Original Research Article

Numerical Study on Micropolar Nanofluid Flow over an Inclined Surface by Means of Keller-Box

Abstract

In this paper, Micropolar Nanofluid boundary layer flow over linear inclined extending surface with magnetic effect investigated. Model utilized in this examination depends on Buongiorno model for the thermal efficiencies of the liquid flow in the presence of Brownian movements and thermophoresis properties. The nonlinear problem for Micropolar Nanofluid flow over slanted channel is demonstrated to consider the heat and mass exchange marvel by considering portent flow parameters to strengthened boundary layers. The administering nonlinear partial differential equations are changed to nonlinear ordinary equations and a short time later outlined numerically by strategies for the Keller-Box plan. A correlation of the set up results in the absence of the incorporated impacts is performed with the accessible results and perceived in a decent settlement. Numerical and graphical outcomes are additionally exhibited in tables and diagrams.

Keywords: Micropolar Nanofluid, MHD, inclined surface.

1 Introduction

Nanofluids set up a subclass of sub-atomic liquids intended to work at the nanoscale. Nanofluids comprise connection between mass materials and sub-atomic structure. The quick advancement of nanotechnology has seen a critical consideration in such fluids through the entire expansiveness of assembling, including building, aviation, restorative creations and vitality innovations. Nanofluid is a blend of various nanoparticles, for example, aluminum, silver, copper and titanium with or without their oxides and base liquids including water, ethylene glycol and oil and so forth when nanoparticles deliberately scattered in the base liquids, the subsequent nanofluids have been affirmed to achieve critical enhancement in the properties of thermal conductivity, introduced by Choi [1]. The elements that play essential principle to upgrade the thermal conductivity of nanofluid has been considered by Buongiorno [2]. He found that the thermal conductivity of the fluid increment due to thermophoresis and Brownian movement impacts in the ordinary liquid. Brownian movement is the unpredictable development of the nanoparticles in the conventional liquid and caused the constant impacts between based liquid and nanoparticles. Thermophoresis is the wonder which diffuses the particles because of the temperature inclination. The heat transfer of nanofluid over a nonlinear porous sheet is numerically discussed by Zaimi et al. [3]. Anwar et al. [4] contemplated the numerical investigation of micropolar nanofluid flow over an extending sheet. Nanofluid flow over a slanted extending surface concentrated by Sandeep and Kumar [5]. They researched heat and mass exchange of dusty nanoparticles improved on account of the volume division of nano particles. Suriyakumar and Devi [6] communicated the impacts of inner heat generation and suction on blended convective nanofluid flow through slanted surface. Ziaei-Rad et al. [7] examined the similarity solution of boundary layer nanofluid flow on an inclined surface. Rashad [8] studied nanofluid flow by considering convective boundaries and anisotropic slip effect. Mitra [9] investigated computational modeling of nanofluid flow over a heated inclined plate. Khan et al. [10] outlined the heat and mass exchange of MHD Jeffery nanofluid flow over slanted sheet. Hatami et al. [11] examined three dimensional relentless nanofluid over a slanted plate.

The boundary layer flow over a slanted extending surface turn into an intriguing field of research on account of its uses in building, for example, paper creation, skin rubbing, grain stockpiling and drag generation. The investigation of boundary layer flow over ceaseless surface begun by Sakiadis [12]. Also, Crane [13] examined the closed form arrangement of boundary layer flow over an extending sheet. The boundary layer stream of dusty liquid over a slanted surface with heat source/sink introduced by Ramesh et al. [14]. Singh [15] explored heat and mass exchange of thick liquid on porous slanted plate. Similarity solution of magnetohydrodynmaic flow over a slanted sheet examined by Ali et al. [16]. Ramesh et al. [17] took a shot at the boundary layer flow over slanted sheet with convective limits. MHD free convection dissipative liquid flow past over a slanted permeable surface was examined by Malik [18]. Hayat et al. [19] investigated radiation effect on the flow induced by stretching cylinder by considering non-uniform heat source/sink. Balla et al. [20] examined an inclined porous cavity filled with nanofluid saturated in permeable medium.

Micropolar liquids are those, which contain unbending arbitrarily situated particles submerged in a gooey medium with microstructure constituent, where bending of the molecule is unnoticed. Eringen [21] built up another reasoning of micropolar liquid to check the impact of small scale revolutions on smooth movement. Rahman et al. [22] talked about the flow of micropolar liquid by thinking about the variable properties. Micropolar fluid flow by taking different effects over an inclined sheet studied by Das [23]. Kasim et al. [24] inspected the micropolar liquid flow on the slanted plate numerically. Srinivasacharya and Bindu [25] researched micropolar liquid move through a slanted channel having parallel plates. Hazbavi and Sharhani [26] analyzed the flow of micropolar liquid between two parallel plates with steady weight slope. Shamshuddin et al. [27] contemplated the heat and mass exchange of micropolar liquid flow through penetrable slanted plate. The impact of two fold scattering on micropolar liquid flow over a slanted surface examined by Srinivasacharya et al. [28].

2 Problem formulation

A steady, two dimensional boundary layer flow of micropolar Nano fluid over a permeable inclined linear stretching plate with an angle γ is considered. The stretching and free stream velocities are supposed to be as, $u_w(x) = ax$ and $u_\infty(x) = 0$ respectively, here 'x' is the coordinate dignified lengthways the enlarging surface and 'a' is a constant. An external transverse magnetic field is taken normal to the flow path. It is supposed that the electric and magnetic field effects are very minor as the magnetic Reynolds number is less Mishra et al. [29].The micropolar finite size particles along with Nano particles are constantly distributed in the base fluids. The fluid particles have extra space to travel about formerly hitting to the other fluid particle, where these particles revolve in the fluid field and fallouts for spinning effects in the micropolar nanofluid. The Brownian motion and thermophoresis effects are taken into account. The temperature T and Nano particle fraction C at the wall take the constant values T_w and C_w, while the ambient forms used for nanofluid temperature and mass fractions T_∞ and C_∞ are attained as y lean towards to immensity shown in fig.1.

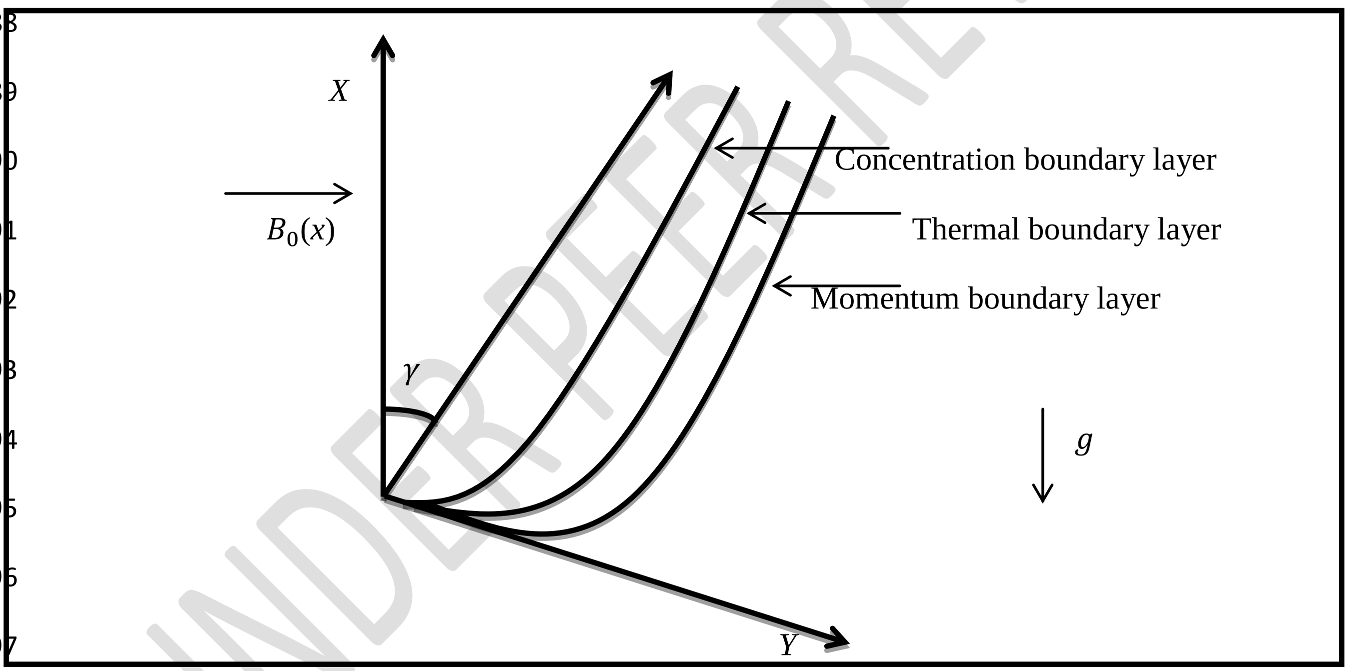

Fig.1. Physical geometry and coordinate system

The flow equations for this study are given by

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\left(\frac{\mu+K_1^*}{\delta}\right)\frac{\partial^2 u}{\partial y^2}+\left(\frac{K_1^*}{\rho}\right)\frac{\partial N^*}{\partial y}+g[\beta_t(T-T_\infty)-\beta_c(C-C_\infty)]cos\gamma-(\frac{\sigma {B_0}^2(x)}{\rho}+\frac{\mu}{\rho k})u, \tag{2}$$

$$u\frac{\partial N^*}{\partial x}+v\frac{\partial N^*}{\partial y}=\left(\frac{\gamma^*}{j^*\delta}\right)\frac{\partial^2 N^*}{\partial y^2}-\left(\frac{{K_1}^*}{j^*\delta}\right)\left(2N^*+\frac{\partial u}{\partial y}\right), \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\ \alpha\frac{\partial^2 T}{\partial y^2}+\tau\left[D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right], \tag{4}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}+\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2}, \tag{5}$$

