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Magnetohydrodynamic Maxwell Nanofluids Flow over a Stretching Surface through a Porous Medium: Effects of Non-Linear Thermal Radiation, Convective Boundary Conditions and Heat Generation/Absorption

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Abstract**—**In this paper, an enhancement of the heat transfer using non-Newtonian nanofluids by magnetohydrodynamic (MHD) mixed convection along stretching sheets embedded in an isotropic porous medium is investigated. Case of the Maxwell nanofluids is studied using the two phase mathematical model of nanofluids and the Darcy model is applied for the porous medium. Important effects are taken into account, namely, non-linear thermal radiation, convective boundary conditions, electromagnetic force and presence of the heat source/sink. Suitable similarity transformations are used to convert the governing equations to a system of ordinary differential equations then it is solved numerically using a fourth order Runge-Kutta method with shooting technique. The main results of the study revealed that the velocity profiles are decreasing functions of the Darcy number, the Deborah number and the magnetic field parameter. Also, the increase in the non-linear radiation parameters causes an enhancement in the local Nusselt number.

Keywords**—**MHD, nanofluids, stretching surface, non-linear thermal radiation, convective condition.

I. Introduction

MHD denotes study of the dynamics of electrically conducting fluids. It establishes a coupling between the Navier-Stokes equations for fluid dynamics and Maxwell's equations for electromagnetism. The main concept behind the MHD is that magnetic fields can induce currents in a moving conductive fluid, which, in turn create forces on the fluid and influence on the magnetic field itself. Vittal et al. [1] investigated MHD stagnation point flow and convective heat transfer of tangent hyperbolic nanofluid over a stretching sheet with zero normal flux of nanoparticles. Shravani et al. [2] studied the heat and mass transfer in a stagnation point flow over a stretching sheet with chemical reaction and suction/injection effects using viscoelastic nanofluids. Cortell [3] examined the fluid flow and radiative nonlinear heat transfer over a stretching sheet. The study showed that effect of Prandtl number on the temperature is negative. Das et al. [4] excogitated the unsteady nanofluid flow over a stretching surface in the presence of a thermal radiation.

Srinivas et al. [5] applied an analytical solution based on the perturbation technique to study the Soret and convective boundary conditions effects on MHD pulsating flow in a horizontal channel. Dessie et al. [6] reported MHD effects on the heat transfer over a stretching sheet embedded in a porous medium with variable viscosity, viscous dissipation and heat source/sink. The results indicated that the impact of Prandtl number on the temperature is decreasing but impact of the magnetic field on the temperature is increasing. Pavithra and Gireesha [7] analyzed the unsteady flow and heat transfer of a fluid-particle suspension over an exponentially stretching sheet. The study showed that as the Prandtl number increases the temperature distributions are reduced. Akbar et al. [8] investigated the radiation effects on MHD stagnation point flow of a nanofluid towards a stretching surface with convective boundary condition. On the other hand, the nanofluids achieved admirable attention due to their practical applications. Nanofluids are actually homogenous mixture of a base fluid and nanoparticles. Concept of the nanofluid refers to a new kind of the heat transport fluids by suspending nano-scaled metallic and nonmetallic particles in the base fluids. Few examples of common base fluids are water, organic liquids (e.g. ethylene, tri-ethyleneglycols, refrigerants, etc.). Mukhopadhyay and Bhattacharyya [9] obtained the unsteady flow of a Maxwell fluid over a stretching surface in presence of chemical reaction. The results showed that the increase of the magnetic field enhances the nanoparticles fraction. Das [10] investigated the radiation and melting effects on MHD boundary layer flow over a moving surface. It is found that the velocity profiles are reduced as the magnetic field parameter increases. Ramesh et al. [11] investigated stagnation point flow of Maxwell fluid towards a permeable surface in the presence of nanoparticles. It is noted that an increase in the Brownian motion parameter enhances the temperature distributions. Manjunatha and Gireesha [12] explained effects of the variable viscosity and thermal conductivity on MHD flow and heat transfer of a dusty fluid. Daniel and Daniel [13] reported effects of the buoyancy and thermal radiation on

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MHD flow over a stretching porous sheet. Raju et al. [14] analyzed MHD heat and mass transfer over a vertical surface saturated in a porous medium in the presence of thermal radiation and chemical reaction effects. Das et al. [15] studied the numerical simulation of nanofluid flow with convective boundary condition. Akbar et al. [16] explained MHD stagnation point flow of Carreau fluid toward a permeable shrinking sheet.

