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Slip Flow and Magneto-NANOFLUID over an Exponentially Stretching Permeable Sheet with Heat Generation/Absorption

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Abstract: *The present study analyzes the steady boundary layer slip flow of magneto-nanofluid due to an exponentially permeable stretching sheet with heat generation/absorption. In this paper, the effects of Brownian motion and thermophoresis on heat transfer and nanoparticle volume friction are considered. Using shooting technique along with fourth-order Runge-Kutta method the transformed equations are solved. The study reveals that the governing parameters, namely, the magnetic parameter, wall mass suction parameter, Prandtl number, the Lewis number, slip parameter, heat generation/absorption parameter, Brownian motion parameter, and thermophoresis parameter, have major effects on the flow field, the heat transfer, and the nanoparticle volume fraction as well as skin friction, local Nusselt number and local Sherwood number has been discussed in detail.*
Keywords: *MHD, nanoparticle, slip flow, heat transfer, heat generation/absorption.*

I. Introduction

Among the tasks facing by the engineer is the development of ultrahigh-performance cooling in many industrial technologies. This is where nanotechnology takes important part for further development of high performance, compact, cost-effective liquid cooling systems. Other than that, nanofluids have effective applications in many industries such as electronics, transportation, biomedical and many more [1]. Nanotechnology has been an ongoing topic of discussion in public health as some of the researchers claimed that nanoparticles could present possible dangers in health and environment [2]. Hamid et al.[3] studied the problem of two-dimensional laminar Marangoni-driven boundary layer flow in nanofluids with the effects of radiation. Three different types of nanoparticles, namely Cu, Al_2O_3, and TiO_2 are considered.

During the last many years, the study of boundary layer flow and heat transfer over a stretching surface has achieved a lot of success because of its large number of applications in industry and technology. Few of these applications are materials manufactured by polymer extrusion, drawing of copper wires, continuous stretching of plastic films, artificial fibers, hot rolling, wire drawing, glass fiber, metal extrusion and metal spinning etc. After the pioneering work by Sakiadis [4], a large amount of literature is available on boundary layer flow of Newtonian and non-Newtonian fluids over linear and nonlinear stretching surfaces [5-10]. Nadeem and Lee [11] investigated the steady boundary layer flow of nanofluid over an exponential stretching surface is investigated analytically.

Magnetohydrodynamics (MHD) boundary-layer flow of nanofluid and heat transfer over a linearly stretched surface have received a lot of attention in the field of several industrial, scientific, and engineering applications in recent years. Nanofluids have many applications in the industries since materials of nanometer size have unique chemical and physical properties. With regard to the sundry applications of nanofluids, the cooling applications of nanofluids include silicon mirror cooling, electronics cooling, vehicle cooling, transformer cooling, etc. This study is more important in industries such as hot rolling, melt spinning, extrusion, glass fiber production, wire drawing, and manufacture of plastic and rubber sheets, polymer sheet and filaments, etc. Khan et al. [12] studied the Unsteady MHD free convection boundary-layer flow of a nanofluid along a stretching sheet with thermal radiation and viscous dissipation effects using finite difference method. Liu [13] investigated the flow and heat transfer of an electrically conducting fluid of second grade over a stretching sheet subject to a transverse magnetic field. Khan et al. [14] studied the viscoelastic MHD flow, heat and mass transfer over a porous stretching sheet with dissipation of energy and stress work.

An effect of viscous dissipation and work done by deformation on the MHD flow and heat transfer of a viscoelastic fluid over a stretching sheet was investigated by Cortell [15].Bhattacharyya [16] analyzes the boundary layer flow and heat transfer caused due to an exponentially shrinking sheet and Bhattacharyya and Pop [17] show the effect of external magnetic field on the flow over an exponentially shrinking sheet. Recently, Bhattacharyya and Layek [18] investigated the magnetohydrodynamic boundary layer flow of nanofluid over an exponentially stretching permeable sheet.

The transient oscillatory MHD convection past a flat plate adjacent to a porous medium with heat generation effects was solved in [19] and transient MHD natural convection with viscous heating was considered by Zueco [20]. Recently the effects of variable suction and thermophoresis on steady MHD flow over a permeable inclined plate was analyzed by Alam et al. [21] while the heat and mass transfer of thermophoretic hydromagnetic flow with lateral mass flux, heat source, Reddy et al.[22] investigated the thermo diffusion and chemical reaction effects on unsteady free mhd convection flow past a vertical porous plate in slip-flow regime using perturbation technique.

However, the interactions of magneto-nanofluid due to an exponentially permeable stretching sheet in the presence of heat generation/absorption and slip effects. 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 using the fourth order Runge-Kutta method along with shooting technique. The effects of various governing parameters on the fluid velocity, temperature, nanoparticle volume friction, local Nusselt number and local Sherwood number are shown in figures and analyzed in detail.

II. Mathematical Formulation

Consider the steady boundary layer flow of nanofluid over an exponentially stretching sheet in presence of a transverse magnetic field. The governing equations of motion and the energy equation may be written in usual notation as [18, 23, 24]

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{2.1}$$

Momentum equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B^2}{\rho_f}u \tag{2.2}$$

Energy equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{(\rho c)_p}{(\rho c)_f}\left[D_B\frac{\partial N}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right]+q\left(T-T_\infty\right) \tag{2.3}$$

Volumetric species equation

$$u\frac{\partial N}{\partial x}+v\frac{\partial N}{\partial y}=D_B\frac{\partial^2 N}{\partial y^2}+\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2} \tag{2.4}$$

The boundary conditions are

$$u=U_w+L\frac{\partial u}{\partial y}, v=v_w, T=T_w=T_\infty+T_0e^{\frac{x}{2L}}, N=N_w=N_\infty+N_0e^{\frac{x}{2L}} \quad \text{at} \quad y=0$$

$$u\to 0, T\to T_\infty, N\to N_\infty \quad \text{as} \quad y\to\infty \tag{2.5}$$

Where u and *v* are the velocity components in x and y directions, respectively, ν is kinematic viscosity and α is thermal conductivity. ρ_f is density of the base fluid, $(\rho c)_f$ and $(\rho c)_p$ are heat capacities of base fluid and nanoparticles, respectively, T is temperature, q is heat generation/absorption rate constant, D_B is Brownian diffusion coefficient, N is nanoparticle volumetric fraction, D_T is thermophoretic diffusion coefficient and T_∞ is the ambient fluid temperature. T_w is the variable temperature at the sheet with T_0 being a constant which measures the rate of temperature increase along the sheet, N_w is the variable wall nanoparticle volume fraction with N_0 being a constant, and N_∞ is constant nanoparticle volume fraction in free stream.

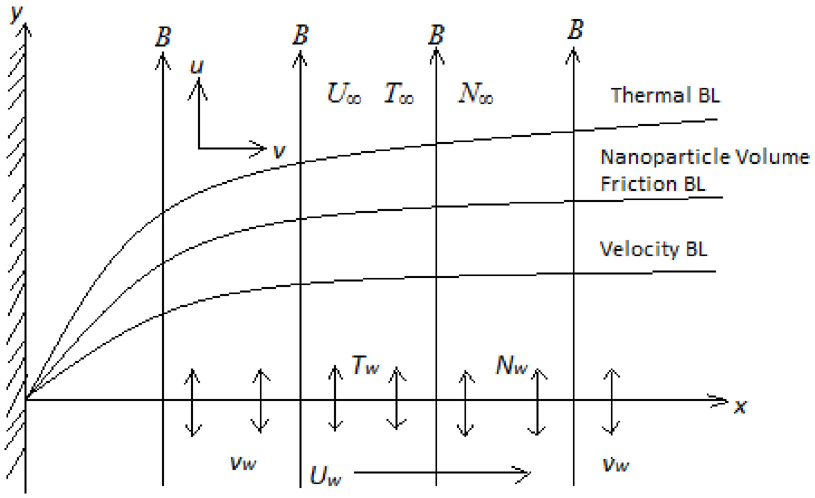

Fig. A: Physical model and coordinate system

Here the variable magnetic field *B(x)* is taken the form [17, 25]

$$B(x) = B_0 e^{\frac{x}{2L}} \tag{2.6}$$

Where B_0 is the constant.

