generation/absorption and Ohmic heating. The impact of Brownian motion and thermophoresis on heat transfer, thermal radiation, chemical reaction and viscous dissipation are also considered. Nonlinear partial differential equations governing the motion are reduced to ordinary differential equations by using similarity transformations. These equations are solved numerically using the Nachtsheim-Swigert shooting technique scheme together with Fourth-order Runge-Kutta integration method, for different values of flow parameter such as magnetic interaction parameter, porosity parameter, Brownian motion, thermophoresis parameter, Eckert number, heat source/sink parameter, Lewis number, chemical reaction parameter, and suction parameter. Quantities of physical interest such as skin-friction coefficient, non-dimensional rate of heat and mass transfer are solved numerically and are tabulated. Comparisons with previously study are performed and are found to be in a good agreement.

Index Terms*: *Exponentially Stretching Sheet, Heat Source/Sink, Joules Dissipation, MHD, Nanofluid, Thermal Radiation.

I. INTRODUCTION

The flow due to a stretching sheet is a prominent problem in classical fluid mechanics due to its large applications in many production processes in industry, such as paper manufacture, wire drawing, hot rolling, polymer sheet, textile industries, production of glass sheets and many others. Due to plentiful applications in varied fields, researches on flow due to stretching sheets have derived the focus of engineers and scientists in recent days. In these applications of stretching sheet, the present work dealt with a problem on convective flow over a stretching sheet. The laminar boundary layer flow of incompressible and viscous fluid to a continuous moving rigid surface was initially discussed by Sakiadis [1]. Later, the flow properties past a stretching sheet problem were investigated by Crane [2]. Chen and Char [3] addressed the boundary layer and heat transfer from a continuous linear stretching sheet to suction or blowing. Boundary layer viscous and incompressible flow past a stretching sheet was discussed by Kumaran and Ramanaiah [4]. Fang and Zhang [5] analyzed the slip condition past a permeable stretching sheet is solved analytically. A few years later, Mukhopadhyay [6] discussed the steady MHD boundary layer flow and heat transfer over an exponentially stretching surface embedded in a thermally stratified medium.

A new genre of fluid known as nanofluid is initially introduced in Argonne National Laboratory in United States by Choi and Eastman [7]. Buongiorno [8] presented the detailed research of convective transport in nanofluid. The upgraded thermal activity of nanofluids could render a basis for a prominent innovation for heat transfer intensification, which is importance to a number of production sectors including transportation, nuclear reactors, and food, etc. In view of above relevance, many authors have been investigated different characteristics of flow and heat transfer of nanofluids [9], [10], and [11].

Magnetohydrodynamic (or) hydromagnetic (MHD) boundary layer flow over a stretching sheet has attracted substantial notice during the last few years. Chandrasekar and Kasiviswanathan [12] considered MHD radiative nanofluid nanofluid over a stretching sheet. Rout and Mishra [13] obtained effect of heat and mass transfer in MHD nanofluid flow past a stretching sheet. Recently, Impacts of heat generation on MHD flow of radiative nanofluid over an exponentially stretching sheet in a porous medium with viscous dissipation are numerically analyzed by Thiagarajan and Dinesh Kumar [14]. Many investigators regarding magnetohydrodynamic flow have been studied [15], [16], [17], and [18].

In special, studies concerned with ohmic heating (Joules dissipation) effect in MHD flows have very significant applications such as in ohmic heaters. Combined influences of magnetic field, viscous and ohmic dissipations on the boundary layer of nanofluids past a flat plate are analyzed theoretically by Makinde and Mutuku [19]. Mishra et al. [20] studied MHD flow of nanofluid over a stretching cylinder in the presence of viscous and ohmic dissipations,

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heat generation/absorption effects. Hayat et al. [21] analyzed the influence of melting heat transfer in boundary layer flow of nanofluid past a stretching sheet joule heating and viscous dissipation.

The thermal radiation impact may substantial at high operating temperatures in engineering procedures. Due to its extensive range of applications, the following authors discussed [22], [23], [24], and [25]. The study of heat source or sink impacts is very significant in cooling procedures. Awais et al. [26] studied heat generation/absorption effects in a non-Newtonian fluid flow over a stretching sheet. Very Recently, Combined effects of viscous-ohmic dissipation and heat source/sink on hydromagnetic flow of nanofluid past a stretching sheet were investigated by Mishra and Manojkumar [27].