Where in the directions x and y the velocity constituents are u and v, individually, g is the gravitational acceleration, the uniform magnetic field strength is given by B_0, σ denotes the electrical conductivity, the viscosity is denoted by μ, the density of the base liquid is given by δ_f, the density of the nanoparticle is given by δ_p, the vortex viscosity is defined as k_1^*, factor of thermal increase is given by β_t, β_c denotes constant of concentration extension, the gyration ascent viscosity is given by γ^*, the micro inertia each component mass is given by j^*, the micro-rotation is given by N^*, D_B denote the Brownian dispersal factor and D_T denotes the thermophoresis dispersion amount, k is the thermal conductivity, the heat capacity of the nanoparticles is denoted by $(\delta c)_p$, $(\delta c)_f$ represents the heat capacity of the conventional liquid, thermal diffusivity parameter is denoted by $\alpha=\frac{k}{(\delta c)_f}$ and the relation among the active heat capacity of the nanoparticle and heat capacity of the liquid is represented by $\tau=\frac{(\delta c)_p}{(\delta c)_f}$.

The subject boundary conditions are

$$u=u_w(x)=ax, v=0\ , T=T_w\ , N^*=-m_0\frac{\partial u}{\partial y}\ , C=C_w\quad at\quad y=0,$$

$$u\rightarrow u_\infty(x)=0, v\rightarrow 0\ , T\rightarrow T_\infty\ , N^*\rightarrow 0,\ \ C\rightarrow C_\infty\quad at\quad y\rightarrow\infty, \tag{6}$$

The nonlinear ordinary differential equations are obtained from nonlinear partial differential equations. The stream function $\psi=\psi(x,y)$ use for this procedure is given as

$$u=\frac{\partial\psi}{\partial y},\ v=-\frac{\partial\psi}{\partial x}, \tag{7}$$

Where, equation (1) i.e. continuity equation is fulfilled identically. The similarity transformations are characterized as

$$u = axf'(\eta), v = -\sqrt{av}f(\eta), \eta = y\sqrt{\frac{a}{v}}$$

$$\theta(\eta) = \frac{T-T_\infty}{T_w-T_\infty}, \phi(\eta) = \frac{C-C_\infty}{C_w-C_\infty}, \quad (8)$$

On substituting equation (8), system of equations (2) to (5) converted to the following nonlinear ordinary differential equations:

$$(1+k)f''' + ff'' - f'^2 + kh' + (\lambda g + \delta q)cos\gamma - (M + K_1)f' = 0, \quad (9)$$

$$\left(1+\frac{k}{2}\right)h'' + fh' - f'h - k(2h + f'') = 0, \quad (10)$$

$$\left(\frac{1}{Pr}\right)\theta'' + f\theta' + Nb\phi'\theta' + Nt\theta'^2 = 0, \quad (11)$$

$$\phi'' + Lef\phi' + Nt_b\theta'' = 0, \quad (12)$$

Where

$$\lambda = \frac{Gr_x}{Re_x}, \delta = \frac{Gc_x}{Re_x}, M = \frac{\sigma {B_0}^2(x)}{a\rho}, K_1 = \frac{\nu}{ak}, Le = \frac{\nu}{D_B} Pr = \frac{\nu}{\alpha}, N_b = \frac{\tau D_B(C_w - C_\infty)}{\nu}, N_t = \frac{\tau D_t(T_w - T_\infty)}{\nu T_\infty},$$

$$Nt_b = \frac{N_t}{N_b}, Gr_x = \frac{g\beta_t(T_w - T_\infty)x}{a\nu}, Re_x = \frac{u_w(x)x}{\nu}, Gc_x = \frac{g\beta_c(C_w - C_\infty)x}{a\nu}$$

(13)

Here, primes means the differentiation concerning η, λ Buoyancy constraint, Solutal buoyancy parameter is given by δ, the magnetic parameter is given by M, kinematic viscidness of the liquid is denoted by ν, Pr denotes the Prandtl number, Le denotes the Lewis number, K_1 represents permeability factor, K is the dimensionless vertex thickness.

The corresponding boundary conditions are transformed to

$$f(\eta) = 0, \quad f'(\eta) = 0, \ \theta(\eta) = 1, \ \phi(\eta) = 1 \quad at \ \eta = 0,$$

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

The skin friction, Sherwood number and Nusselt number for the present problem are defined as

$$Nu_x = \frac{xq_w}{k(T_w - T_\infty)}, Sh_x = \frac{xq_m}{D_B(C_w - C_\infty)}, C_f = \frac{t_w}{{u_w}^2\rho_f} \quad (15)$$

The related terms for the skin-friction factor $C_{fx}(0) = f''(0)$, the reduced Nusselt number $-\theta'(0)$ and the reduced Sherwood number $-\phi'(0)$ are defined as

$$-\theta'(0) = \frac{Nu_x}{\sqrt{Re_x}}, -\phi'(0) = \frac{Sh_x}{\sqrt{Re_x}}, C_{fx} = C_f\sqrt{Re_x} \quad (16)$$

Where, $Re_x = \frac{u_w(x)x}{\nu}$, is the local Reynolds number built on the extending velocity. The converted nonlinear differential equations (9) to (12) by applying equation (14) are elucidated by

Keller box scheme consisting on the steps as, finite-differences technique, Newton's scheme and block elimination process clearly explained by Anwar et al. [30].

3 Results and Discussion

This portion of study deals with the calculated results of converted nonlinear ordinary differential equations (9-12) with boundary conditions (14) solved via Killer-box method. For numerical result of physical parameters of our concern including Brownian motion constraint Nb, thermophoresis constraint Nt, magnetic factor M, buoyancy factor λ, solutal buoyancy factor δ, inclination factor γ, Prandtl number Pr, Lewis number Le, and material factor K several figures and tables are prepared. In Table 3.1, in the deficiency of buoyancy factor λ, solutal buoyancy factor δ, magnetic factor M, porosity parameter K_1 and material parameter K with γ = 90^o outcomes for reduced Nusselt number $-\theta'(0)$, reduced Sherwood number $-\phi'(0)$ are equated with the existing results of Khan and Pop [31]. The consequences are established brilliant settlement. The effects of reduced Nusselt number $-\theta'(0)$, reduced Sherwood number $-\phi'(0)$ and skin friction coefficient $C_{fx}(0)$ against altered values of involved physical parameters $Nb, Nt, M, K, \lambda, \delta, \gamma, K_1, Le$, and Pr are shown in table 3.2. It is eminent that $-\theta'(0)$ declines for increasing the values of Nb,Nt, M,Le, K_1, γ, and increased by enhancing the numerical values of K, λ, δ, and Pr. Moreover, it is perceived that $-\phi'(0)$ enhanced with the larger values of $Nb, \lambda, \delta, Nt, Le$, $K$and drops for bigger values of M, K_1, Pr and γ. On the other hand, $C_{fx}(0)$ rises with the growing values of Nb, Le, M, K, γ, K_1, and drops with the higher values of Nt, λ, δ, and Pr.

Table 3.1: Contrast of the reduced Nusselt number $-\theta'(0)$ and the reduced Sherwood number $-\phi'(0)$ when *M*, *K*, K1, δ, λ = 0, Pr = *Le* = 10 and γ = 90°.

Nb	***Nt***	Khan and Pop (2010)		Present Results	
		$-\theta'(0)$	$-\phi'(0)$	$-\theta'(0)$	$-\phi'(0)$
0.1	0.1	0.9524	2.1294	0.9524	2.1294
0.2	0.2	0.3654	2.5152	0.3654	2.5152
0.3	0.3	0.1355	2.6088	0.1355	2.6088
0.4	0.4	0.0495	2.6038	0.0495	2.6038
0.5	0.5	0.0179	2.5731	0.0179	2.5731

Table 3.2: Values of the reduced Nusselt number $-\theta'(0)$, the reduced Sherwood number $-\phi'(0)$ and the Skin-friction coefficient $C_{fx}(0)$.