The stretching velocity U_w is given by

$$U_w(x) = ce^{\frac{x}{L}} \tag{2.7}$$

where $c > 0$ is stretching constant. A physical model with the coordinate system of the problem is sketched in Fig. A.

Here v_w is the variable wall mass transfer velocity and is given by

$$v_w(x) = v_0 e^{\frac{x}{2L}} \tag{2.8}$$

where v_0 is a constant with $v_0 < 0$ formass suction and $v_0 > 0$ for mass injection.

The continuity equation (2.1) is satisfied by the Cauchy Riemann equations

$$u = \frac{\partial \psi}{\partial y} \quad \text{and} \quad v = -\frac{\partial \psi}{\partial x} \tag{2.9}$$

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

In order to transform the equations (2.2) to (2.5) into a set of ordinary differential equations, the following similarity transformations and dimensionless variables are introduced.

$$\begin{gathered}
\psi = \sqrt{2\nu Lc}\, f(\eta) e^{\frac{x}{2L}}, \eta = y\sqrt{\frac{c}{2\nu L}} e^{\frac{x}{2L}} \\
\theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \phi(\eta) = \frac{N - N_\infty}{N_w - N_\infty} \\
\Pr = \frac{\nu}{\alpha}, Le = \frac{\nu}{D_B}, M = \frac{2L\sigma B_0^2}{\rho c}, \beta = \frac{2qL}{c}, q = q_0 e^{x/L} \\
Nb = \frac{D_B (\rho c)_p (N_w - N_\infty)}{\nu (\rho c)_f}, Nt = \frac{D_T (\rho c)_p (T_w - T_\infty)}{T_\infty (\rho c)_f \nu}
\end{gathered} \tag{2.10}$$

where $f(\eta)$ is the dimensionless stream function, θ - the dimensionless temperature, ϕ - the dimensionless nanoparticle volume fraction, η - the similarity variable, M - the magnetic parameter, Le - the Lewis number, Nb - the Brownian motion parameter, Nt - the thermophoresis parameter, *Pr* - the Prandtl number.

In view of the equation (2.10), the equations (2.2) to (2.6) transform into

$$f'''+ff''-2f'^2-Mf'=0 \tag{2.11}$$

$$\theta''+\Pr(f\theta'-f'\theta+Nb\theta'\phi'+Nt\theta'^2+\beta)=0 \tag{2.12}$$

$$\phi''+Le(f\phi'-f'\phi)+\frac{Nt}{Nb}\theta''=0 \tag{2.13}$$

The transformed boundary conditions can be written as

$$f=S,\ f'=1+\gamma f''(0), \theta=1, \phi=1 \quad \text{at} \quad \eta=0$$
$$f'\to 0, \theta\to 0, \phi\to 0 \quad \text{as} \quad \eta\to\infty \tag{2.14}$$

where $S=-v_0/\sqrt{\nu c/2L}$ is the wall mass transfer parameter. $S>0(v_0<0)$ corresponds to mass suction and $S<0(v_0>0)$ corresponds to mass injection and $\gamma=\sqrt{\frac{cL}{2\nu}}$ is the slip parameter.

Physical quantities of interest are Local skin friction coefficient C_f, Local Nusselt number Nu and Local Sherwood number Sh, defined as [24]

$$C_f=\frac{\nu}{U_w^2 e^{2x/L}}\left(\frac{\partial u}{\partial y}\right)_{y=0}, Nu=\frac{-x}{(T_w-T_\infty)}\left(\frac{\partial T}{\partial y}\right)_{y=0}, Sh=\frac{-x}{(N_w-N_\infty)}\left(\frac{\partial N}{\partial y}\right)_{y=0} \tag{2.15}$$

or by introducing the transformations (2.10), we have

$$\sqrt{2\mathrm{Re}_x}C_f=f''(0), \frac{Nu}{\sqrt{2\mathrm{Re}_x}}=-\sqrt{\frac{x}{2L}}\theta'(0), \frac{Sh}{\sqrt{\mathrm{Re}_x}}=-\sqrt{\frac{x}{2L}}\phi'(0) \tag{2.16}$$

Where $\mathrm{Re}_x=\frac{U_w x}{\nu}$ is the local Reynolds number

III. Solution Of The Problem

The highly nonlinear coupled ODEs (2.11-2.13) along with the boundary conditions (2.14) form a two-point boundary value problem (BVP) and those are solved using shooting method [26–27]. The following first-order system is set:

$$\begin{aligned}
&f'=p, p'=q\\
&q'=2p^2-fq+Mp\\
&\theta'=r\\
&r'=-pr(fr-p\theta+Nbrz+Ntr^2+\beta\theta)\\
&\phi'=z\\
&z'=-le(fz-p\phi)-\frac{Nt}{Nb}r'
\end{aligned} \tag{3.1}$$

with the boundary conditions

$$f(0)=S, p(0)=1+\gamma q(0), \theta(0)=1, \phi(0)=1 \tag{3.2}$$

The set of nonlinear first-order ordinary differential equations (3.1) with boundary conditions (3.2) have been solved by shooting method using the fourth-order Runge-Kutta algorithm with a systematic guessing of $q(0)$, that is, $f''(0)$, $r(0)$, that is, $\theta'(0)$, and $z(0)$, that is, $\phi'(0)$. The step size is taken as $\Delta\eta$ = 0.01 and the suitable finite value of $\eta\to\infty, \eta_\infty$, is taken as 30 in all cases. The guess values $f''(0)$, $\theta'(0)$, and $\phi'(0)$ are adjusted using "secant method" to give better approximation for the solution. An asymptotic convergence criterion of 10^{-5} level for the boundary conditions $f'(\eta_\infty)$, $\theta(\eta_\infty), \phi(\eta_\infty)$ is taken in the computation.

IV. Results And Discussion

In order to get a clear insight of the physical problem, the velocity, temperature and nanoparticle volume friction have been discussed by assigning numerical values to the governing parameters encountered in the problem. Numerical computations are shown from figs.1-13.

The velocity, temperature and nanoparticle volume friction are plotted in Fig. 1(a)-(c) for different values of the magnetic field parameter (*M*). As is now well known, the velocity of the fluid decreases with increases in the magnetic field parameter due to an increase in the Lorentz drag force that opposes the fluid motion. Also noticed that temperature and nanoparticle volume friction increases with an increasing the magnetic parameter. Figs. 2(a)-(c) shows the effect of the mass suction parameter on the velocity, temperature and mass volume fraction profiles. It is observed that the velocity, temperature and concentration of the fluid decrease with an increase the mass suction parameter. Due to mass suction, the fluid is brought closer to the sheet and it thins velocity boundary layer thickness as well as the thermal and nanoparticle volume boundary layer thicknesses. Opposite effect is found for mass injection case; that is, the fluid is taken away from the sheet. Consequently, the velocity, thermal, and nanoparticle volume boundary layer thicknesses become broader. Figs. 3(a)-(c) shows the effect of the slip parameter on the velocity, temperature and mass volume fraction profiles. It is observed that the velocity of the fluid decreases with an increase the slip parameter and temperature of the fluid as well as mass volume friction of the fluid increases the slip parameter.