The main objective of the paper is to analyze the Chemical reaction effects on MHD flow of a radiative nanofluid and heat transfer over a porous exponentially stretching sheet. Due to these practical importance, no studies have thus far been made with regard to heat source/sink and chemical reaction effects on MHD flow of a radiative nanofluid and heat transfer over a porous exponentially stretching sheet in the presence of viscous and joules dissipation and hence the present analysis is concerned with such a study. Using similarity variables, nonlinear partial differential equations governing the motion are reduced to ordinary differential equations by using similarity transformations. These equations are solved numerically using the Nachtsheim-Swigert shooting technique scheme together with Fourth-order Runge-Kutta integration method. Due to the quantities of engineering interest such as Skin-friction coefficient, dimensionless rate of heat and mass transfer are obtained numerically and are portrayed in tabular form.

II. PROBLEM FORMULATION

Consider a steady, two dimensional, nonlinear, magnetohydrodynamic laminar boundary layer flow of an incompressible, viscous radiative nanofluid and heat transfer past a porous exponentially stretching sheet. The sheet is coincident with the plane $y=0$ and the flow being confined to $y>0$ as given in Fig. 1. The sheet is assumed to be permeable such that possible suction impact occurs at the surface. A variable magnetic field of strength $B(x)$ is applied normal to the sheet and parallel to $y-$axis as shown in the figure. The $x-$axis runs along the stretching sheet and they $y-$axis is perpendicular to it. The stretching sheet velocity $U_w(x)=bx^{x/L}$ where b is a positive constant and the sheet is subjected to the variable suction that $v=-V_w(x)$, the value of which will be defined later.

Using the boundary layer approximations, the simplified steady, two dimensional, nonlinear magnetohydrodyamic boundary layer equations governing the flow and heat transfer. Under these conditions, the governing boundary layer equations of continuity, momentum, energy, and concentration equations with viscous dissipation and ohmic heating effects are,

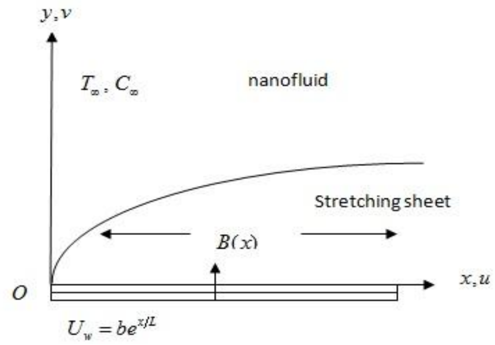

Fig. 1 Sketch of the Problem

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{1}{\rho_f}\left[\mu_f\frac{\partial^2 u}{\partial y^2}-\sigma B^2(x)u-\mu_f\frac{u}{K_1}\right] \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{\nu}{(c_p)_f}\left(\frac{\partial u}{\partial y}\right)^2+\frac{\sigma B^2(x)u^2}{(\rho c_p)_f}$$
$$+\frac{(\rho c)_p}{(\rho c)_f}\left\{D_B\left(\frac{\partial T}{\partial y}\frac{\partial C}{\partial y}\right)+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right\} \tag{3}$$
$$+\frac{Q'(x)(T-T_\infty)}{(\rho c_p)_f}-\frac{1}{(\rho c_p)_f}\frac{\partial q_{rad}}{\partial y}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}+\frac{D_T}{T_\infty}\left(\frac{\partial^2 T}{\partial y^2}\right)-K_R(C-C_\infty) \tag{4}$$

The boundary conditions are,

$$\begin{aligned}
&u=U_w(x)=be^{x/L},\ v=-V_w(x),\\
&T=T_w=T_\infty+T_0\ e^{x/2L}\\
&C=C_w=C_\infty+C_0\,e^{x/2L} \qquad at\ \ y=0\\
&u\to 0,\ T\to T_\infty,\ C\to C_\infty \qquad as\ \ y\to\infty
\end{aligned} \tag{5}$$

where u and v are the velocity components in the x and y directions, ρ is the fluid density, μ is the viscosity, ν is the kinematic velocity, σ is the electrical conductivity, c_p is the heat capacity, D_B is the Brownian diffusion coefficient, D_T is the thermophoresis diffusion coefficient, T is the temperature, C is the nanoparticle volume fraction, $B(x)$ is the variable magnetic field, $Q'(x)$ is the variable heat generation parameter and V_w is the mass transfer velocity ($V_0>0$ for mass injection and $V_0<0$ for mass suction). These variable magnetic field, variable heat generation parameter, and mass transfer are considered as

$$B(x)=B_0e^{x/2L},\ \ Q'(x)=Q_0e^{x/L},\ \ V_w(x)=V_0e^{x/2L} \tag{6}$$

where B_0 is the constant magnetic field and Q_0 is the heat generation constant. Using Rosseland approximation for thermal radiation (Hossain et al., 1999), has the form,

$$q_{rad}=-\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y}$$

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where σ^* is the Stefan-Boltzman constant and k^* is the mean absorption coefficient. We assuming that the temperature difference within the flow is such that T^4 may be expanded in a Taylor series and expanding T^4 and T_∞ and neglecting higher orders, we obtain