Nb	*Nt*	Pr	*Le*	*M*	*K*	*λ*	*δ*	*K1*	*γ*	$-\theta'(0)$	$-\phi'(0)$	$C_{fx}(0)$
0.1	0.1	7.0	5.0	0.5	1.0	0.1	0.9	1.0	45^0	1.1054	1.0880	1.8913
0.5	0.1	7.0	5.0	0.5	1.0	0.1	0.9	1.0	45^0	0.2060	1.6011	1.9459
0.1	**0.5**	7.0	5.0	0.5	1.0	0.1	0.9	1.0	45^0	0.5104	1.3906	1.7176
0.1	0.1	**10.0**	5.0	0.5	1.0	0.1	0.9	1.0	45^0	1.1531	1.0852	1.8882
0.1	0.1	7.0	**10.0**	0.5	1.0	0.1	0.9	1.0	45^0	0.9672	2.0567	1.9689
0.1	0.1	7.0	5.0	**1.0**	1.0	0.1	0.9	1.0	45^0	1.0949	1.0550	2.1075
0.1	0.1	7.0	5.0	0.5	**3.0**	0.1	0.9	1.0	45^0	1.1331	1.1755	2.6215
0.1	0.1	7.0	5.0	0.5	1.0	**0.5**	0.9	1.0	45^0	1.1090	1.0963	1.8040
0.1	0.1	7.0	5.0	0.5	1.0	0.1	**2.0**	1.0	45^0	1.1195	1.1254	1.5847
0.1	0.1	7.0	5.0	0.5	1.0	0.1	0.9	**2.0**	45^0	1.0851	1.0246	2.3071
0.1	0.1	7.0	5.0	0.5	1.0	0.1	0.9	1.0	$\mathbf{90^0}$	1.0917	1.0507	2.1758

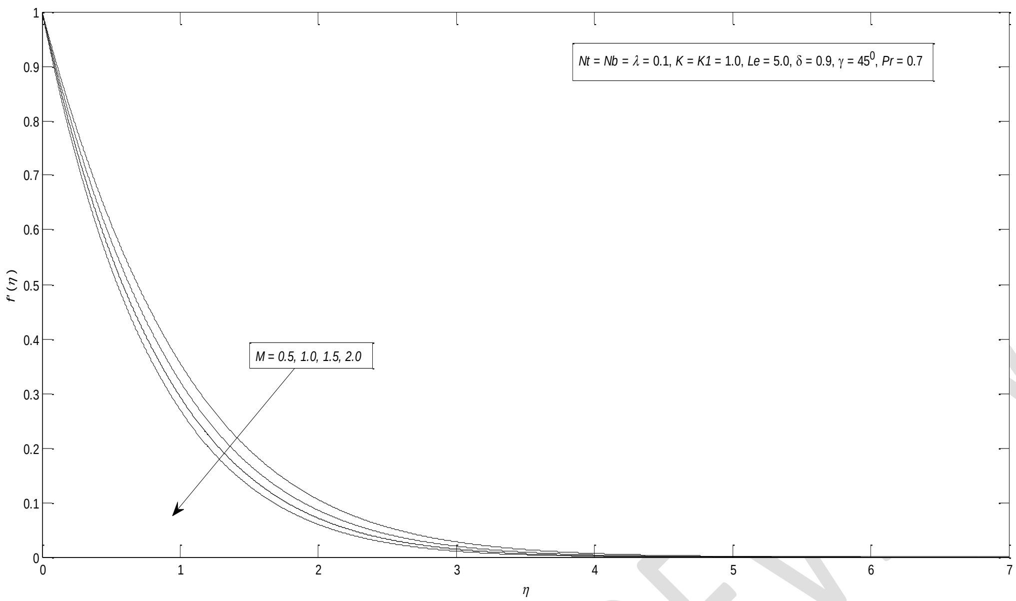

Fig. 2. Variations in velocity profile for several values of M.

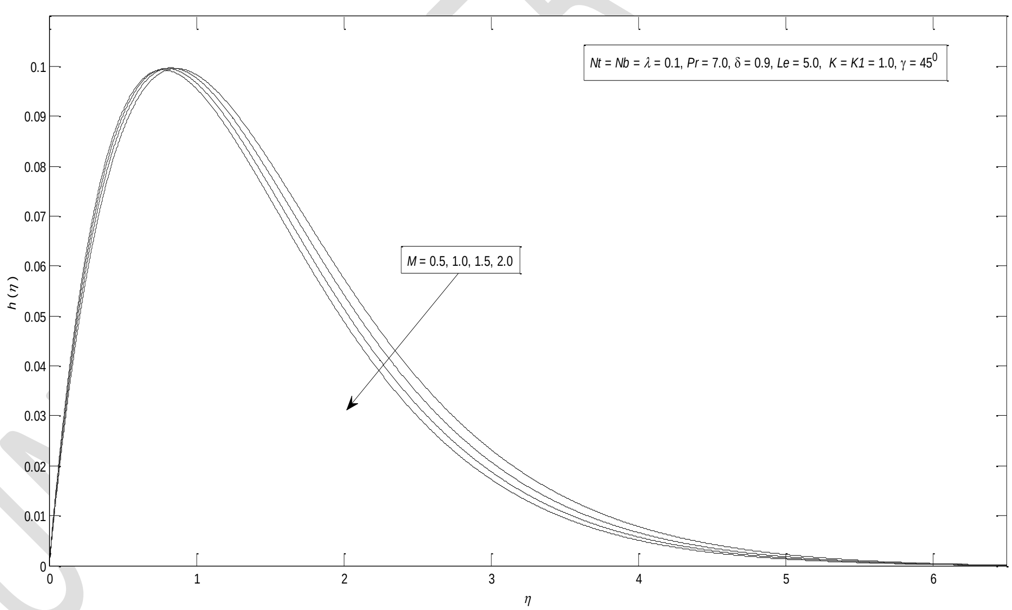

Fig. 3. Variations in angular velocity for several values of M.

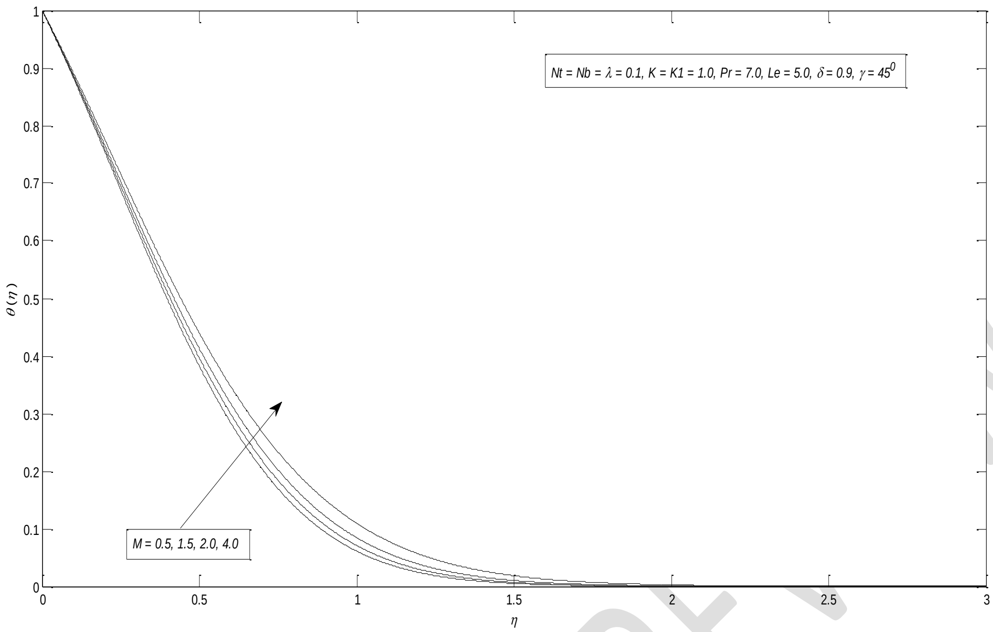

Fig. 4. Variations in temperature profile for several values of M.

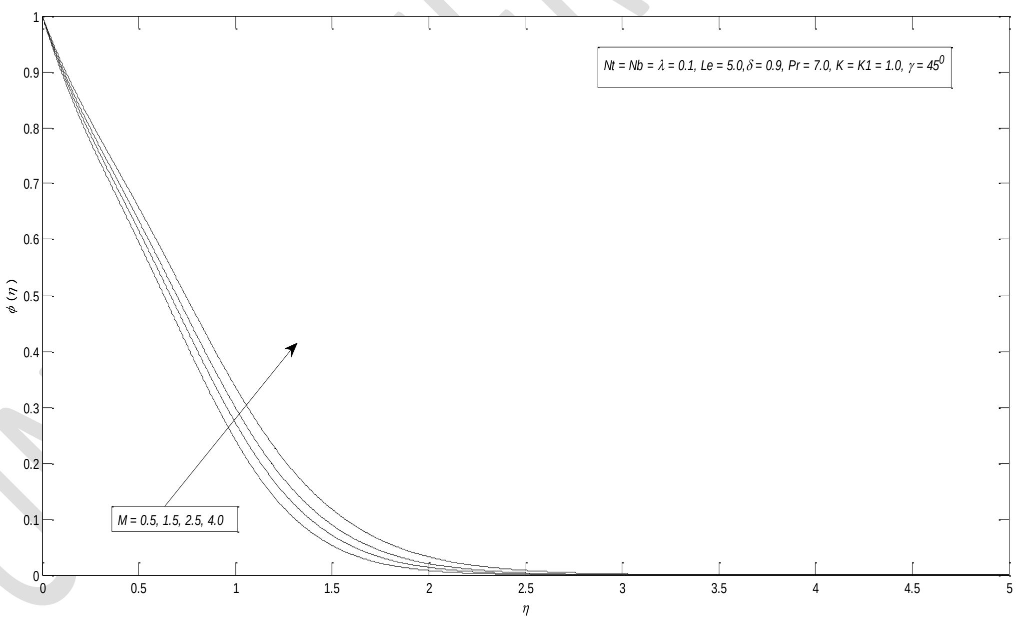

Fig. 5. Variations in concentration profile for several values of M.

Fig. 2 gives a picture of the upshot of factor M on velocity profile. The velocity outline slow down as we upsurge the magnetic field constraint M. It is since the use of magnetic field yields Lorentz force, by means retard the speed of the fluid. The similar result has seen in the instance of the angular velocity against changed values of M in Fig. 3. Whereas, the different impacts of M on the temperature distribution presented in Fig. 4 and concentration profile in Fig. 5.