The effect of thermophoresis parameter on temperature and mass volume friction is shown in figs. 4(a) & (b). An increase in *Nt* the temperature of the fluid is increases as well as mass volume friction. The effect of Brownian motion parameter *Nb* on the dimensionless temperature and the dimensionless nanoparticle volume fraction is plotted in Figure 5(a) & 5(b). The figure reveals that the temperature of the fluid increases and the nanoparticle volume fraction decreases with increasing values of *Nb*. In nanofluid system, due to the presence of nanoparticles, the Brownian motion takes place and for the increase in *Nb* the Brownianmotion is affected and consequently the heat transfer characteristic of the fluid changes. Also, when the value of *Nb* increases, the nanoparticle volume boundary layer thickness decreases. The effect of heat generation/absorption parameter on the dimensionless temperature and the dimensionless nanoparticle volume fraction is plotted in Figure 6(a) & 6(b). The figure reveals that the temperature and the nanoparticle volume fraction with increasing values of heat generation/absorption. The effect of the Prandtl number (*Pr*) on temperature is shown in fig.7. Since the Prandtl number is the ratio of momentum diffusivity to the nanofluid thermal diffusivity. It is noticed that temperature of the fluid decreases with an increases the Prandtl number. From fig. 8 show that the effect of Lewis number (*Le*) on temperature. Since Lewis number is the ratio of nanoparticle thermal diffusivity to Brownian diffusivity. It is observe that the temperature of the fluid decreases with an increase in the Lewis number.

Fig.9 shows the effects of S, γ, and M on skin friction. From fig.9 it is seen that the skin friction increases with an increase M or S and decrease with an increase γ. The variations of S, γ and M on reduced Nusselt number is shown in fig.10. It is observed that the reduced Nusselt number increases with an increase the parameter S and decrease with an increasing the parameters γ or M. The effect of S, γ and M on Sherwood number is shown in fig.11. It is found that the Sherwood number enhances with a decrease in the parameters γ or M whereas increases with S. The variations of *Nt* and *Nb* on reduced Nusselt number is shown in fig.12. It is observed that the reduced Nusselt number decrease with an increasing the parameters *Nt* or *Nb*. The effect of *Nt* and *Nb* on Sherwood number is shown in fig.13. It is found that the Sherwood number enhances with a increase in the parameter *Nb* whereas decreases with *Nt*. Table 1 is shows to compare our results for the viscous case in the absence of the parameter M, γ and S. These results are found to be in good agreement.

V. Conclusions

In this paper numerically investigated the nanoparticle effect on magnetohydrodynamic boundary layer flow of Williamson fluid over a stretching surface with slip effect. The important findings of the paper are:

- The velocity of the fluid decreases with an increase of the magnetic field.
- The fluid temperature increases with the influence of magnetic field parameter or slip parameter or heat generation/absorption parameter.
- The nanoparticle volume friction enhances the magnetic field or thermophoresis parameter or Brownian parameter.
- Due to mass suction, the velocity boundary layer thickness as well as the thermal and nanoparticle volume boundary layer thicknesses becomes thinner, whereas mass injectionmakes those thicker.
- The skin friction coefficient and local Nusselt number and local Sherwood number enhances the mass suction parameter.
- The skin friction coefficient and local Nusselt number and local Sherwood number reduces the slip parameter.
- The local Nusselt number and local Sherwood number reduces the Brownian parameter.