$T^4 \cong 4T_\infty^3 - 3T_\infty^4$

Therefore, the equation (3) becomes,

$$\left.\begin{aligned} & u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{\nu}{(c_p)_f}\left(\frac{\partial u}{\partial y}\right)^2+ \\ & \frac{\sigma B^2(x)u^2}{(\rho c_p)_f}+\frac{(\rho c)_p}{(\rho c)_f}\left\{D_B\left(\frac{\partial T}{\partial y}\frac{\partial C}{\partial y}\right)+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right\} \\ & \qquad +\frac{Q'(x)(T-T_\infty)}{(\rho c_p)_f}-\frac{1}{(\rho c_p)_f}\frac{16\sigma T_\infty^3}{3k^*}\frac{\partial^2 T}{\partial y^2} \end{aligned}\right\} \quad (7)$$

The continuity equation (1) is satisfied by introducing a stream function $\psi(x, y)$ such that

$$u=\frac{\partial \psi}{\partial y}, \qquad v=-\frac{\partial \psi}{\partial x} \quad (8)$$

Now following Similarity transformations

$$\left.\begin{aligned} & \eta = y\sqrt{\left(\frac{b}{2\nu_f L}\right)}e^{x/2L}, \psi=\sqrt{2\nu_f L b}\,e^{x/2L}f, \\ & u=b e^{x/L}f', v=-\sqrt{\left(\frac{\nu_f b}{2L}\right)}e^{x/2L}\{f+\eta f'\}, \\ & \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty}, \ h(\eta)=\frac{C-C_\infty}{C_w-C_\infty} \end{aligned}\right\} \quad (9)$$

Committed to the transformed non-dimensional of the form

$$f''' + ff'' - 2f'^2 - M f' - K_p f' = 0 \quad (10)$$

$$\frac{1}{\Pr}\left(1+\frac{4R_d}{3}\right)\theta'' + \left[\begin{aligned} & f\theta' - f'\theta + Ec\{f''^2 + M f'^2\} \\ & + Nb\theta' h' + Nt\theta'^2 + Q_H\theta \end{aligned}\right] = 0 \quad (11)$$

$$h'' + Le f h' - Le f' h - Le C_R h + \left(\frac{Nt}{Nb}\right)\theta'' = 0 \quad (12)$$

with boundary conditions

$$\begin{aligned} & f(0)=f_w,\ f'(0)=1,\ \theta(0)=1,\ h(0)=1 \quad \text{at } \eta=0 \\ & f'(\eta)\to 0,\ \theta(\eta)\to 0,\ h(\eta)\to 0 \qquad \text{as } \eta\to\infty \end{aligned} \quad (13)$$

where M is the magnetic interaction parameter, $\Pr$ is the Prandtl number, R_d is the thermal radiation parameter, Ec is the viscous dissipation (Eckert number), Q_H is the heat source/sink parameter, Le is the Lewis number, C_R is the chemical reaction parameter, Nb is the Brownian motion parameter, Nt is the thermophoresis parameter, and K_p is the porosity parameter. They are respectively defines as,

$$M=\frac{2\sigma B_0^2 L}{b\rho_f}, \quad \Pr=\frac{\nu}{\alpha} \ R_d=\frac{4\sigma^* T_\infty^3}{k^* k_{nf}},$$

$$Ec=\frac{U_w^2}{(C_p)_f(T_w-T_\infty)}, \ Q_H=\frac{2LQ'}{(\rho C_p)_f\, b},$$

$$C_R=\frac{2K_R L}{b}, \ Nb=\tau\frac{D_B(C_w-C_\infty)}{\nu},$$

$$Nt=\tau\frac{D_T(T_w-T_\infty)}{\nu}, \ K_p=\frac{\nu L}{bK_1}, \ Le=\frac{\nu}{D_B}$$

The physical quantities of interest in this study are the local skin friction coefficient C_f, Nusselt number Nu, and Sherwood number Sh which are defined as

$$C_f=\frac{\mu}{\rho_f e^{2x/L}b^2}\left(\frac{\partial u}{\partial y}\right)_{y=0},$$

$$Nu=-\frac{x}{(T_w-T_\infty)}\left(\frac{\partial T}{\partial y}\right)_{y=0},$$

$$Sh=-\frac{x}{(C_w-C_\infty)}\left(\frac{\partial C}{\partial y}\right)_{y=0} \quad (14)$$

Using equation (9), it is obtained as,

$$\sqrt{2\mathrm{Re}_x}C_f = f''(0),$$

$$\frac{Nu}{\sqrt{2\mathrm{Re}_x}}=-\frac{x}{2L}\theta'(0),$$

$$\frac{Sh}{\sqrt{2\mathrm{Re}_x}}=-\sqrt{\frac{x}{2L}}g'(0) \quad (15)$$

where $\mathrm{Re}_x=\dfrac{U_w x}{\nu}$ is the local Reynolds number.