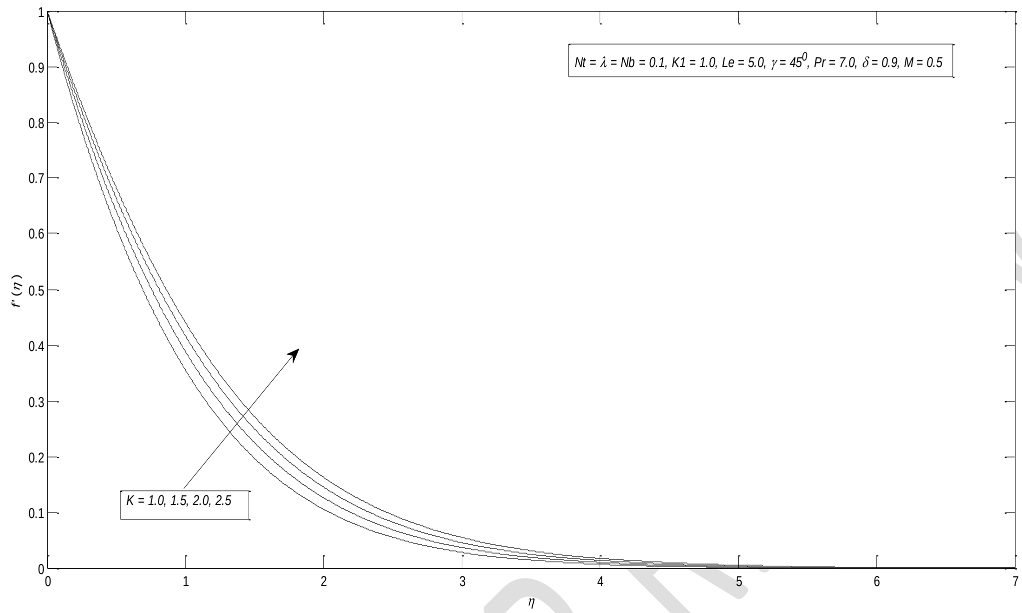

Fig. 6. Variations in velocity profile for several values of K.

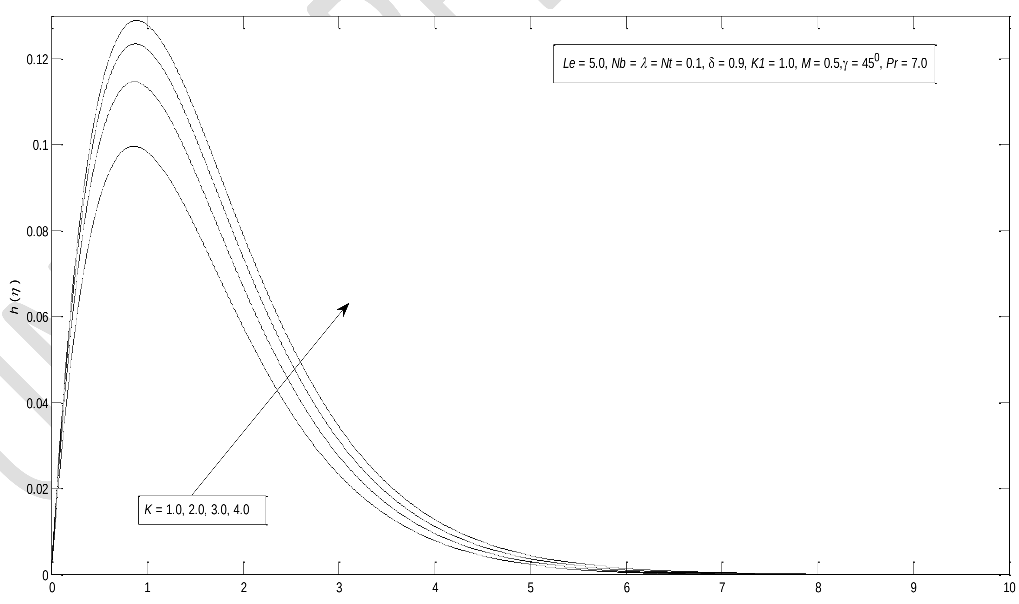

Fig. 7. Variations in angular velocity profile for several values of K.

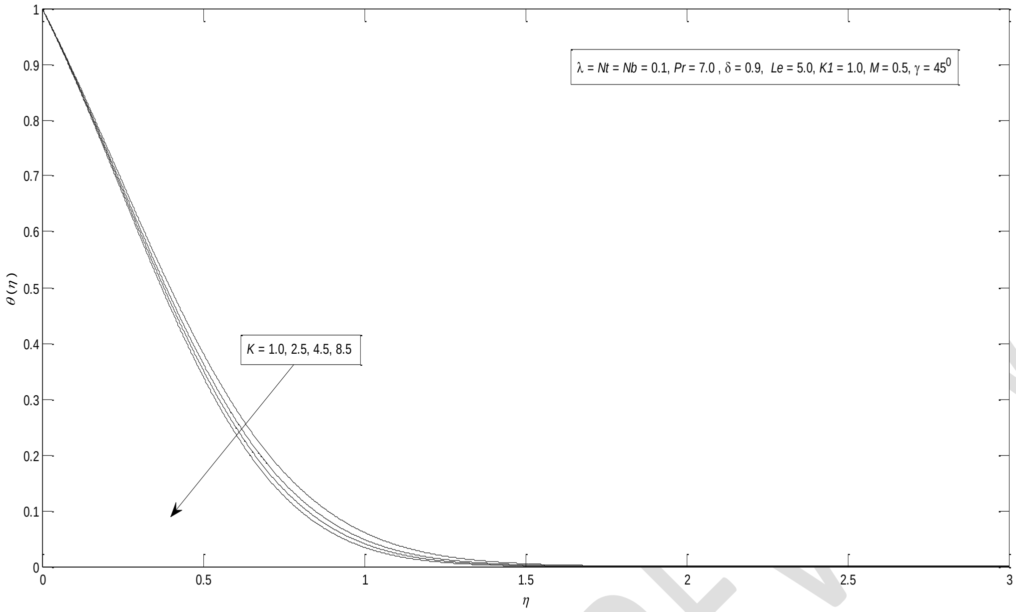

Fig. 8. Variations in temperature profile for several values of K.

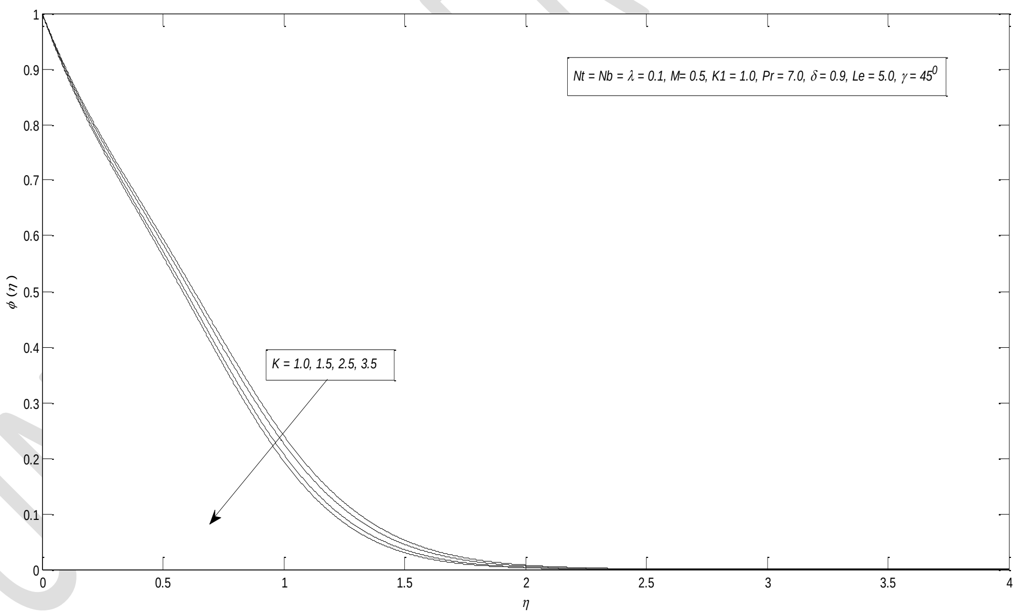

Fig. 9. Variations in concentration profile for several values of K.

It is noticed in Fig.6 the velocity profile upturn by enhancing the values of K. The angular velocity profile rise by growing the values of K indicates in Fig. 7. The boundary layer thickness losses by improving the values of K. On the other hand Figs. 8 and 9 depict the opposite effects against different values of K.