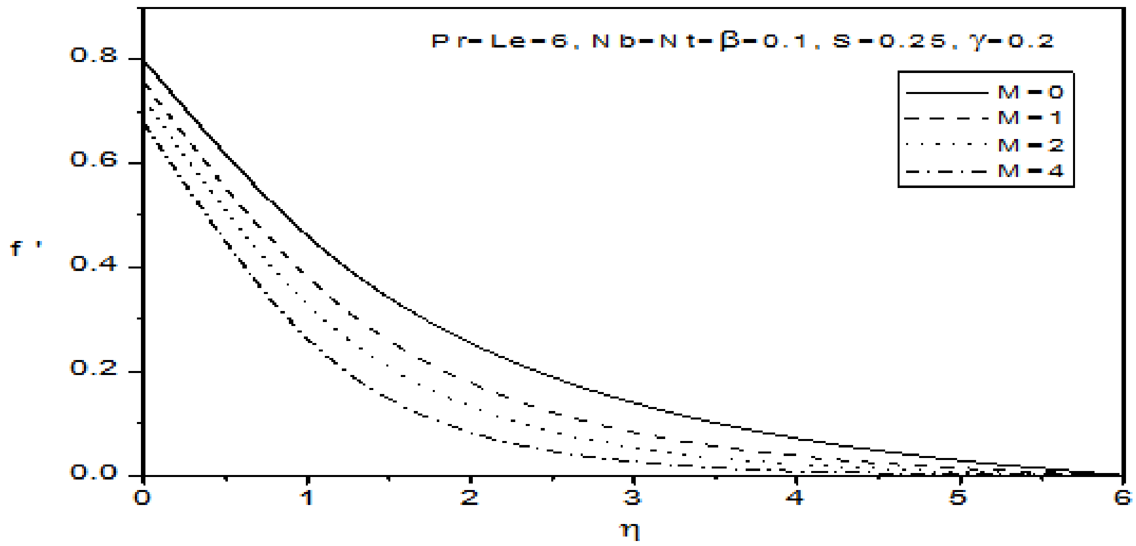

Fig.1 (a) Velocity for different values of *M*

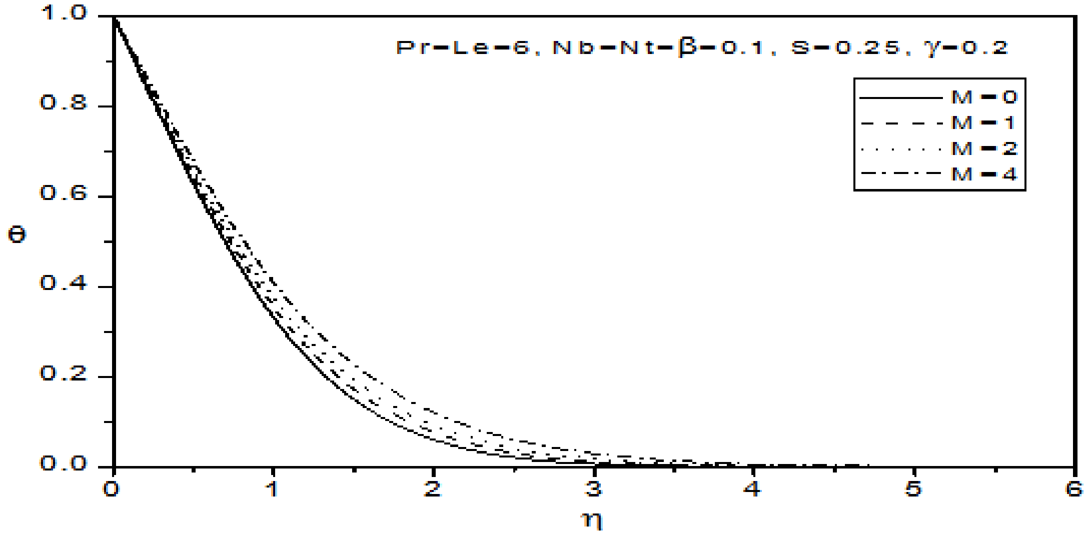

Fig.1 (b) Temperature for different values of *M*

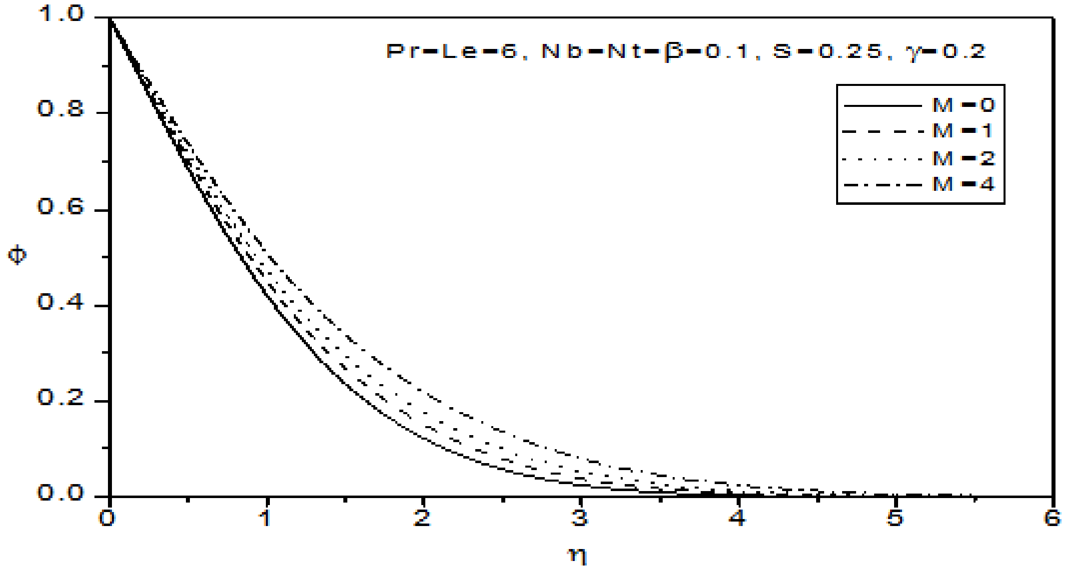

Fig.1(c) Nan particle volume fraction for different values of *M*

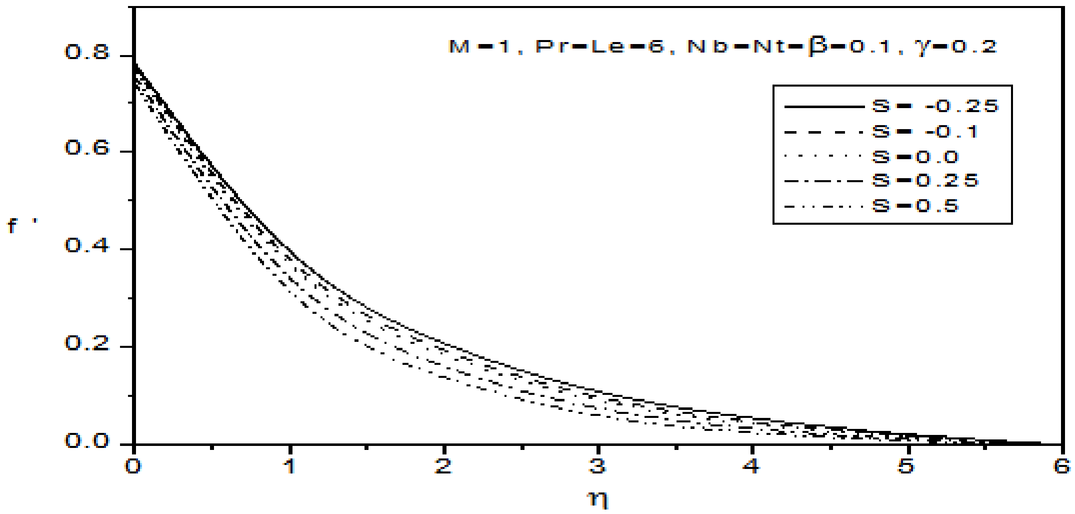

Fig.2 (a) Velocity for different values of *S*

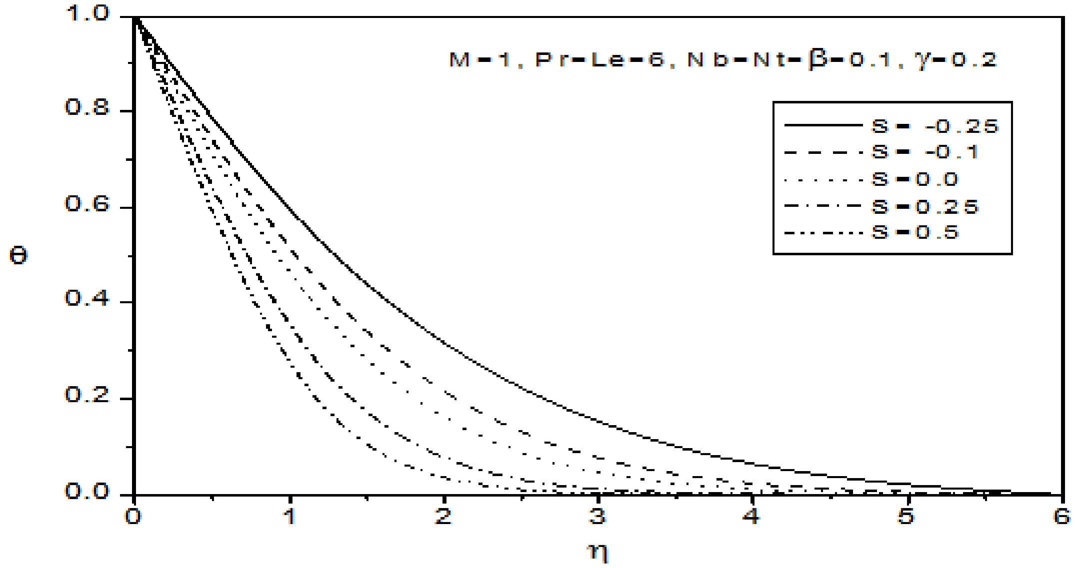

Fig.2 (b) Temperature for different values of *S*