The flow that is produced due to stretching of an elastic flat sheet which moves in its plane with velocity varying with the distance from a fixed point due to the application of a stress is known as stretching flow. The production of sheeting material arises in numbers of industrial manufacturing processes and includes both metal and polymer sheets. The tangential velocity imported by the sheet induces motion in the surrounding fluid, which alters the convection of the sheet. Das [17] reported the flow and heat transfer characteristics of the nanofluids. Rashidi et al. [18] studied MHD heat and mass transfer over stretching sheets in the presence of the thermal radiation and convective boundary conditions. Both of temperature and nanoparticles decrease as the Biot number varied. Akinbobola and Okoya [19] analyzed effects of the variable properties on the mixed convective flow of the second grade fluids over a stretching sheet. Haroun et al. [20] presented the unsteady natural convective boundary-layer flow of MHD nanofluid over stretching surfaces with chemical reaction using the spectral relaxation method. Salahuddin et al. [21] investigated the analysis of tangent hyperbolic nanofluid impinging on a stretching cylinder near the stagnation point. Hayat et al. [22] studied the Newtonian heating effect in the nanofluid flow by a permeable cylinder. Ahmmed et al. [23] examined the unsteady MHD free convection flow of the nanofluid through an exponentially accelerated inclined plate embedded in a porous medium with variable thermal conductivity in the presence of radiation

Study of thermal radiation, particularly in case of the external flow, attracted the attention of many researchers due to its importance in numerous applications in industrial areas. These applications include for example electrical power generation, astrophysical flows, solar power technology, space vehicle re-entry. Ismail et al. [24] analyzed the thermal radiative effects on MHD Casson nanofluid boundary layer over a moving surface. Haritha et al. [25] studied MHD natural convection heat transfer in a porous square cavity filled by nanofluids with viscous dissipation. Mondal et al. [26] investigated MHD flow and heat transfer of Maxwell nanofluids over an unsteady permeable shrinking sheet with convective boundary conditions. Nirmala et al. [27] showed an integral Vonkarman treatment of MHD natural convection on the heat and mass transfer along a radiating vertical surface saturated in a porous medium. Nandeppanavar et al. [28] studied the three-dimensional flow, heat and mass transfer of MHD non-Newtonian nanofluids due to stretching Sheet. Nayak et al. [29] analyzed free convective 3D stretched radiative flow of nanofluids in the presence of variable magnetic field and internal heating. Rajendar and Babu [30] studied MHD stagnation point flow of Williamson nanofluid over an exponentially inclined stretching surface with thermal radiation and viscous dissipation. Several studies in convective transport using nanofluids in cases of external flow and boundary layer flow are given in recent papers [31]-[40].

The main objective of this paper is to study MHD flow of Maxwell nanofluid over a stretching surface through a porous medium in the presence of non-linear thermal radiation and heat generation/absorption. Self-similar transformations are introduced to transform the governing partial differential equations (PDE) to a system of ordinary differential equations (ODE). The ODE are solved numerically by using the Runge-Kutta method. The results of the problem are presented in terms of, velocity, temperature, nanoparticles volume fraction, local Nusselt number and local Sherwood numbers.

II. Problem Formulation

Consider a steady and laminar flow of a non-Newtonian nanofluid in the presence of magnetic field. The physical model consists of a starching surface located at *y = 0* and *x = 0*. Magnetic field of an intensity *Bo* is applied in the y-direction normal to the surface. The flow field is exposed the influence of buoyancy effect, temperature dependent heat source and thermal radiation. Surface of the plate is maintained at uniform temperature *Tw* and this value is assumed to be greater than the ambient temperature *T*∞. Two-phase mathematical model is used to investigate case of the nanofluids and the Darcy model is applied for the porous medium. The local thermal equilibrium (LTE) between the porous and fluid phases is taken into account and a heat source is taken place in the flow region. The problem under consideration is governed by the following boundary layer equations:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}-k_0\left(u^2\frac{\partial^2 u}{\partial x^2}+v^2\frac{\partial^2 u}{\partial y^2}+2uv\frac{\partial^2 u}{\partial x\,\partial y}\right)-\frac{\mu}{\rho_f k}u-\frac{\sigma B_0^2}{\rho_f}u, \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial y^2}\right)+\frac{Q_0}{\rho_f c_p}(T-T_\infty)-\frac{1}{(\rho_f c)_f}\frac{\partial q_r}{\partial y}+\tau\left\{D_B\left(\frac{\partial C}{\partial y}\frac{\partial T}{\partial y}\right)+\left(\frac{D_T}{T_\infty}\right)\left[\left(\frac{\partial T}{\partial y}\right)^2\right]\right\} \tag{3}$$

