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Chemical reaction and non-Darcian effects on MHD generalized Newtonian nanofluid motion

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Abstract

The aim of this paper is to study generalized Newtonian (Carreau) nanofluid flow with heat transfer through a non-Darcy porous medium in the presence of ectromagnetic field and biot number effects. Morever, The heat source, viscous and Ohmic dissipation,and chemical reaction effects are taken into consideration. The system of non linear equations which govern the motion is transformed into ordinary differential equations by using a suitable similarity transformations. These equations are solved by making use of Rung-Kutta-Merson method in a shooting and matching technique. The numerical solutions of the velocity, temperature and nanoparticles concentration are obtained as a functions of the physical parameters of the problem. Moreover the effects of these parameters on these solutions are discussed numerically and depicted graphically. It is found that bothtangential and normal velocities increaseor decease as the Darcy number increases. Morever, the temperature increases as both Forschheimer and Reynolds numbers increase, and both Weissenberg and Biot numbers leads to increase the nanoparticles concentration.

Keywords: Non-Newtonian nanofluid; heat transfer; non-Darcyporous medium; chemical reaction.

1.Introduction

A liquid with very small particles of diameter less than 100 nm is called nanofluid.By adding these nanoparticles up to the fluid makes itnon-homogeneous, consequently, thermodynamic is in theflow increases that will cause more energy and power lossesinto the system. Saving helpful energy will depend on how to designthe effective heat transfer process from a thermodynamicpoint of view. Energy transformation processes will tend to a proportionalincrease in entropy. Consequently, even if the energy is preserved,the high quality of energy that decreases converting them intoa different form of energy at which less work can be obtained.One of the first people whoadded the entropy generation to thefluid flow was Bejan [1, 2]. Also, he presenteda method which is called the entropy generation minimization (EGM) tomeasure and optimization disorder or disorganization generatedduring a process. There is no question that by ‘‘optimize’’ we meanthe stabled process in which the system loses the least energywhile still performing its fundamental engineering function.The method is also known as second law analysis and thermodynamicoptimization. This field has been developed astoundinglyduring the 1990s, in both engineering and physics. Good example of such efforts found in references [3-6].

Magnetohydrodynamics (MHD) is interested with Newtonian or non- Newtonian fluids motion and with the interaction of electrically conducting fluids. The concept of MHD was investigated by Alfvén [7]. The MHD fluid flow has received remarkable attention by scientists and researchers due to its enormous applications in the field of geophysics, mechanical, electrical, biological, geothermal as well as many other technical and industrial processes like cooling of generators, nuclear reactors, power generators, …etc. Radially varying magnetic field effects on the Jeffery fluid peristaltic flow with heat and mass transfer in the presence of radiation and heat source was analyzed by Eldabe and Abouzeid [8].Sheikholeslami et al. [9] studied the flow of a

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nanofluid in the presence of thermal radiation and magnetic field. MHD non-Newtonian nanofluid flow through a porous medium with couple stresses effects is discussed by Abouzeid [10]. El-dabe et al.[11] have investigated the electromagnetic steady motion of Casson fluid with heat and mass transfer through porous medium past a shrinking plate.MHD fluid flow has received remarkable attention by scientists and researchers [12-19].

Th problems in which the flow initiates from zero velocity at the wall to extreme velocity within the main flow is called boundary layer problem .The concept of boundary layer has a sence in all of viscous fluid dynamics within the hypothesis of heat transfer. The boundary layer flow with heat transfer over a stretching or shrinking platehas a great importance due to its applications including glass-fiber production, plastic pieces aero-dynamic extrusion, hot rolling and paper production. Carreau nanofluid flow over a stretching porous platewith thermal diffusion and diffusion thermo effects was studied by Eldabe et al. [20].Kamran and Wiwatanapataphee[21] reported that chemical reaction with the Newtonian heating impact is significant in the solidification process of liquid crystals and polymeric suspensions. The boundary layer flow with heat and mass transfer properties are achieved analytically in the presence of viscous dissipation and heat source by Abouzeid [22]. Many researchers considered various non-Newtonian fluid models in their studies [23-26].