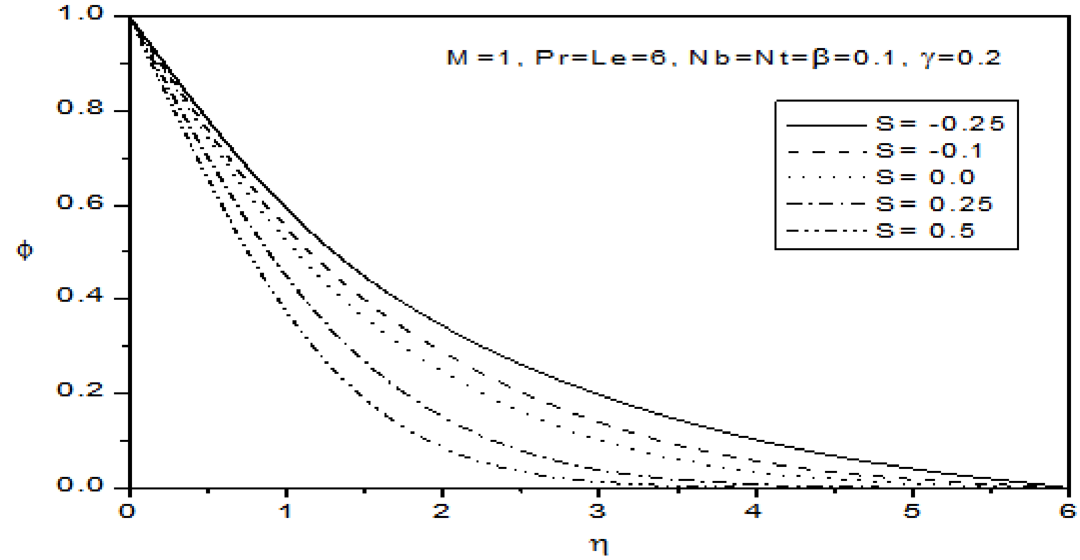

Fig.2(c) Nanoparticle volume fraction for different values of *S*

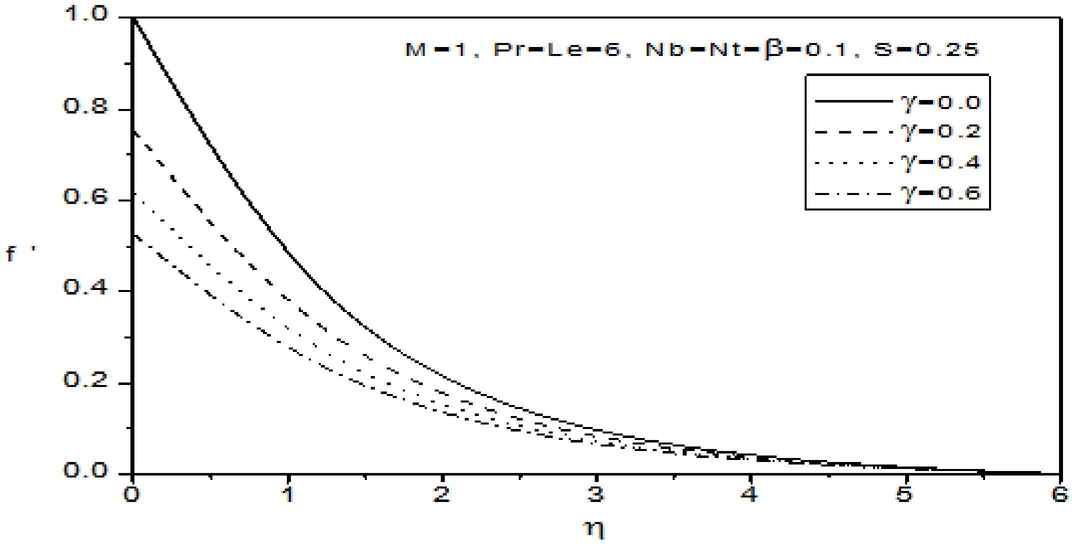

Fig.3 (a) Velocity for different values of *γ*

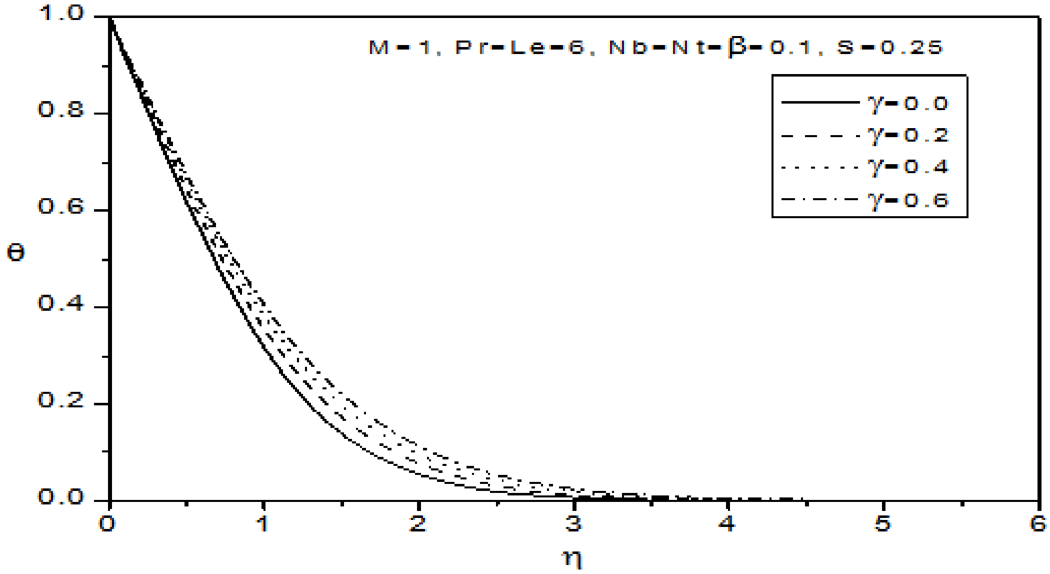

Fig.3 (b) Temperature for different values of *γ*

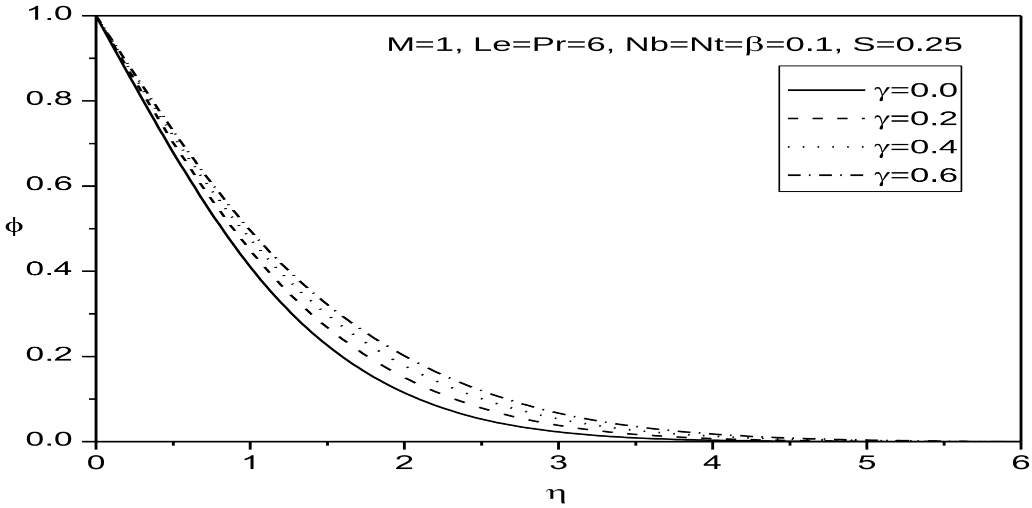

Fig.3(c) Nanoparticle volume fraction for different values of *γ*

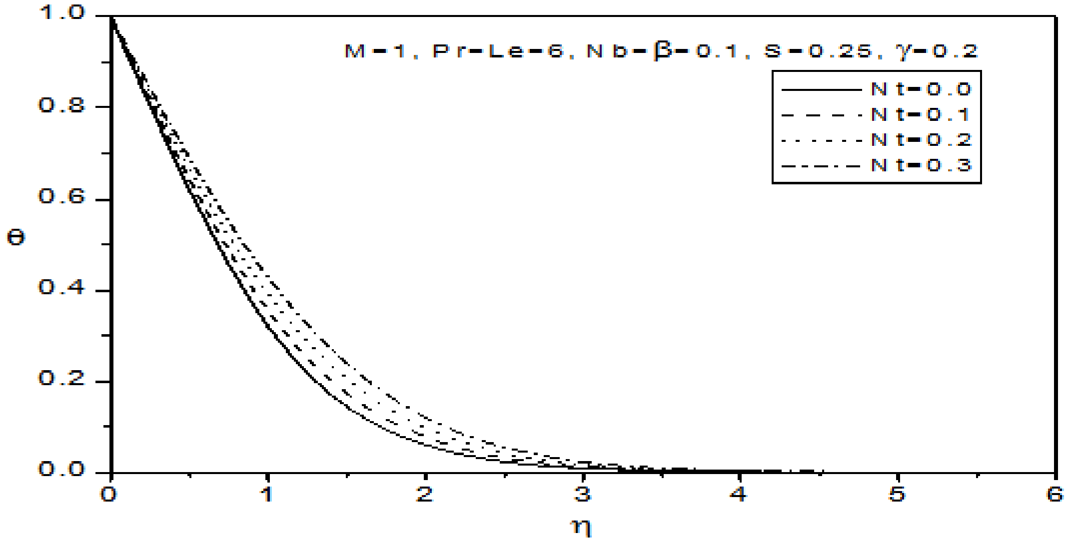

Fig.4 (a) Temperature for different values of *Nt*