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

where u and v are the velocity components along the x and y axes, respectively. α is the diffusivity, ρ_f is density of the base fluid, ρ_p density of the particles, ν kinematic viscosity of the fluid, T is the fluid temperature, T_∞ ambient fluid temperature, k_0 is the relaxation time, Q_0 is the dimensional heat generation/absorption D_B is the Brownian diffusion coefficient, D_T is the thermophoresis diffusion c_p is the specific heat at constant pressure, $(\rho_f c)_f$ is the heat capacity of fluid q_r the nonlinear radiative heat flux, μ is the dynamic viscosity, σ is the electrical conductivity, k is the thermal conductivity, τ is the ratio of the effective heat capacity of the nanoparticles material and the heat capacity of the ordinary fluid and C is the nanoparticles volume fraction. The boundary conditions for the current problem are given by:

$$u = U_x(x), v = 0\,, k\frac{\partial T}{\partial y} + h_f(T_f - T) = 0\,, D_B\frac{\partial C}{\partial y} + \frac{D_T}{T_\infty}\frac{\partial T}{\partial y} = 0 \text{ at } y = 0$$

$$u \to 0\,, v \to 0\,, T \to T_\infty\,, C \to C_\infty \text{ at } y \to \infty \quad (5)$$

where C_w and C_∞ are the nanoparticles volume fraction at wall and ambient nanoparticles volume fraction respectively, $c = U_x(x)/x$ is known as a stretching rate. Introducing the following similarity transformations:

$$\eta = y\sqrt{\frac{c}{\nu}}\,, f(\eta) = \frac{\chi}{\sqrt{(x\nu U_w)}}\,, \theta(\eta) = \frac{T-T_\infty}{T_f-T_\infty}\,, \varphi = \frac{C-C_\infty}{C_w-C_\infty}, u = cxf'(\eta), v = -\sqrt{c\nu}f(\eta) \quad (6)$$

where η, f, θ and φ represent similarity variable, stream function, temperature function and concentration function respectively. Substituting (6) in (1)-(4), the following system is obtained:

$$f'^2 + (M + Da)f' - ff'' - f''' + \beta(f^2f''' - 2ff'f'') = 0 \quad (7)$$

$$\theta'' + Pr\left(S\theta + Nb\theta'\varphi' + Nt\theta'^2 + \frac{4}{3}R((Ct + \theta)^3\theta')'\right) = 0 \quad (8)$$

$$\varphi'' + LePrf\varphi' + \frac{Nt}{Nb}\theta'' = 0 \quad (9)$$

The corresponding boundary conditions in the non-dimensional form are:

$$f = 0, f' = 1, \theta' = -Bi(1 + \theta), Nb\varphi' + Nt\theta' = 0 \text{ at } \eta = 0$$
$$f' \to 0, \theta \to 0, \varphi \to 0 \text{ at } \eta \to \infty \quad (10)$$

where $\beta = k_0c$ is parameter of the non-Newtonian fluid, $Bi = \sqrt{(\nu/a)}h_f/k$ is the Biot number parameter, $S = \frac{Q_o}{c\rho_f c_p}$ is the heat source ($S > 0$) or sink ($S < 0$), $Nb = \frac{\tau D_B(C_w-C_\infty)}{\nu}$ is the Brownian motion parameter, $Nt = \frac{\tau D_T(T_w-T_\infty)}{\nu T_\infty}$ is the thermophoresis parameter, $Le = \frac{\alpha}{D_B}$ is the Lewis number, $Da = \frac{\mu}{\rho_f ck}$ is the Darcy number, $R = \frac{16\sigma^*(T_w-T_\infty)^3}{3kk^*}$ is the non-linear thermal radiation parameter, $Pr = \frac{\nu}{\alpha}$ is the Prandtl number and $M = \frac{\sigma {B_0}^2}{\rho_f c}$ is the magnetic field parameter, $Ct = \frac{T_\infty}{T_w-T_\infty}$ is the radiation parameter. Mathematical forms of the skin friction coefficient, local Nusselt number and Sherwood number are, respectively, given by:

$$C_f = \frac{(1+\beta)f''(0)}{Re_x^{1/2}}, \frac{Nu_x}{Re_x^{1/2}} = -\theta'(0)\,, \frac{Sh_x}{Re_x^{1/2}} = -\varphi'(0)$$

III. Result and Discussions

The transformed ODE (7) and (9) with the boundary conditions (10) are solved numerically using the fourth order Runge-Kutta method with shooting technique. This technique has two steps. In the first step, the system of equations is converted to first order differential equations using new variables. In the second step, an initial guesses for the dependent variables is given then the system is so2lved iteratively. The controlling parameters in this study are the Deborah number β, the Brownian motion parameter N_b, the thermophoresis parameter N_t , the Prandtl number parameter Pr, the Lewis number parameter Le, the magnetic field parameter M, the Darcy number parameter Da, the non-linear thermal Radiation parameter R, the heat source parameter S, the Biot number Bi and the Radiation parameter Ct.