The main aim of this work is to extend the work of Eldabe et al. [11] to include Carreau nanofluid, pressure deriven flow, non-Darcian porousity and Biot number effects. Then the boundary layer motion of Carreau nanofluid conducting fluid with heat transfer over a shrinking plate is analyzed. The system is stressed by both uniform magneticand electric fields. A heat generation with radiation and chemical reaction are taken in consideration. This motion is modulated mathematically by a system of non-linear partial differential equations which transformed into non-linear ordinary differential equations by using suitable transformation. This system is solved numerically subjected to the appropriate boundary conditions in the presence of Biot number to obtain the velocity, temperature and nanoparticles concentration distributions. The influences of the physical parameters of the problem on these solutions are discussed numerically and illustrated graphically through a set of figures. Physically, our model corresponds to the airfoils flow with low or high Reynolds number.

2 Mathematical formulations

Cartesian coordinates (x, y, z) are considered, where x is along the direction of fluid flow, y is normal to x, and z is normal to the plane (xy). An electrically conducting Carreau nanofluid flows steadily over a shrinking sheet. The external applied magnetic field $B=(0,B_0,0)$, while the electric field $E=(0,0,-E_0)$.

The constitutive equation ofCarreau fluid can be written as follows:

$$\tau_{ij}=-\eta_0\left[1+\frac{(n-1)}{2}\Gamma^2\dot{\gamma}^2\right]\dot{\gamma}_{ij}\ , \qquad (1)$$

$$\dot{\gamma}_{11}=2\frac{\partial u}{\partial x},\quad \dot{\gamma}_{12}=\dot{\gamma}_{21}=\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x},\quad \dot{\gamma}_{22}=2\frac{\partial v}{\partial y}, \qquad (2)$$

where $\dot{\gamma}$ is defined as:

$$\dot{\gamma}=\sqrt{\frac{1}{2}\sum_i\sum_j\dot{\gamma}_{ij}\dot{\gamma}_{ij}}=\sqrt{\frac{1}{2}\prod_{\dot{\gamma}}}, \qquad (3)$$

where $\prod_{\dot{\gamma}}$ is second invariant of strain-rate tensor $\dot{\gamma}_{ij}$.

The governing equations ofcontinuity, momentum,energy, andnanoparticles concentration can be written,respectively, as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (4)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{-1}{\rho}\frac{\partial p}{\partial x}-\frac{\eta_0}{\rho}\frac{\partial}{\partial y}\left\{\left(1+\frac{n-1}{2}\Gamma^2\left(\frac{\partial u}{\partial y}\right)^2\right)\frac{\partial u}{\partial y}\right\}, \qquad (5)$$
$$+\frac{\sigma}{\rho}(E_0B_0-B_0^2u)-\frac{\nu}{k}u+C^*u^2$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{K}{\rho c_p}\frac{\partial^2 T}{\partial y^2}-\frac{\eta_0}{\rho c_p}\left\{\left(1+\frac{n-1}{2}\Gamma^2\left(\frac{\partial u}{\partial y}\right)^2\right)\frac{\partial u}{\partial y}\right\}\frac{\partial u}{\partial y} \qquad (6)$$
$$+\frac{\sigma}{\rho c_p}(uB_0-E_0)^2-\frac{1}{\rho c_p}\frac{\partial q_r}{\partial y}+\frac{Q_0}{\rho c_p}(T-T_\infty)+D_T\left(\frac{\partial T}{\partial y}\right)^2+D_B\left(\frac{\partial T}{\partial y}\right)\left(\frac{\partial C}{\partial y}\right)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_B\frac{\partial^2 C}{\partial y^2}+\frac{D_T}{T_0}\frac{\partial^2 T}{\partial y^2}-A(C-C_\infty) \qquad (7)$$

where the thermal radiation heat flux; $q_r=-\frac{4\sigma^*}{3k_0}\frac{\partial T^4}{\partial y}$. We assume that the differences of fluid-phase temperature in the flow are sufficient small such that T^4 may be expressed as a linear function of temperature

$$T^4=4T_\infty^3 T-3T_\infty^4 \qquad (8)$$

In order to simplify the above system, we use the following transformations,

$$u=-bx\,f'(\eta),\quad v=\sqrt{b\nu}f(\eta),\quad \theta=\frac{T-T_\infty}{T_0-T_\infty}, \quad \varphi=\frac{C-C_\infty}{C_0-C_\infty},\quad \eta=\sqrt{\frac{b}{\nu}}y \qquad (9)$$