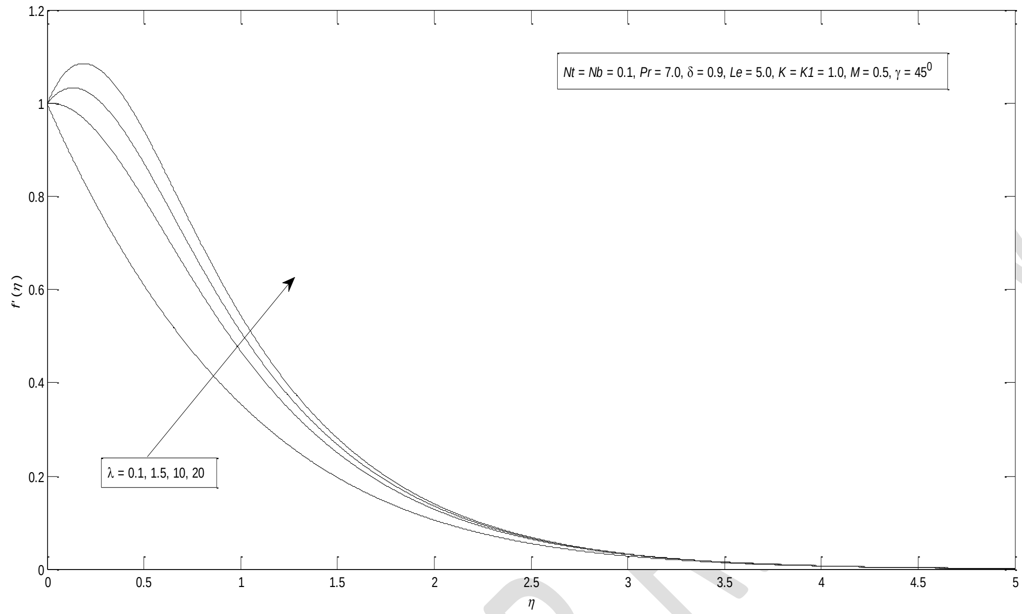

Fig. 10. Variations in velocity profile for several values of λ.

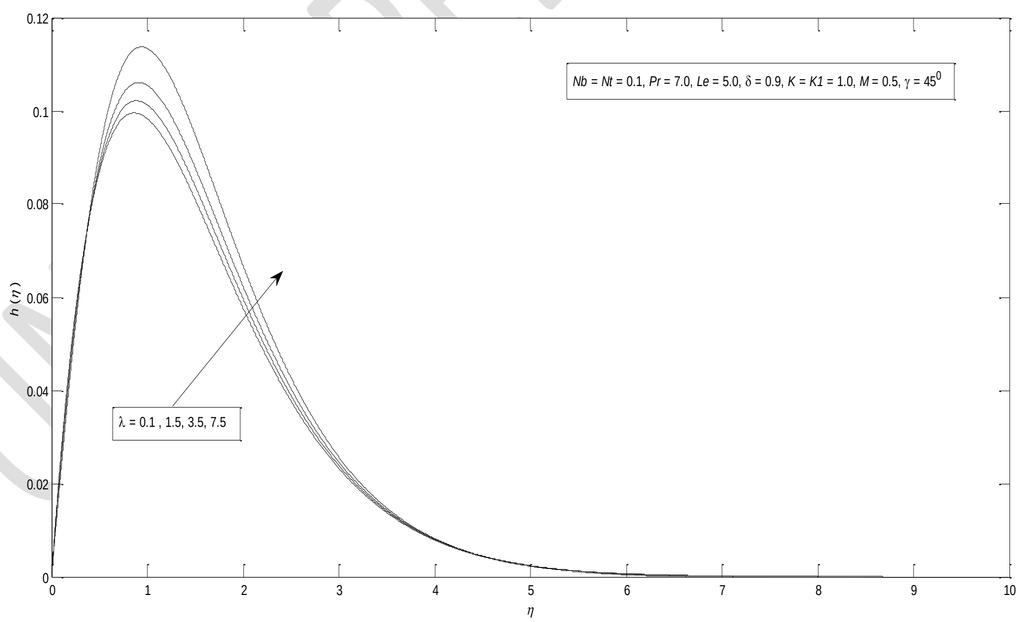

Fig. 11. Variation in angular velocity profile for sevral values of λ.

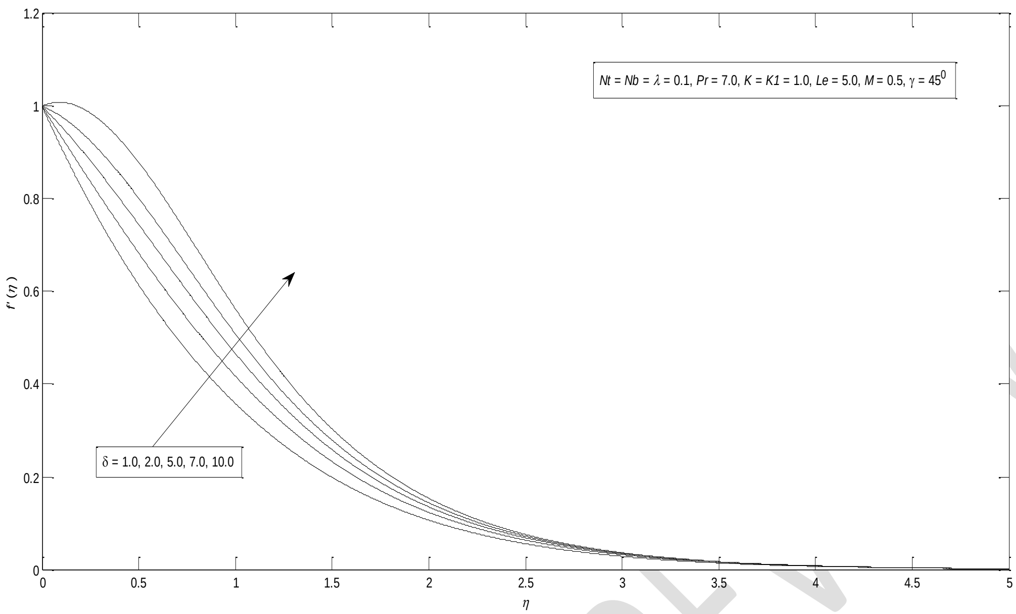

Fig. 12. Variations in velocity profile for several values of δ.

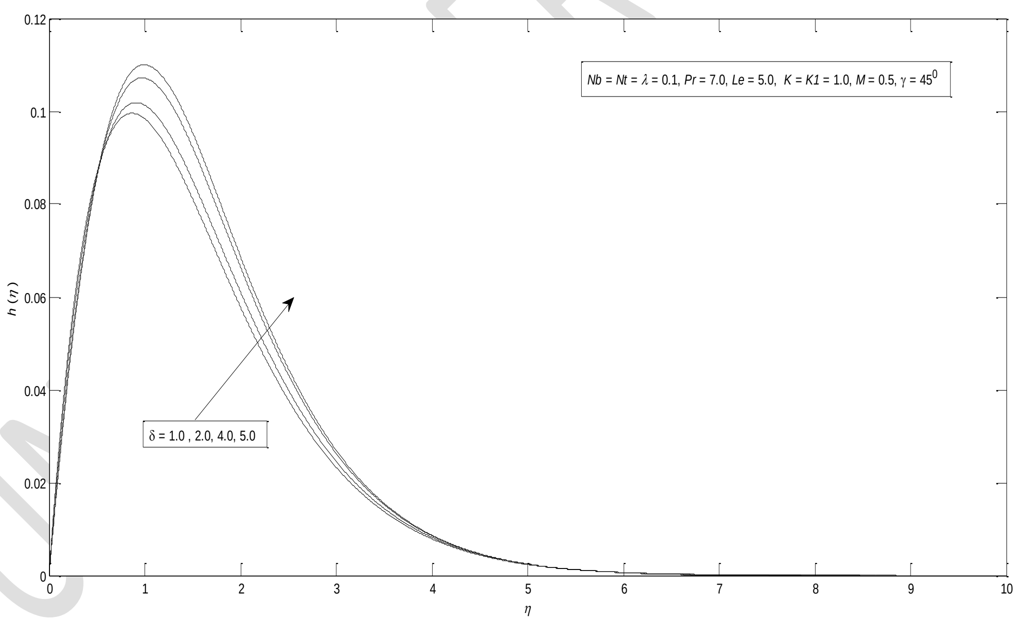

Fig. 13. Variations in angular velocity profile for several values of δ.

The velocity shape upturns in Fig. 10 by enhancing bouncy parameter λ. Similarly the angular velocity also enhanced with large values of λ clearly shown in Fig. 11. Moreover, the similar result for solutal bouncy parameter δ on velocity distribution and angular velocity contour prominent in Figs.12 and 13.

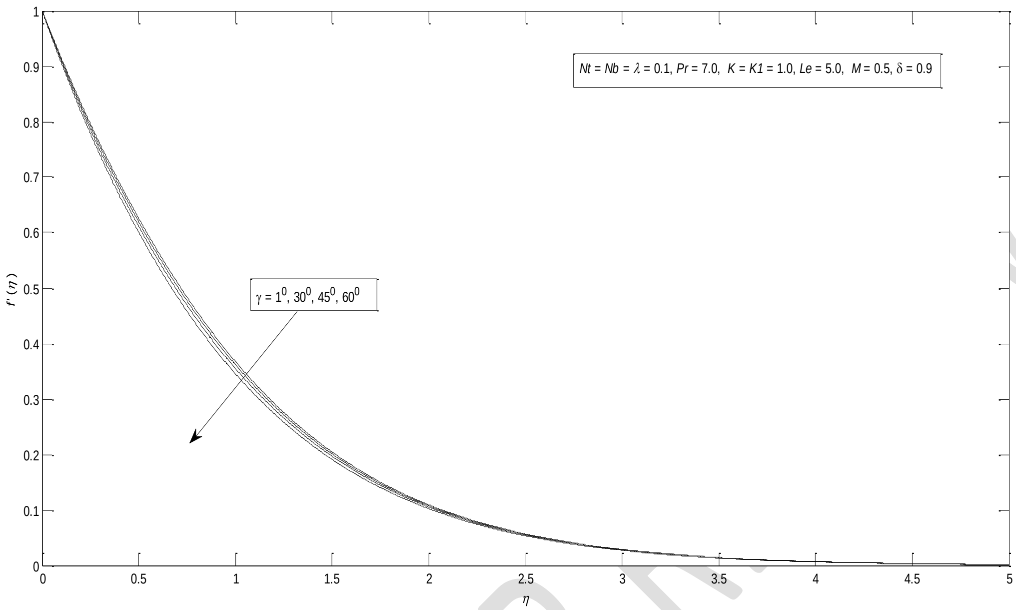

Fig. 14. Variations in velocity profile for several value of γ.