A. Velocity Profiles

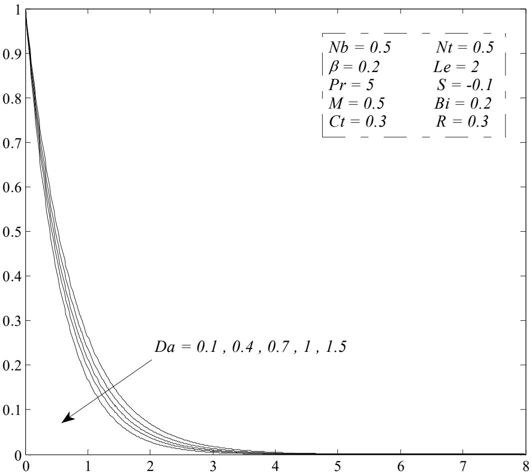

Fig. 1 Effects of the Darcy number Da on the velocity profiles

Fig. 1 displays profiles of the nanofluid velocity for different values of the Darcy number *Da*. Case of the presence of a heat sink is considered. It is found that a clear reduction in the fluid activity is obtained as *Da* increases due to decreases the permeability of the porous medium. In addition, the velocity profiles for different values of the Deborah number β are presented in Fig. 2. Here it should be mentioned that case of $\beta = 0$ represents case of Newtonian nanofluid. It is noted that the fluid in case of non-Newtonian fluid is much slower than case of the Newtonian fluid. Moreover, the increase in the Deborah number β leads to suppression the fluid flow. Physically, the increase in the Deborah number β means that the fluid becomes more viscous which in turn decreases rate of the fluid flow. Additionally, influences of the electromagnetic force represented by variations of M are depicted in Fig. 3. As it is known, presence of the magnetic field in the flow domain results in force that is known as a Lorentz force leads to decrease the fluid flow. That is the reason of the reduction in the velocity profiles as M increases as it is noted in Fig. 3.