III. NUMERICAL SOLUTIONS OF THE PROBLEM

The governing nonlinear partial differential equations are converted to nonlinear ordinary differential equations by similarity transformations with the necessary similarity variables. The equations (10) to (12) represent a highly nonlinear boundary value problem of third and second order, which is arduous to solve analytically. Then the equations are solved numerically using the most efficient shooting technique such as the Nachtsheim-Swigert shooting iteration scheme for satisfaction of asymptotic boundary conditions along with Fourth-order Runge-Kutta based integration method with step size $h=0.01$. The numerical values of non-dimensional velocity, temperature, and concentration are obtained for different values of physical parameters. The level of the accuracy for convergence is taken upto 10^{-5}.

IV. RESULTS AND DISCUSSION

Similarity solutions are obtained utilizing the efficient shooting method such as Nachtshim-Swigert shooting iteration scheme for satisfaction of asymptotic boundary conditions together with fourth order Runge-Kutta integration method. Nachtshim-Swigert shooting iteration scheme justifies the unique solution.

In order to have the physical insight of the problem, numerical solutions are obtained for various values of the physical parameters and are illustrated graphically.

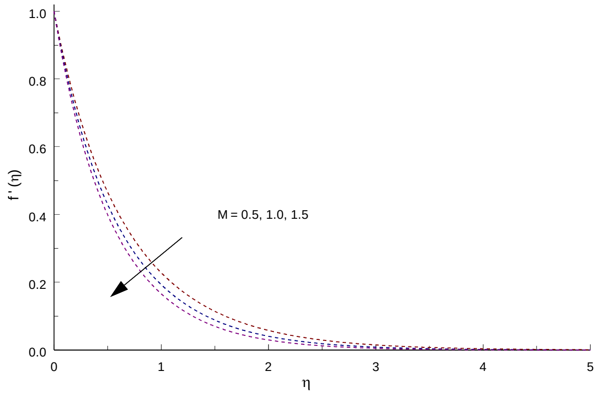

Fig. 2 Velocity profiles for various values M

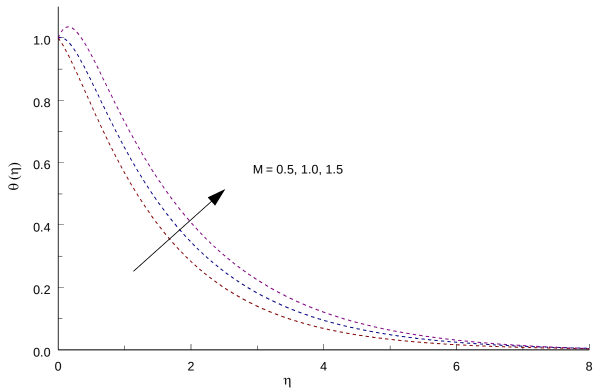

Fig. 3 Temperature profiles for various values M

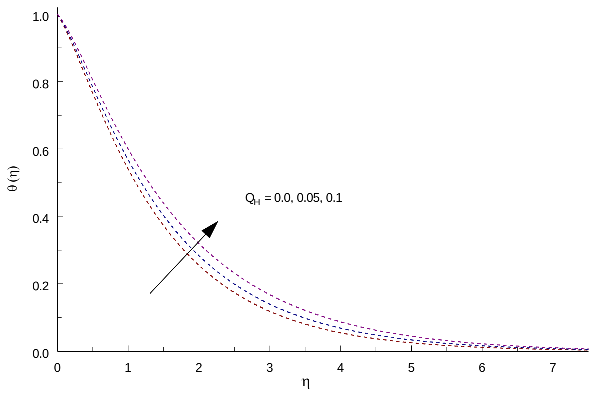

Fig. 4 Temperature profiles for various values of heat source parameter

The dimensionless velocity for several values of magnetic interaction parameter M is portrayed in fig. 2. Due to the presence of transverse magnetic field the velocity gets decelerated. This eventuated due to the force rising from the magnetic interaction and electrical fields during the motion of the electrically conducting fluid. It is noted that the dimensionless velocity of the fluid reduces as magnetic interaction parameter increases. Fig. 3 shows the influence of magnetic interaction