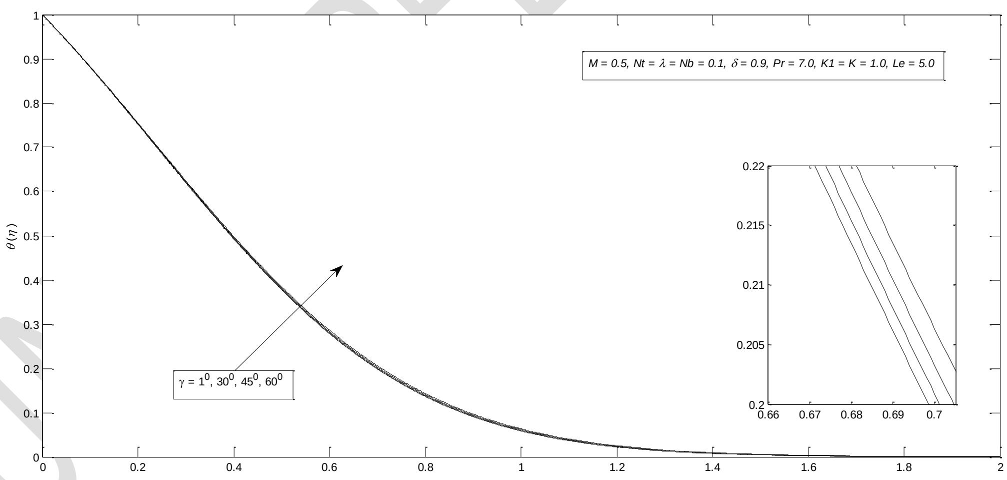

Fig. 15. Variations in temperature profile for several values of γ.

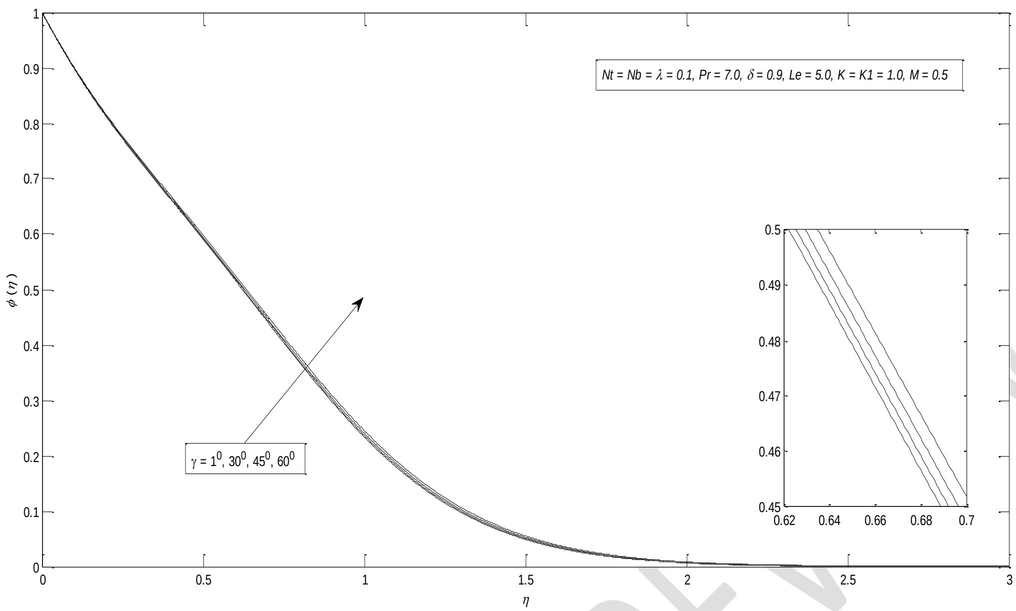

Fig. 16. Variations in concentration profile for several values of γ.

Fig. 14 portrays the consequence of inclination factor γ on velocity outline. It is openly perceived the velocity outline depreciate as we enhance the values of inclination parameter γ. This can be ascribed to the circumstance that the maximum gravitational force act on flow when the inclination parameter $\gamma = 0$ because in this situation the sheet will be vertical. On the other hand, for $\gamma = 90^0$ the sheet will be horizontal which cause the reduction in the velocity profile as the strength of the bouncy forces decrease. Besides, opposite result recovered in Figs. 15 and 16 for large values of inclination parameter γ in the instance of temperature and concentration sketches.

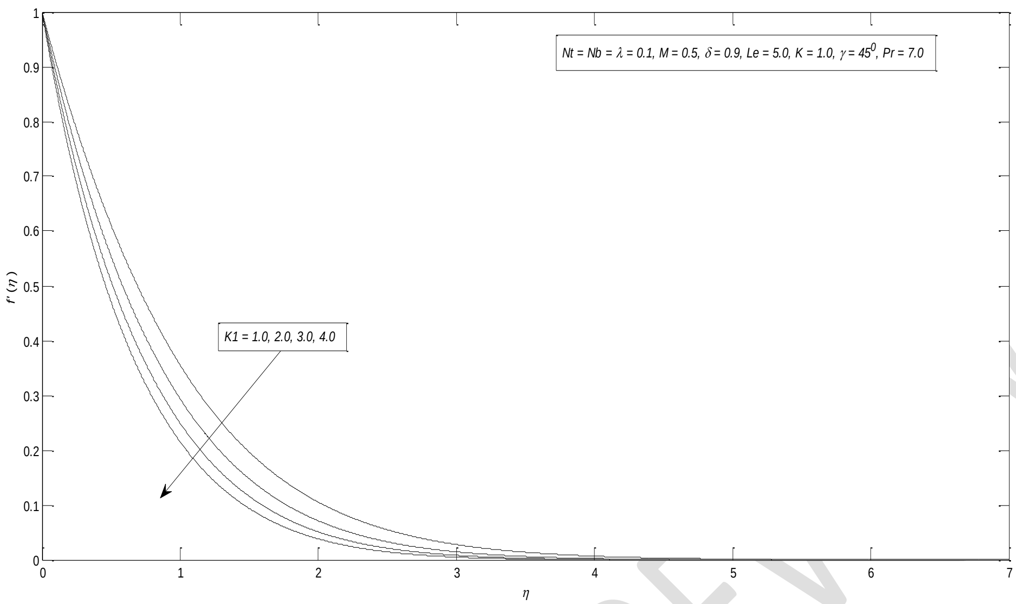

Fig. 17. Variations in velocity profile for several values of K_1.

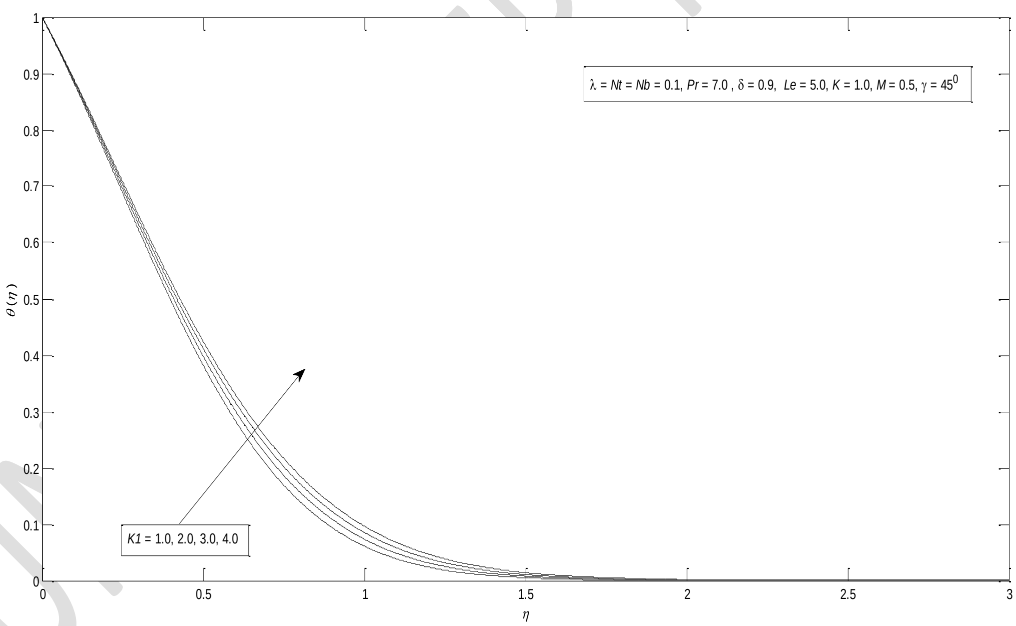

Fig. 18. Variations in temperature profile for several value of K_1.