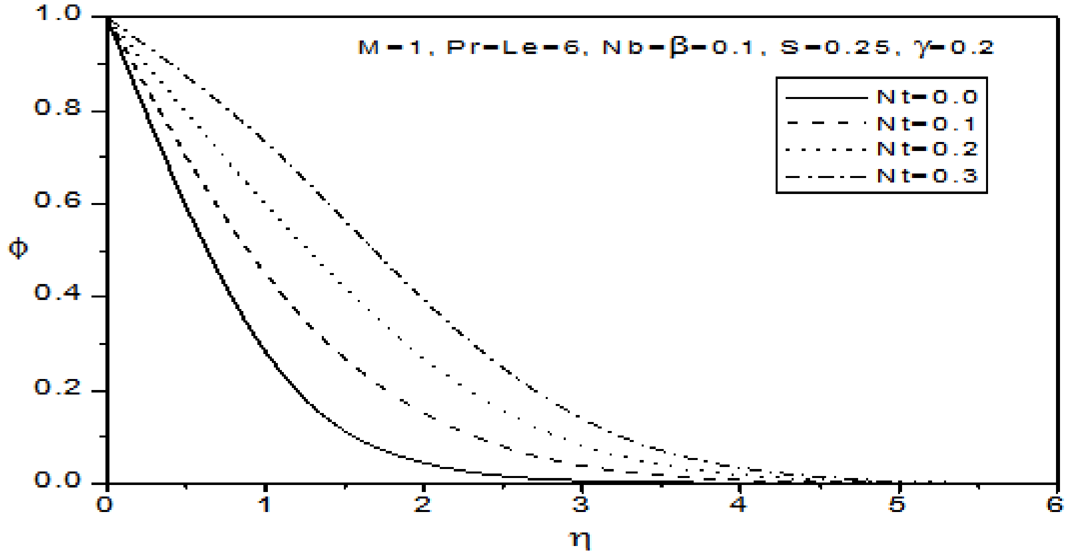

Fig.4 (b) Nanoparticle volume fraction for different values of *Nt*

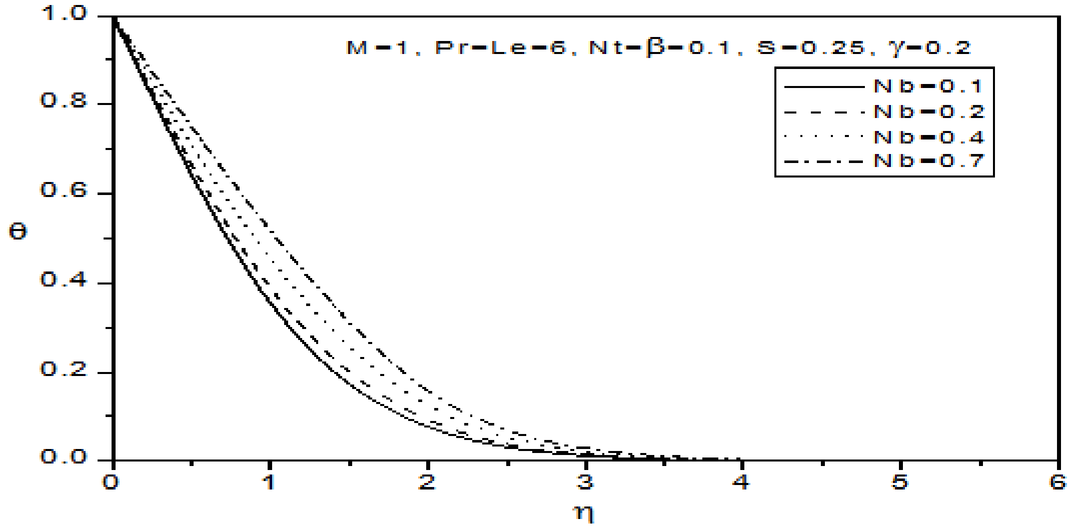

Fig.5 (a) Temperature for different values of *Nb*

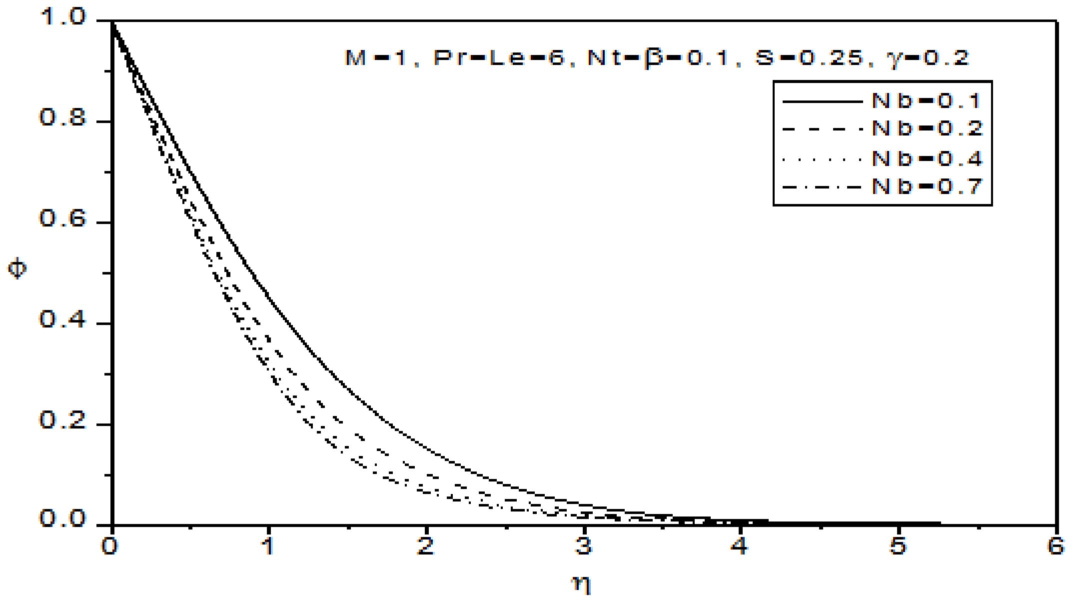

Fig.5 (b) Concentration for different values of *Nb*

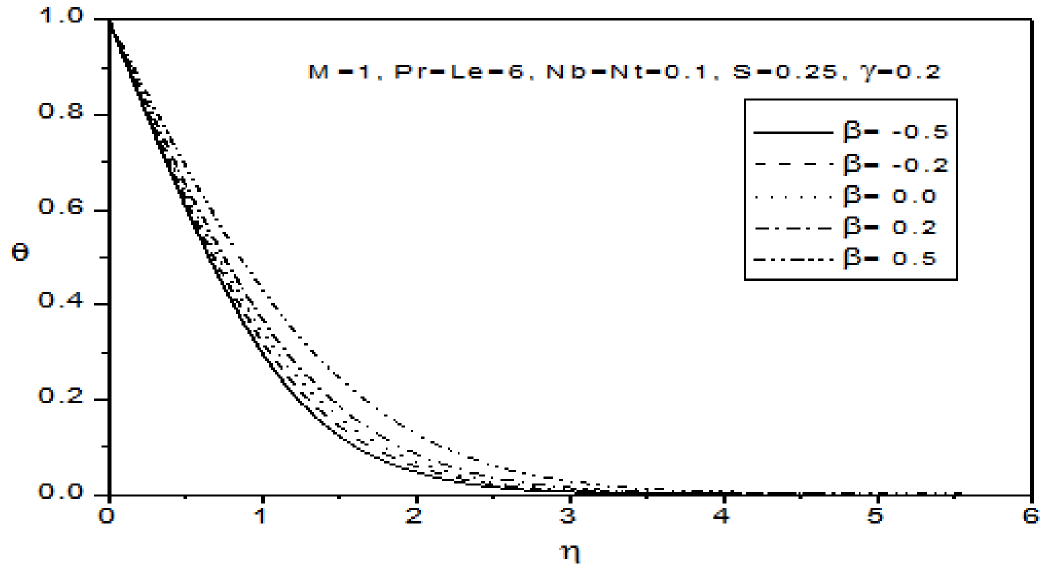

Fig.6 (a) Temperature for different values of *β*

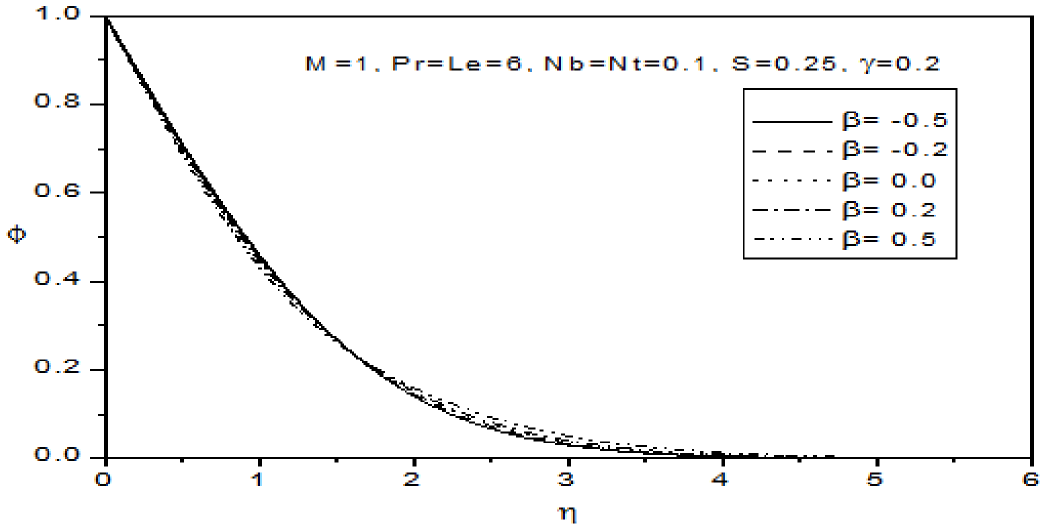

Fig.6 (b) Concentration for different values of *β*