parameter M on temperature distribution. From this figure, we can seen that the temperature is enhanced owing to the increase in the value of magnetic interaction parameter M. It is further remarked that the thickness of thermal boundary layer enhances with the raise in severity of magnetic interaction parameter M. Fig. 4 demonstrates the impact of heat generation (or source) Q_H on dimensionless temperature profiles. It is observed that the heat generation Q_H enhances then the temperature distribution increased. It is exhibit that the heat energy is created in thermal physical aspect that causes the temperature. Fig. 5 show the effect heat absorption (Q_H) parameter on dimensionless temperature $\theta(\eta)$. It is a display that decreases of temperature profiles with enhancing values of $(Q_H = 0.0, -0.05, -0.1)$ heat absorption parameter.

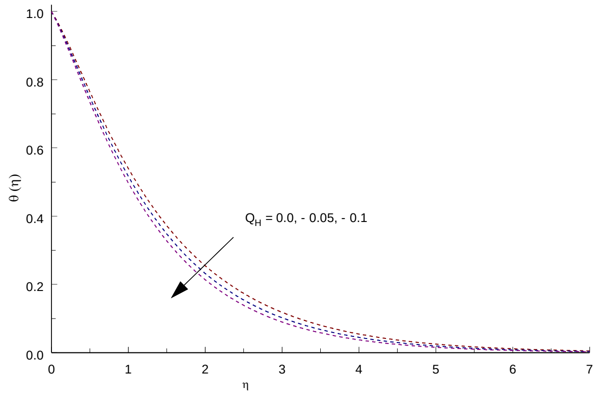

Fig. 5 Temperature profiles for various values of heat sink parameter

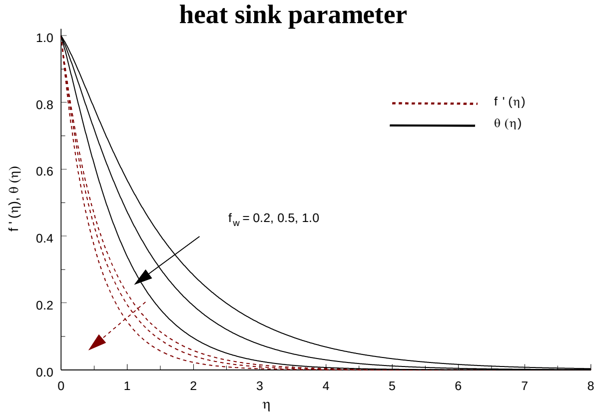

Fig. 6 Velocity and temperature profiles for various values of suction parameter

The variation of dimensionless velocity and temperature profiles for different values of suction parameter f_w is portrayed in Fig. 6. It is inferred that as suction parameter enhances, the velocity of the fluid flow decreases and it is remarked that increasing suction parameter f_w, reduces the temperature profile. Also, thermal boundary layer thickness reduces due to the influence of suction parameter. The non-dimensional concentration profile for several values of suction parameter f_w is depicted in Fig. 7. It is observed that a steady decrease in concentration profile accompanies a rise in suction parameter f_w. The effect of viscous dissipation (Eckert number) Ec over the dimensionless temperature is visualized in Fig. 8. It is obviously seen that the temperature is enhanced due to the dissipation effects.

Further, the thermal boundary layer thickness is broadened as a result of step up in the values of Eckert number Ec, which converges the fact that the dissipative energy becomes more important with an enhancement in temperature distribution.