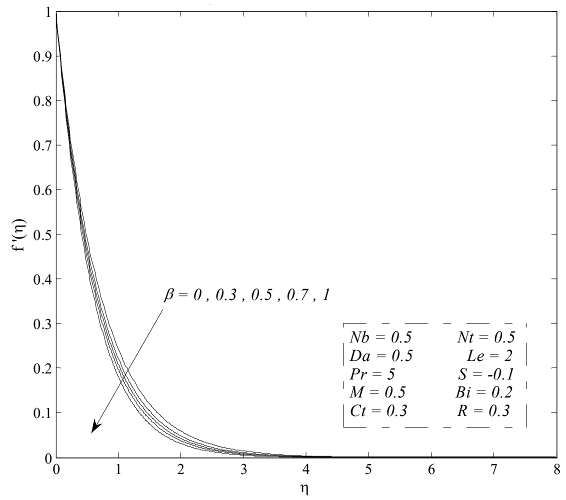

Fig. 2 Effects of the Deborah number β on the velocity profiles

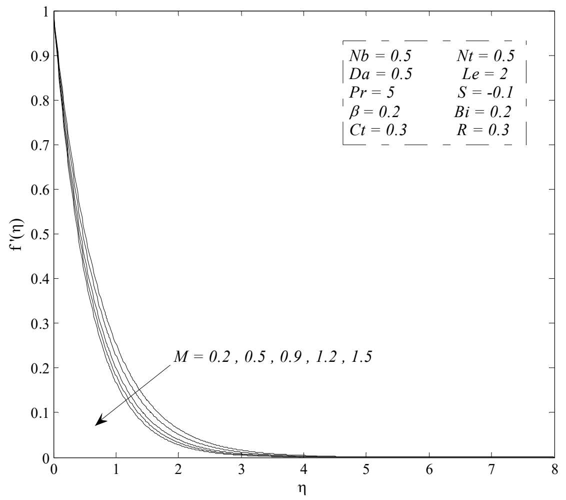

Fig. 3 Velocity profiles for variations of the magnetic field parameter M

B. Temperature Distributions

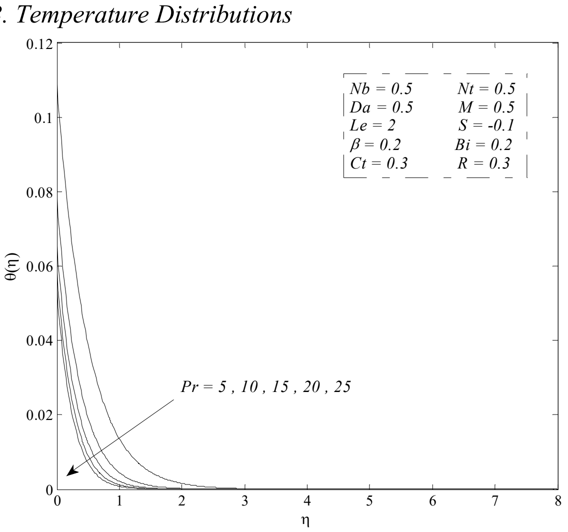

Fig. 4 Effects of the Prandtl number Pr on the temperature distributions

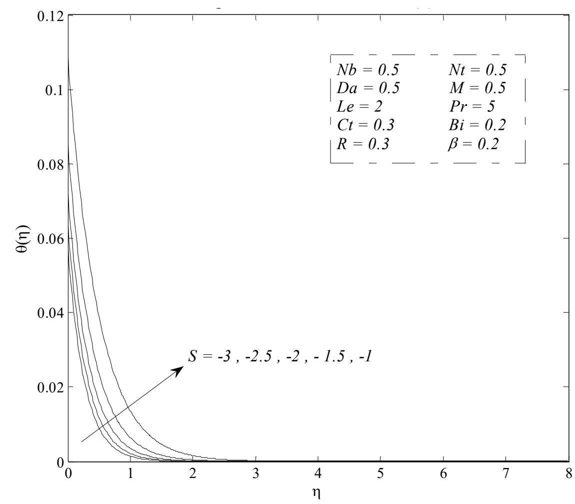

Fig. 5 Effects of the heat generation/absorption parameter S on the temperature profiles

Fig. 4 illustrates variations of the Prandtl number Pr on the temperature distributions. As it can be seen, the increase in Pr reduces the temperature profiles due to the reduction in the thermal conductivity. On the contrary, the growing in the heat generation/absorption parameter S enhances the temperature due to the increase in temperature generation in the flow domain as S increases. This behavior is clearly noted with the help of Fig. 5. Also, like effects of S, Figs. 6 and 7 show a good boost in behaviors of the temperature as the radiation parameters R and Ct increase. This can be explained as follows: The increase in R or Ct leads to generation of heat in flow region and consequently the fluid temperature is enhanced. Finally, Fig. 8 presents profiles of the nanofluid temperature for variations of the Biot number Bi. The results revealed that the increase in Bi enhances the temperature at the boundary and hence the nanofluid temperature increases.