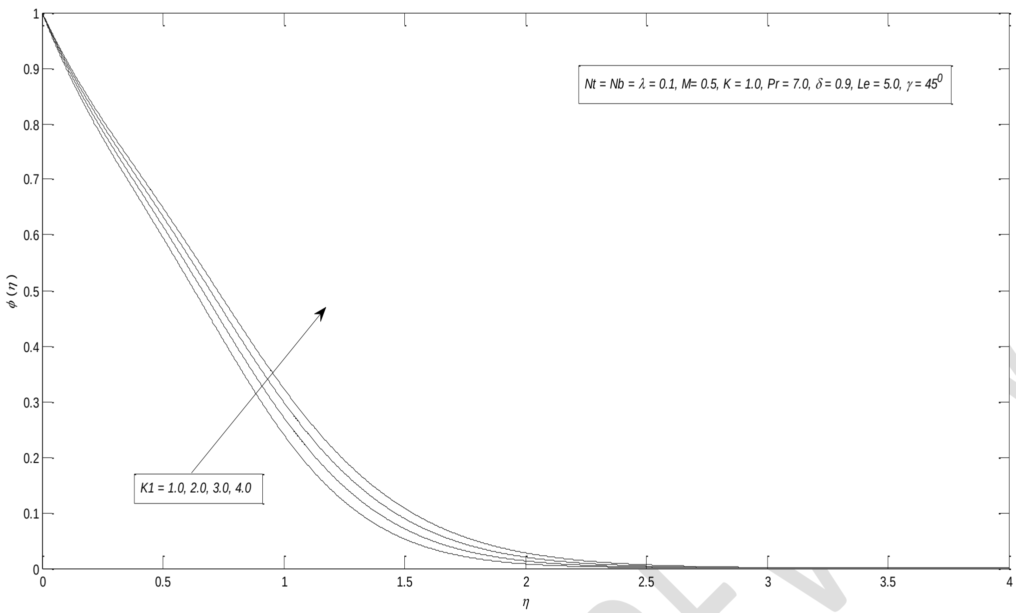

Fig. 19. Variations in concentration profile for several values of K_1.

It is well known that the porous medium offers high resistance that cause rising of shear stress. This shear stress work opposite to the fluid motion over a stretching sheet and fluid motion tends to slow. That's why, velocity profile illustrate reduction by increasing the values of K_1 in this case as indicated by Fig. 17. Moreover, oppoite impact ilustrate in Figs. 18 and 19 for verious values of K_1.

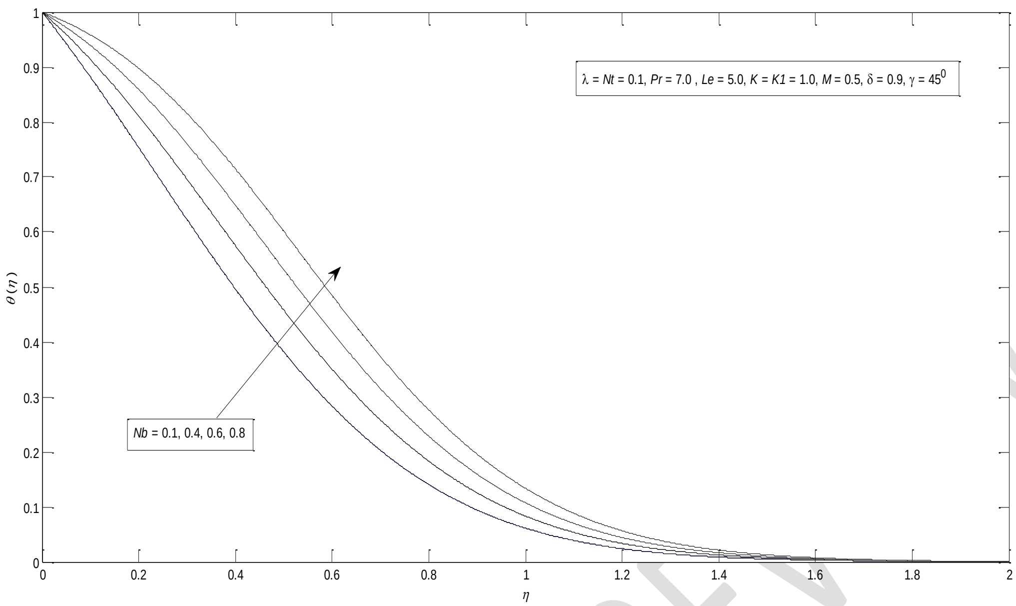

Fig. 20. Variations in temperature profile for several values of Nb.

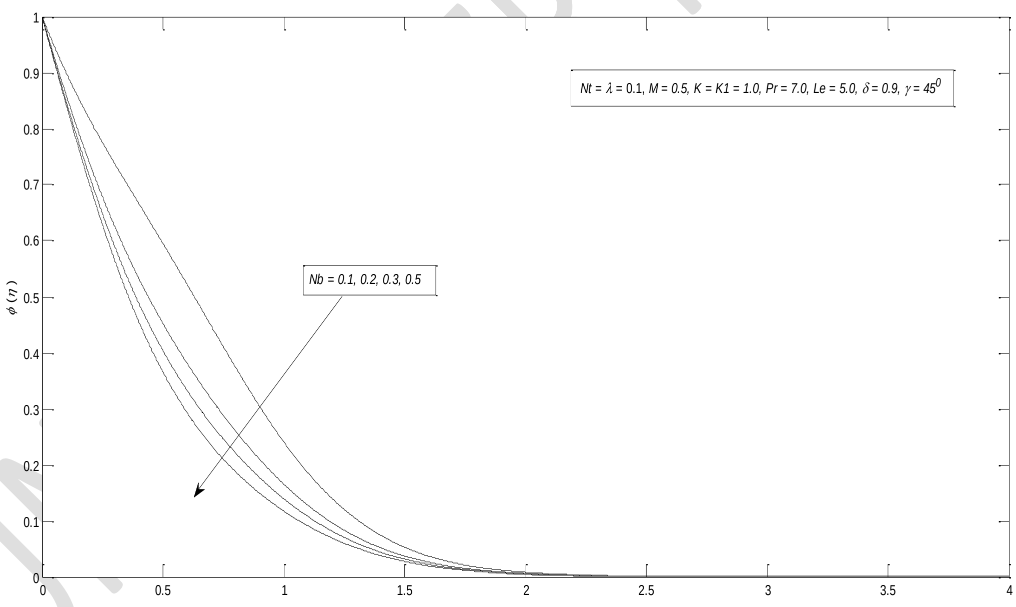

Fig. 21. Variations in concentration profile for several values of Nb.

Figures. 20 and 21 display the of effect of Brownian movement on the temperature and concentration sketches separately. The temperature sketch enlarges on enlarging Nb, on the other hand concentration distribution enlighten dissimilar style. Physically, boundary layer heat up due to the development in Brownian motion which inclines to travel nanoparticles from the extending sheet to the motionless liquid. Therefore the absorption nanoparticle lessens.

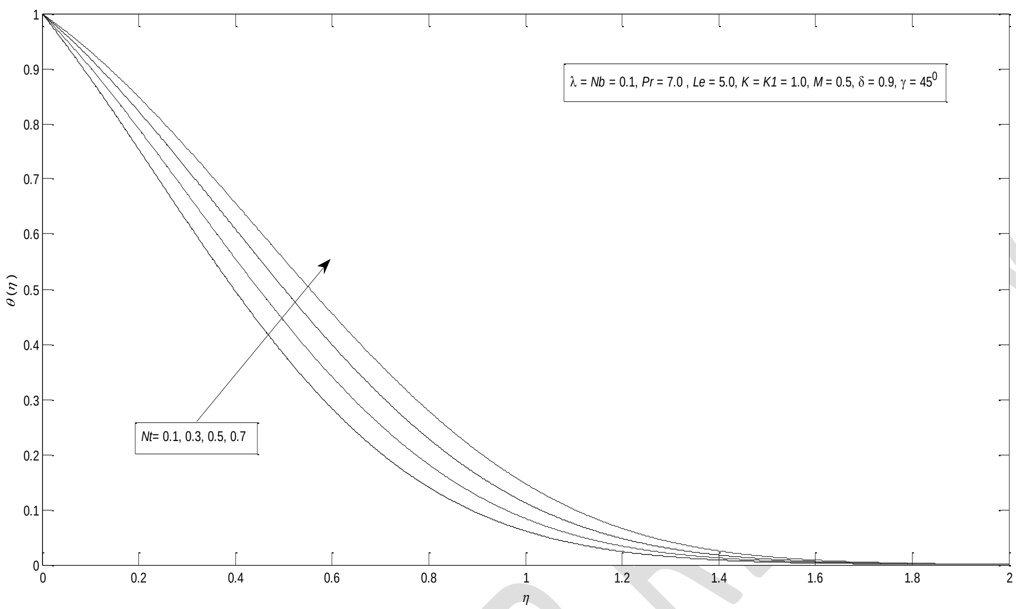

Fig. 22. Variations in temperature profile for several values of Nt.