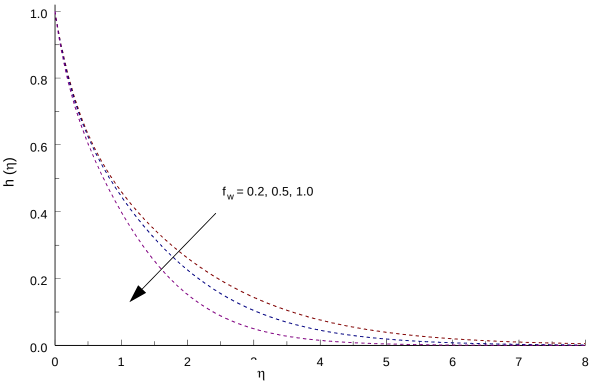

Fig. 7 Concentration profiles for various values of suction parameter

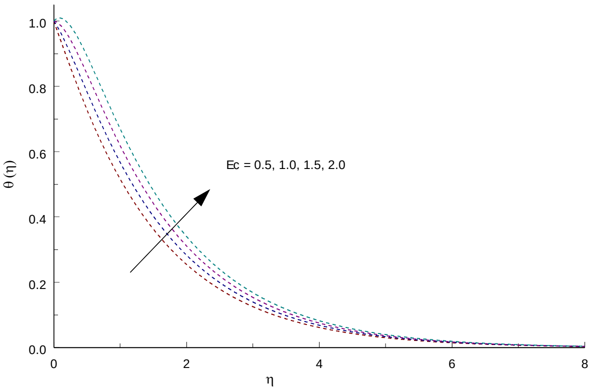

Fig. 8 Temperature profiles for various values of Eckert number

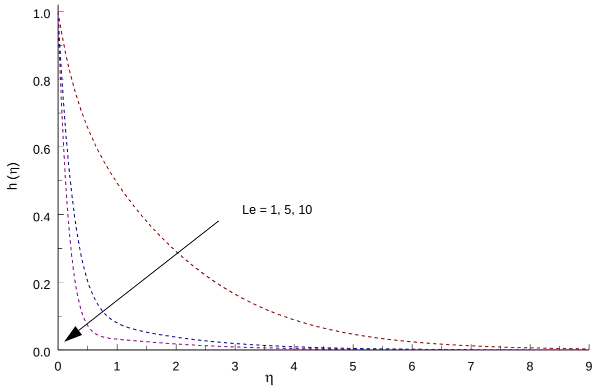

Fig. 9 Concentration profiles for various values of Lewis number

Fig. 9 shows the variation of concentration profile for various values of Lewis number Le. The larger values of Lewis number $(Le = 1, 5, 10)$ creates the lower molecular diffusivity. It is remarked that an enhance in the Lewis number Le impacts in decline in the concentration distribution within the boundary layer. Fig. 10 illustrates the influence of thermal radiation on dimensionless temperature. It is remarked that an enhance in the thermal radiation parameter R_d causes a rise in thermal radiation and the thermal boundary layer thickness as portrayed in Fig. 10.

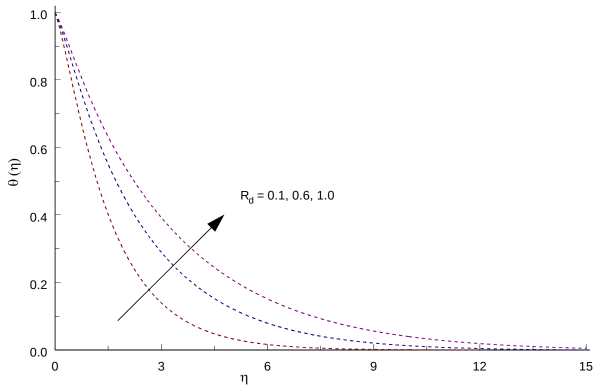

Fig. 10 Temperature profiles for various values of radiation parameter

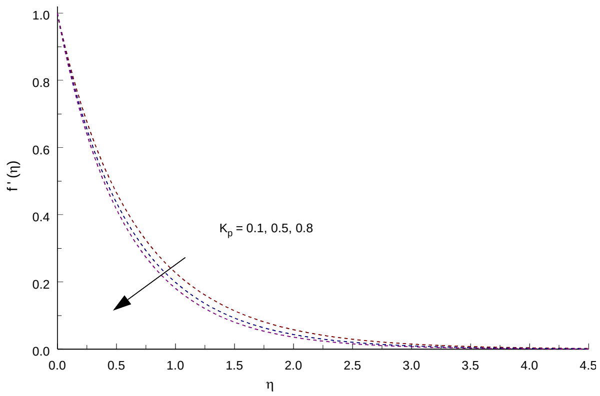

Fig. 11 Velocity profiles for various values of porosity parameter

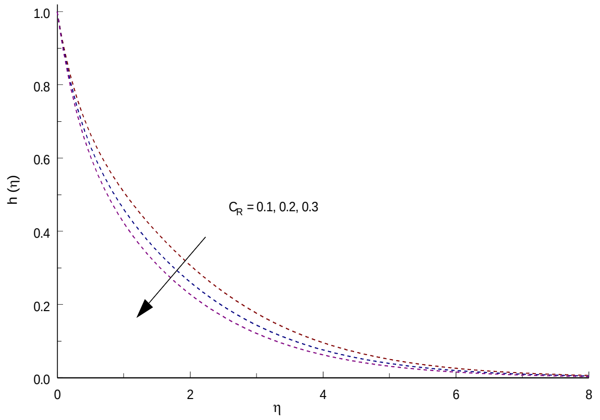

Fig. 12 Concentration profiles for various values of chemical reaction parameter

Fig. 11 displays how permeability parameter K_p affects the dimensionless temperature of the fluid. It is noted that an enhance in permeability parameter K_p reduces the temperature and also remarked that the presence of porous medium causes higher limitation to the fluid flow. Fig. 12 depicts the impact of chemical reaction parameter C_R on concentration profile.