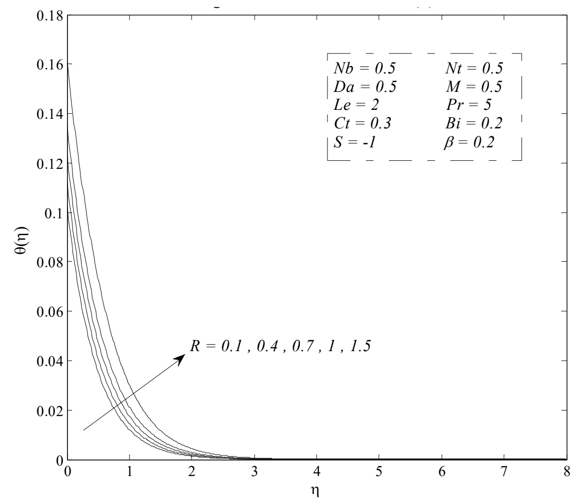

Fig. 6 Effects of the radiation parameter R on the temperature profiles

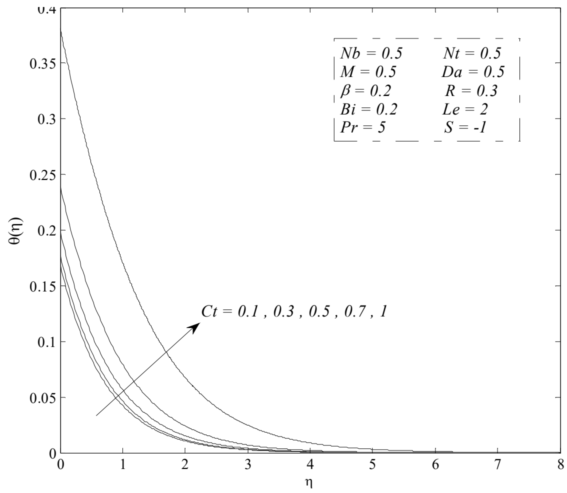

Fig. 7 Effects of Ct on the temperature distributions

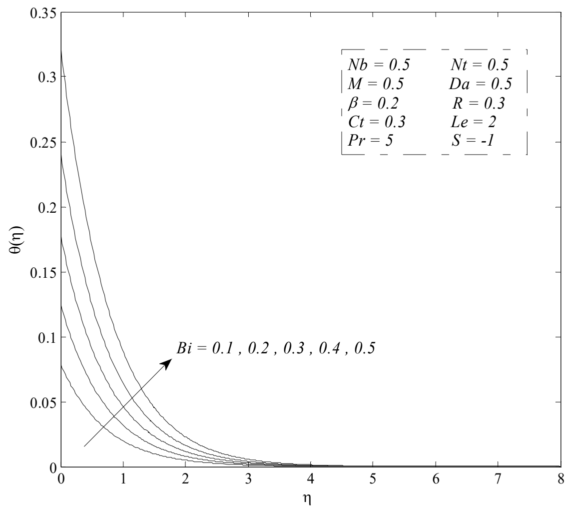

Fig. 8 Effects of the Biot number Bi on the temperature profiles

C. Nanoparticles' Distributions

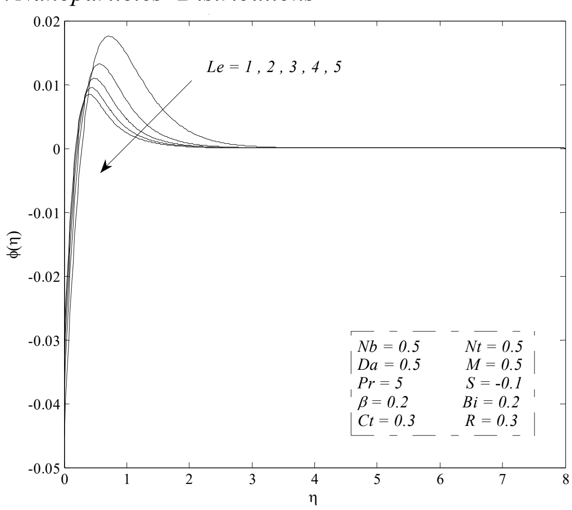

Fig. 9 Effects of the Lewis number Le on the nanoparticles volume fraction profiles

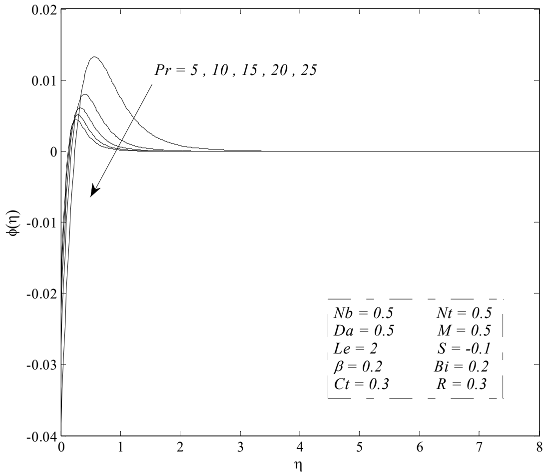

Fig. 10 Effects of the Prandtl number Pr on the nanoparticles volume fraction profiles

Figs. 9 and 10 depict the nanoparticle volume fraction for different values of the Lewis number Le and Prandtl number Pr, respectively. It is observed that, the Lewis number reduces distributions of the nanoparticle volume fraction due to decrease in the mass diffusion. Like effects of Le, the Prandtl number decreases the nanoparticle volume fraction due to the decrease in the fluid temperature as Pr increases. In addition, the inverse behaviors for the nanoparticle volume fraction can be noted in Figs. 11 and 12. In these figures, effects of the Brownian motion parameter Nb and thermophoresis parameter Nt on $\phi(\eta)$ are examined. The figures showed that the increases in Nb reduce the nanoparticle volume fraction while $\phi(\eta)$ is enhanced as the thermophoresis parameter is increased. Moreover, it can be stated that the behavior of the nanofluid temperature affected the behavior of the nanoparticle volume fraction strongly. Therefore, as it can be seen from Fig. 13 which displays effects of the Biot number on $\phi(\eta)$ that a clearly support in behaviors of $\phi(\eta)$ is obtained as Bi increases due to increase the temperature at the surface of the plate.

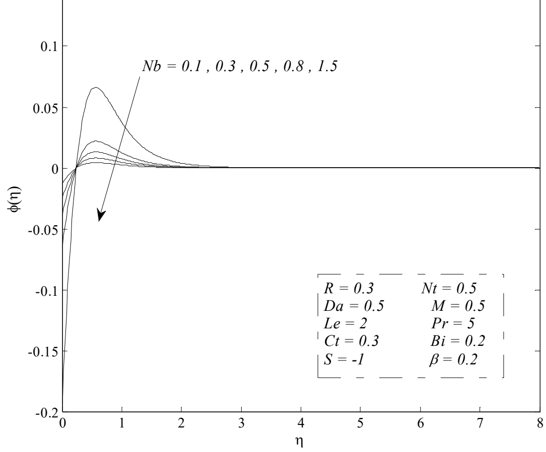

Fig. 11 Effects of the Brownian motion parameter Nb on the nanoparticles volume fraction profiles