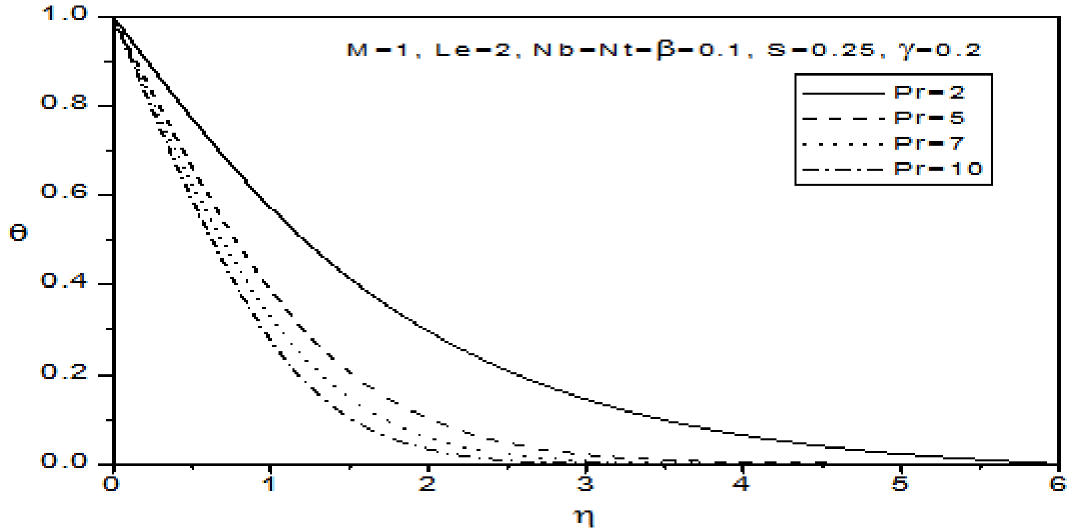

Fig.7 Temperature for different values of *Pr*

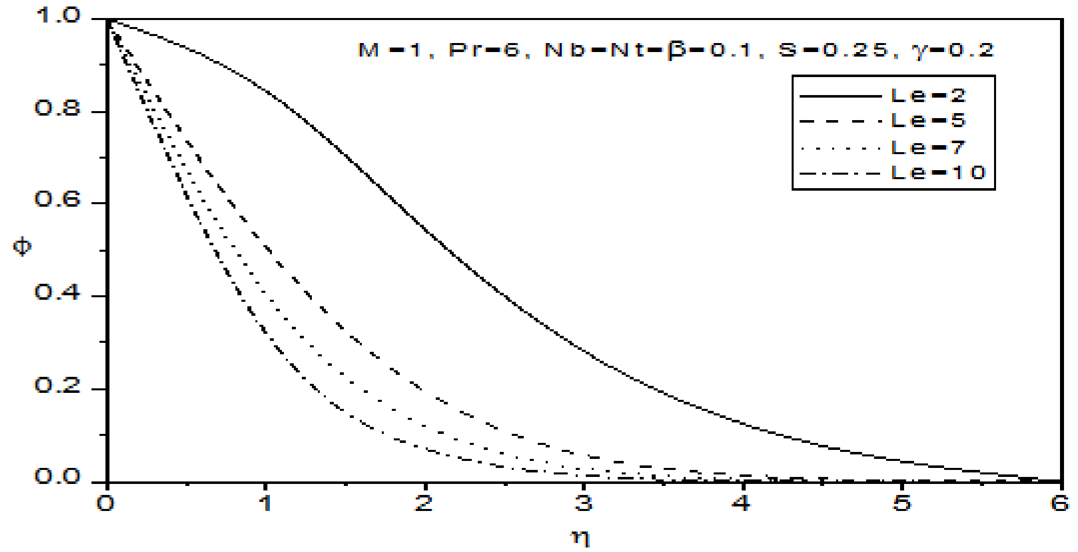

Fig.8 Nanoparticle volume fraction for different values of *Le*

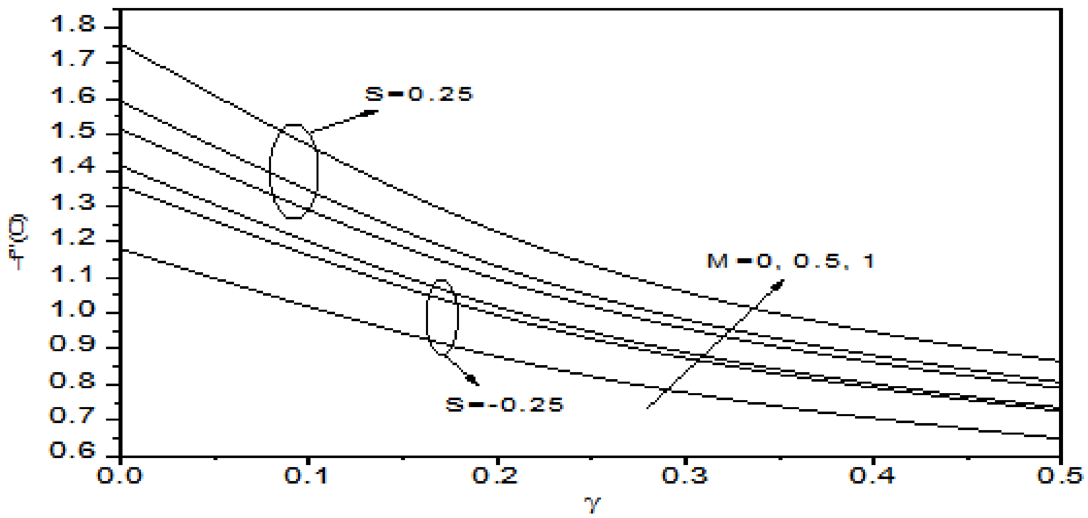

Fig.9 Effect of *S*, *γ* and *M* on the reduced skin friction

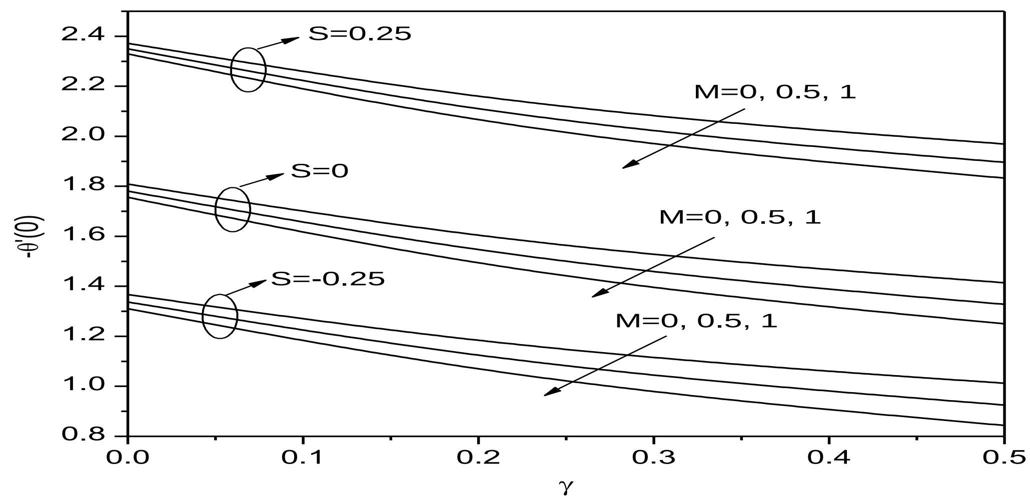

Fig.10 Effect of *S, γ* and *M* on the reduced Nusselt number

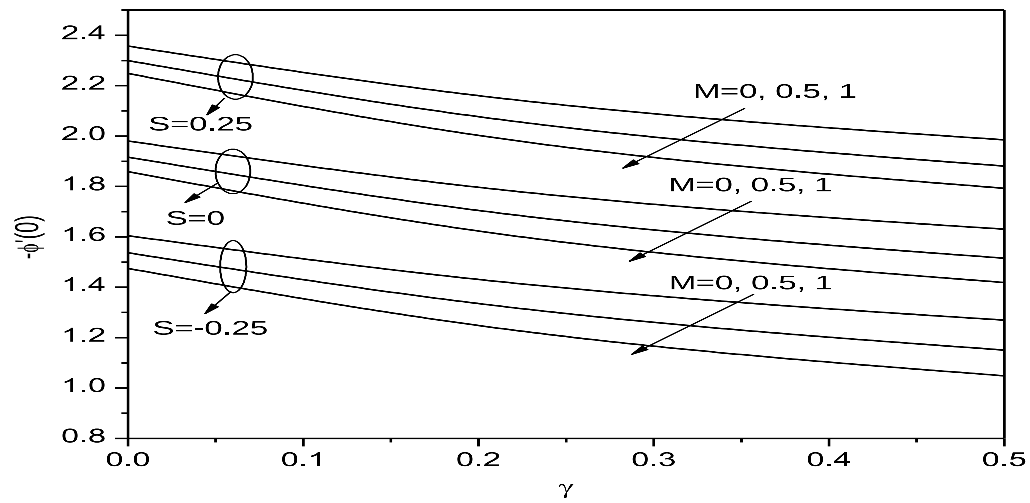

Fig.11 Effect of *S, γ* and *M* on the reduced Sherwood number