It is cleared that the concentration boundary layer thickness reduces with enhancing the different value of chemical reaction parameter $(C_R = 0.1, 0.2, 0.3)$. This is due to the higher the chemical reaction rate, the thicker the concentration boundary layer.

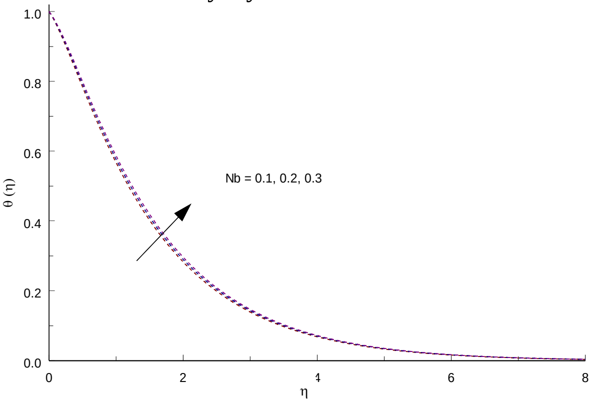

Fig. 13 Temperature profiles for various values of Brownian motion

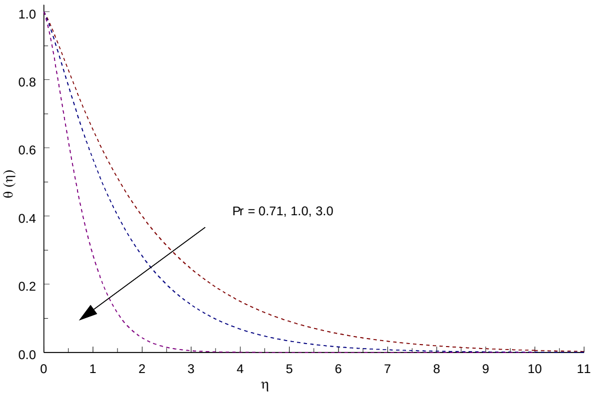

Fig. 14 Temperature profiles for various values of Prandtl number

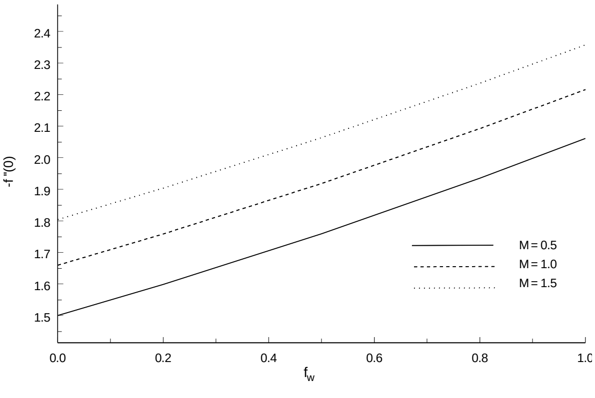

Fig. 15 Effects of M and f_w on skin friction coefficient

The influence of Brownian motion parameter Nb on non-dimensional velocity profiles is portrayed graphically through Fig. 13. It is remarked that the thermal boundary layer thickness and the temperature enhances as Brownian motion parameter Nb increases. Also, it is observed that the effect of Brownian motion parameter Nb has a slightly significant effect over the temperature. Fig. 14 is represented the dimensionless temperature for several values of Prandtl number $\Pr$. It is evident that for that the enhancing values of Prandtl number $\Pr$, reduces the temperature. Further the thermal boundary layer thickness is broadened as a result of step up in the values of Prandtl number, is obviously seen from Fig. 14. Fig. 15 portrays the local skin-friction $-f''(0)$ against suction parameter f_w for several values of magnetic interaction parameter $M = 0.5, 1.0,$ and $1.5.$ It is clear from Fig. 15 that the local skin-friction $-f''(0)$ enhances with the rise of magnetic interaction parameter and suction parameter. Table 1 portrays, in order to validate our results compared the value of skin-friction coefficient $-f''(0)$ in the absence of magnetic interaction parameter, permeability parameter, and suction parameter. The table shows the comparison between the results prevailed to those of Magyari and Keller (1999) and is exhibit that results agrees to each other.