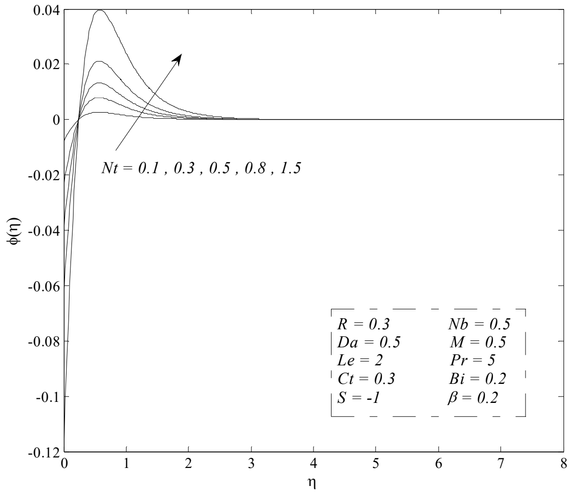

Fig. 12 Effects of the thermophoresis parameter Nt on the nanoparticles volume fraction profiles

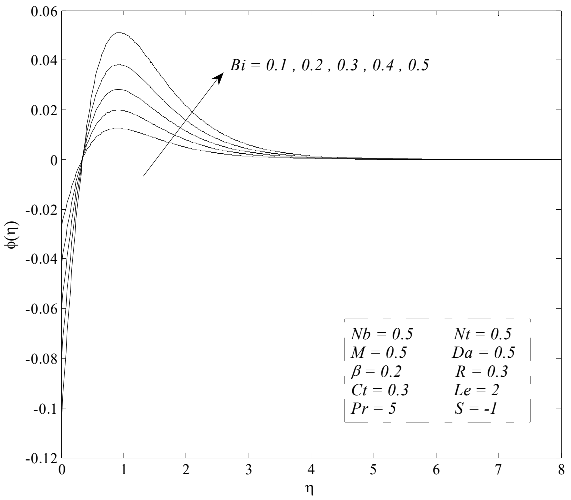

Fig. 13 Effects of the Biot number Bi on the nanoparticles volume fraction profiles

D. Profiles of Skin Friction, Local Nusselt and Sherwood Numbers

Via Fig. 14, effects of the Darcy number Da and magnetic parameter M on profiles of the skin friction $f''(0)$ are examined. It is noted that the increase in both of Darcy number and magnetic field parameter results in a support in gradients of velocity at the surface and hence the skin friction coefficient increases. Like these effects, Fig. 15 shows that the local Nusselt number is enhanced as the heat absorption parameter S or radiation parameter R increases due to an increase in the thermal boundary layer. Similar effects of R on the local Nusselt number are noted for variations of Ct on the local Nusselt number.

Fig. 16 shows that the increase in *Ct* causes an increase in the local Nusselt number. Finally, Figs. 17 and 18 present profiles of the local Sherwood number for different values of the radiation parameters R and Ct, the heat absorption parameter S and the Prandtl number Pr. It is observed that the increase in the radiation parameters R and Ct causes a decrease in the gradients of the nanoparticle volume fraction and consequently the Sherwood number is reduced.

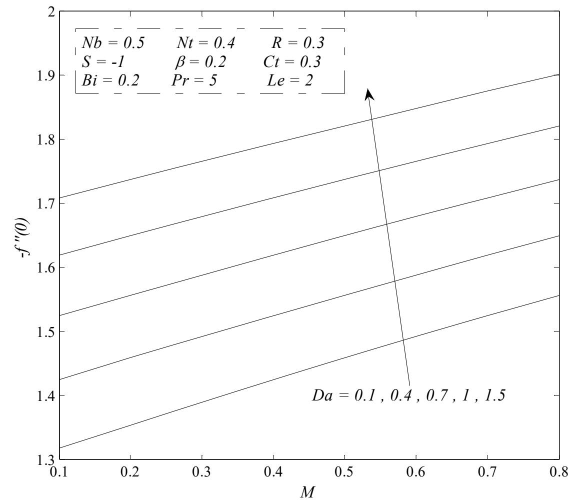

Fig. 14 Effects of the Darcy number Da and magnetic parameter M on the skin friction $f''(0)$

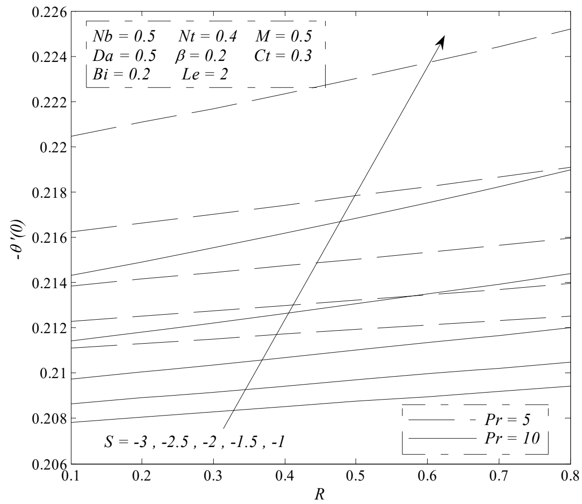

Fig. 15 Effects of the radiation parameter R and heat absorption parameter S on the local Nusselt number $\theta'(0)$