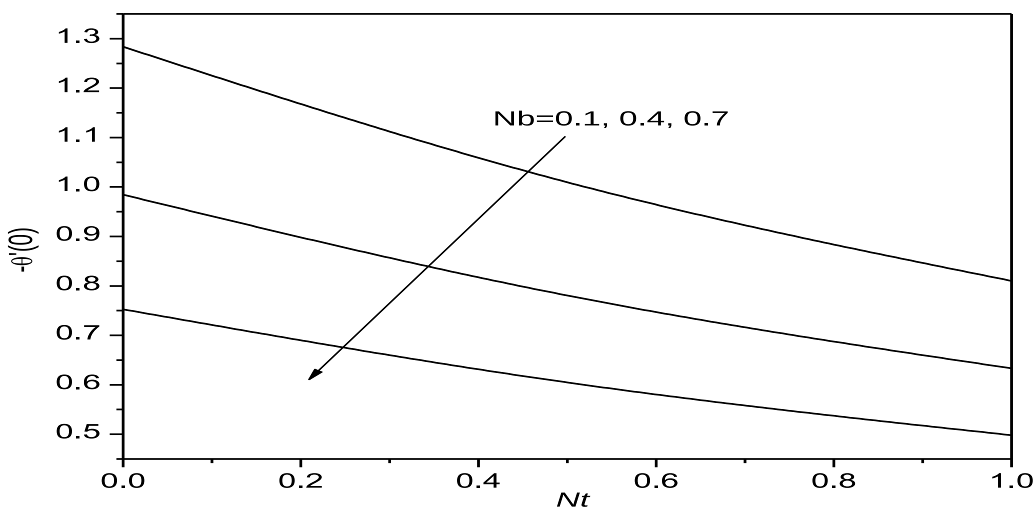

Fig.12 Effect of *Nb* and *Nt* on the reduced Nusselt number

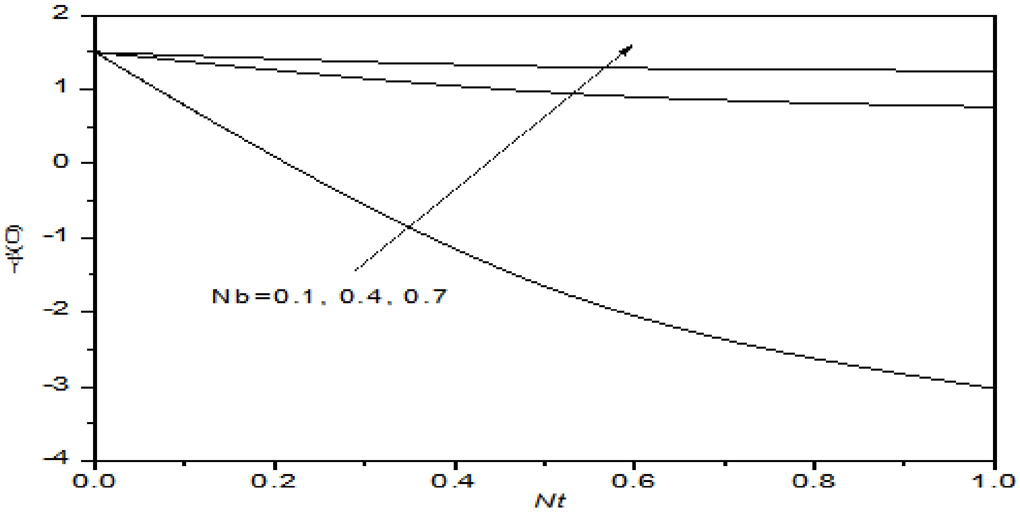

Fig.13 Effect of *Nb* and *Nt* on the reduced Sherwood number

Table 1 Comparison for $-f''(0)$ and $f(\infty)$ for M=S=γ=0 and β=0

	Present Study	Magyari and Keller [28]	Bhattacharyya and Layek [18]
$-f''(0)$	1.28181	1.281808	0.905639
$f(\infty)$	0.905641	0.905639	0.90564328

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