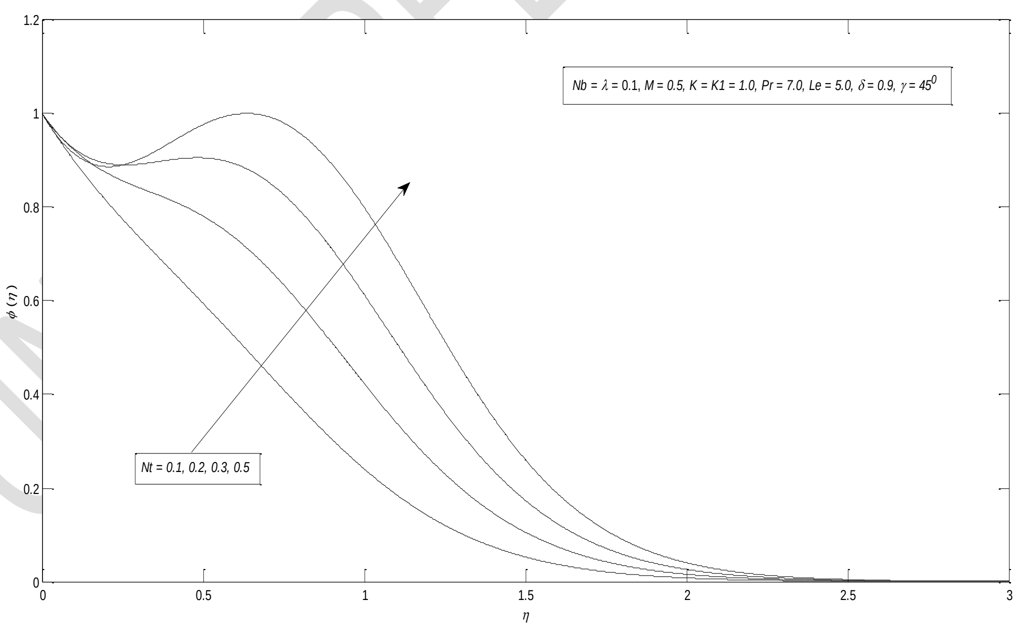

Fig. 23. Variations in concentration profile for several values of Nt.

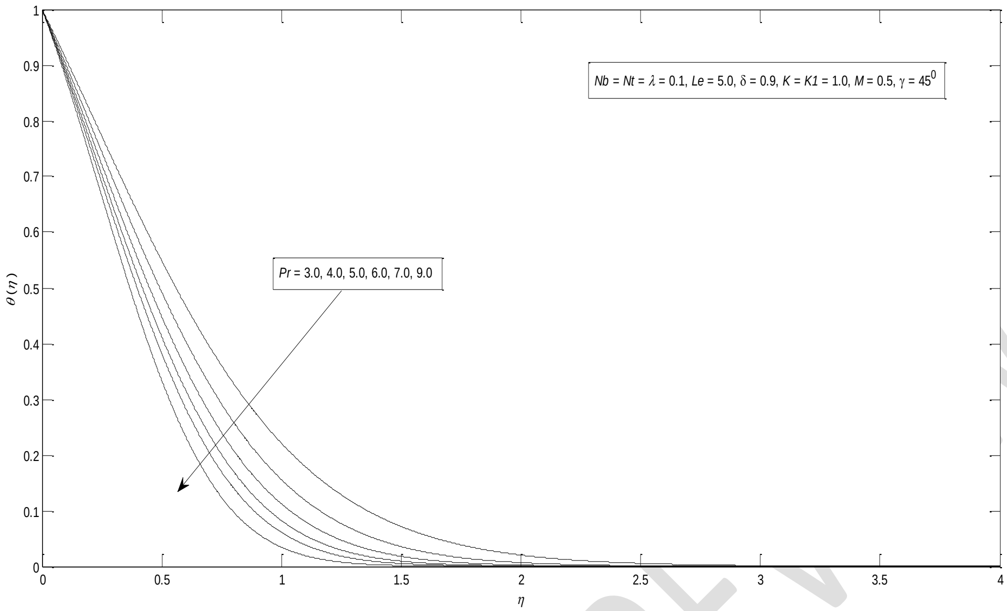

Fig. 24. Variations in temperature profile for several values of Pr.

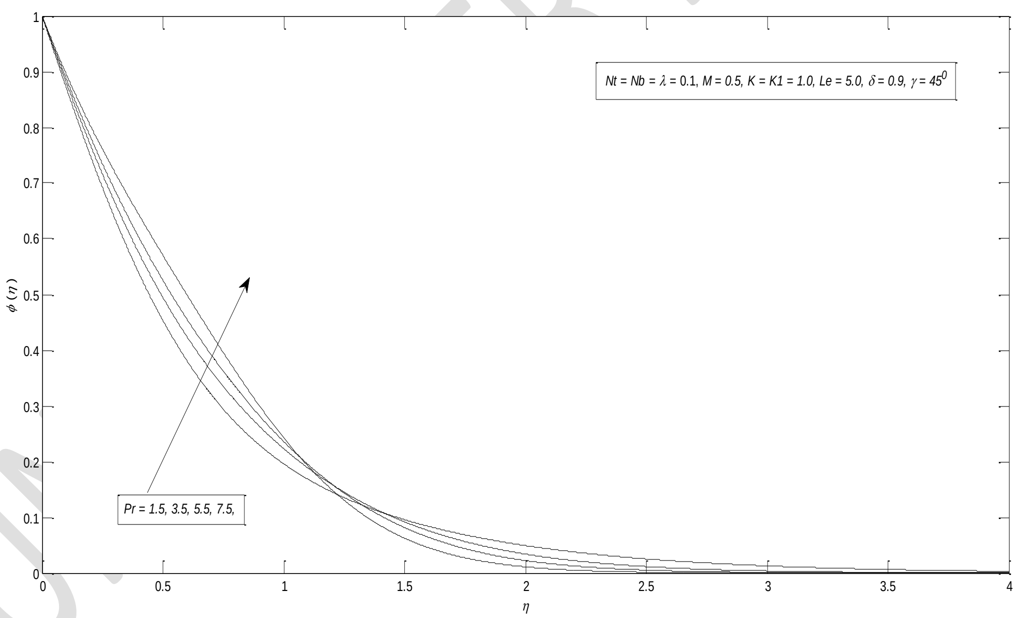

Fig. 25. Variations in concentration profile for several values of Pr.

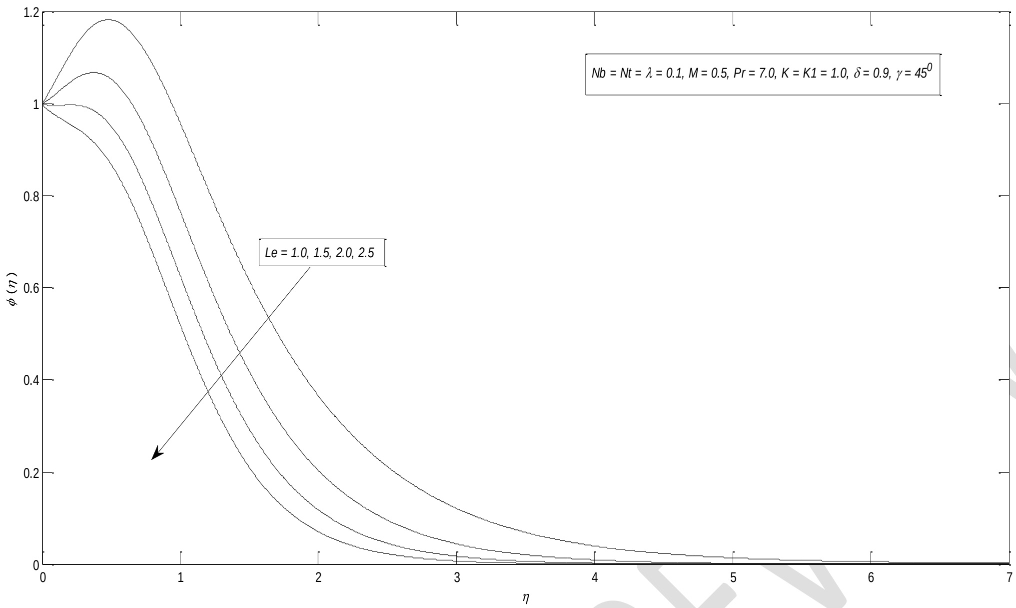

Fig. 26. Variations in concentration profile for several value of Le.

Figs. 22 and 23 present temperature and concentration profile against several values of thermophoresis parameters Nt. It is observed that both temperature and concentration contours upsurge by growing the thermophoresis parameter. Thermophoresis works to heat up boundary layer against several values of Prandtl number and Lewis number. Besides the amount of heat and mass exchange reduce by improving thermophoresis constraint Nt. Fig. 24 reveals that by growing the values of Prandtl number factor Pr the temperature profile drop, because thermal boundary layer viscosity declining by growing the Prandtl number Pr. In short an upturn in Prandtl number Pr mean deliberate amount of thermal dispersion. Whereas, concentration profile fall with large values of Pr presented in Fig. 25. Fig. 26 displays the result of Lewis number Le on concentration profile. The boundary layer viscosity lessening by improving the values of Lewis number Le.

4 Conclusions

This study is explored the heat and mass exchange of micropolar nanofluid flow over linear inclined extending sheet. It is noted that $-\theta'(0)$ falls for growing the values of Nb,Nt, M,Le, K_1, γ, and improved by enhancing the numerical values of K, λ, δ, and Pr. Moreover, it is observed that $-\phi'(0)$ boosted with the larger values of $Nb, \lambda, \delta, Nt, Le,$ $K$and falls for bigger values of M, K_1, Pr and γ. On the other hand, $C_{fx}(0)$ rises with the cumulative values of Nb, Le, M, K, γ, K_1, and falls with the higher values of Nt, λ, δ, and Pr.

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