IV. Conclusions

The problem of MHD flow of non-Newtonian nanofluids over a stretching surface through a porous medium in the presence non-linear thermal radiation, heat sink and convective boundary conditions effects has been investigated in the current paper. Case of the nanofluid is represented by the two phase mathematical model while the nan-Newtonian case is represented by Maxwell fluids. Similar solutions are used to convert the governing equations to ODE; those are solved numerically using shooting technique. The following conclusions can be outlined:

- The velocity profiles are decreasing function of the Darcy number, the Deborah number and the magnetic field parameter.
- Temperature and nanoparticles' volume fraction are

promoted with an increase in each of radiation R, thermophoresis *Nt*, Biot number *Bi* and heat generation *S* parameters.

- The local Nusselt number is enhanced as either the radiation parameters or the heat absorption increase.
- The increase in the radiation parameter reduces the local Sherwood number.
- The skin friction coefficient is promoted when the Darcy number and magnetic field parameter are increased.

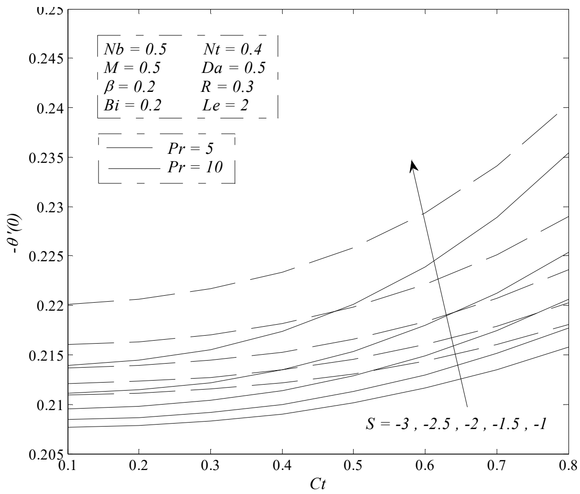

Fig. 16 Effects of the radiation parameter Ct and heat absorption parameter S on the local Nusselt number $\theta'(0)$

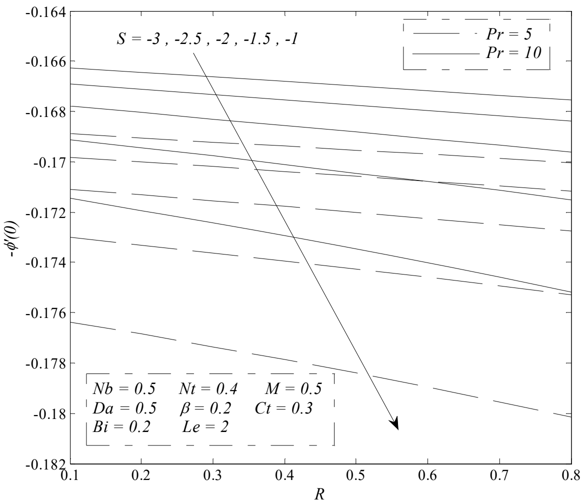

Fig. 17 Effects of the radiation parameter R and heat absorption parameter S on the local Sherwood number $\phi'(0)$

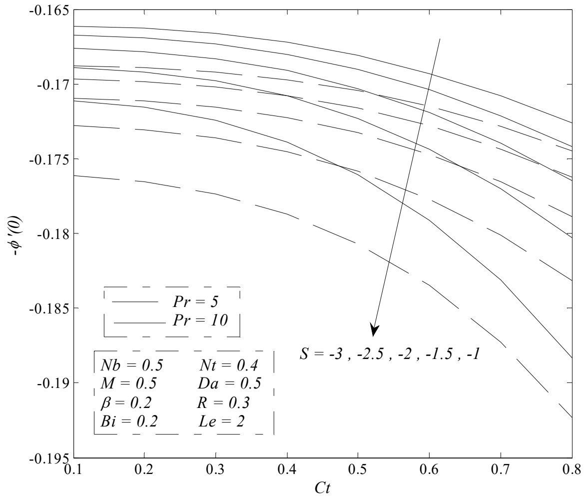

Fig. 18 Effects of the radiation parameter Ct and heat absorption parameter S on the local Sherwood number $\phi'(0)$

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