Table 1

The comparison of values of skin-friction coefficient $-f''(0)$ for $M = 0,\ K_p = 0,\ R_d = 0,\ Q_H = Ec = C_R = 0,$ and $f_w = 0,$

	Magyari and Keller (1999)	Present Results
$-f''(0)$	1.281808	1.28181
$f(\infty)$	0.905639	0.90565

Table 2 The non-dimensional Skin-friction coefficient for various M, K_p, and f_w when $\Pr = 1.0.$

M	K_p	f_w	$f''(0)$
0.5 1.0 1.5	0.1	0.2	–1.59883 –1.75872 –1.90405
0.5	0.1 0.5 1.0	0.2	–1.59883 –1.72805 –1.81837
0.5	0.1	0.2 0.5 1.0	–1.59883 –1.75948 –2.06126

Table 2 infers the local skin-friction coefficient for several values of magnetic interaction parameter, permeability parameter, and suction parameter. It is seen that the local skin-friction coefficient increases for increasing values of all these parameters. The numerical values of non-dimensional rate of heat transfer (nusselt number) for different values of Eckert number, thermal radiation parameter, Prandtl number, heat source/sink parameter, and Brownian motion are provided in Table 3.

Table 3
The dimensionless rate of heat transfer for different values of Pr, R_d, Ec, Nb, and Q_H when $K_p = 0.1$, $C_R = 0.2$ and $f_w = 0.2$

Ec	R_d	Pr	Q_H	Nb	$-\theta'(0)$
0.5 1.0 1.5 2.0	0.1	1.0	0.05	0.1	0.56253 0.29737 0.03203 –0.23389
1.0	0.1 0.6 1.0	1.0	0.05	0.1	0.29737 0.22548 0.18388
1.0	0.1	0.71 1.0 3.0	0.05	0.1	0.24504 0.29737 0.37493
1.0	0.1	1.0	–0.05 –0.1 0.0 0.05 0.1	0.1	0.38642 0.42481 0.34441 0.29737 0.24376
1.0	0.1	1.0	0.05	0.1 0.2 0.3	0.29737 0.27236 0.24881

Table 4
The dimensionless rate of mass transfer for different values of Le, C_R, and f_w when $\Pr = 1.0$, $M = 0.5$, and $Nb = Nt = 0.1$

Le	C_R	f_w	$-h'(0)$
1.0 5.0 10.0	0.2	0.2	1.09571 3.31081 5.20234
1.1	0.1 0.2 0.3	0.2	1.08273 1.17746 1.25825
1.1	0.2	0.2 0.5 1.0	1.17746 1.25151 1.37190

It is noted that for enhancing values of the Pr and heat source parameter, the non-dimensional rate of heat transfer increases and the non-dimensional rate of heat transfer reduces in magnitude for rising R_d, Ec, Nb, and heat sink parameter. Table 4 reveals the dimensionless rate of mass transfer (local Sherwood number) for several values of Le, C_R, and f_w. It is remarked that the dimensionless rate of mass transfer enhances for increasing values of all these parameters.

V. CONCLUSION

The numerical solution of two dimensional, laminar, nonlinear MHD boundary layer and heat transfer flow of a radiative nanofluid with dissipation effects over a porous exponentially stretching sheet in the presence of heat source/sink and chemical reaction is obtained for various values of governing physical parameters in this investigation. The numerical results predict the effects of different physical parameters such as magnetic interaction parameter, Prandtl number, Eckert number, radiation parameter, Lewis number, heat source/sink parameter, chemical reaction parameter, and suction parameter.

The main findings of this investigation can be summarized as follows:

- The effect of suction is to decrease respectively the non-dimensional velocity, skin-friction coefficient, temperature and concentration for its enhancing values.
- Due to the effect of Prandtl number, temperature is reduced and hence the thermal boundary layer thickness becomes thinner.
- The concentration distribution decelerated for increasing values of suction parameter, Lewis number, and chemical reaction.
- An enhance in magnetic interaction parameter, heat source parameter, Eckert number, thermal radiation parameter, and Brownian motion increases the dimensionless temperature in the boundary layer region whereas heat sink parameter decreases the temperature.
- The energy dissipation (being indicated by Eckert number) due to Joule heating and viscous dissipation has the tendency to thicken the thermal boundary layer, so as to raise the non-dimensional temperature.
- The effect of porosity parameter is to reduce the dimensionless velocity, momentum boundary layer thickness, and Skin-friction coefficient for its increasing values while the temperature and thermal boundary layer thickness are increased by it.
- All the profiles tend to zero asymptotically which satisfies the far field boundary conditions.

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