Nomenclature

A	Reaction rate constant		Pr	Prandtl number
B_0	Constant		q_r	Thermal radiation heat flux
Bi	Biot number		Q_0	Heat source parameter
C	The nanoparticles concentration		R	Radiation parameter
C^*	Forchheimer ś constant		Re	Reynolds number
c_p	The specific heat at constant pressure		Sc	Schmidt number
Da	Darcy number		T	The fluid temperature
D_B	Brownian diffusion coefficient		u	Tangential component of velocity
D_T	Thermophoretic diffusion coefficient		v	Normal component of velocity
E_0	Constant		We	Weissenberg number
E_1	Local electric parameter		x	Tangential coordinate
Ec	Eckert number		y	Normal coordinate
Fs	Forchheimer number			**Greek symbols**
K	Thermal conductivity		δ	Chemical reaction parameter
k	Permeability constant		η_0	Zero-shear-rate viscosity
k_0	the mean absorption coefficient		Γ	time constant
M	Magnetic field parameter		ν	Kinematic viscosity
n	dimensionless power-law index		ρ	Fluid density
N_b	Brownian motion parameter		σ	The electrical conductivity of the fluid
N_t	Thermophoresis parameter		σ^*	Stefan-Boltzmann constant
p	The fluid pressure		τ_{ij}	the stress tensor components,

Eq. (4) is autommatically satisfied. Substitution of Eqs.(9) in Eqs.(5-7), we get

$$f'^2-ff''=-\frac{\partial p}{\partial x}-\frac{1}{\mathrm{Re}}(1+\frac{n-1}{2}We\,f''^2)f''' -(M^2-\frac{1}{Da})f'+M^2E_1+Fs\,f'^2, \qquad (10)$$

$$f\theta'=\frac{1+4R}{3\mathrm{Pr}}\theta''-\frac{Ec}{\mathrm{Re}}\left(1+\frac{n-1}{2}We^2\,f''^2\right)f''^2 +Ec\,M^2(f'+E_1)^2+Q_0\,\theta+Nt\,\theta'+Nb\,\theta'\varphi' \quad , \qquad (11)$$

$$Sc\,f\,\varphi'=\varphi''+\frac{Nt}{Nb}\theta''-\delta\,\varphi^m \qquad (12)$$

It may be pointed out here that n=1 leads to the boundary-layer flow of ordinary Newtonian conducting fluid. While if we put F_s= $\frac{\partial p}{\partial x}$ =0, n=1 and Bi→ ∞, this problem have been studied for the same boundary conditions by Eldabe et al. [11].Eq.(10-12) arecoupled non-linear ordinary differential equation of order three. For Carreau fluid, as the parameter$n$ tends to zero, the fluid becomes ordinary Newtonian.

The boundary conditions in the non-dimensional form are:

$$f(0)=0,\quad f'(0)=1,\quad \theta(0)=1+\frac{1}{Bi}\theta'(0), \quad \varphi(0)=1,\quad f'(\infty)=\theta(\infty)=\varphi(\infty)=0 \qquad (13)$$

3.Numerical solutions

NAG Fortran library with the help of subroutine D02HAF is used to solve the above system of equations (10-12). Moreover, then, shooting technique is applied. This subroutine requires to guess missing initial and terminal conditions. The governing equations (10-12) are solved by Rung-Kutta-Merson method of order five. In this subroutine, we used variable step size in order to control the local truncation error, then, a modified Newton-Raphson method is used to obtain successive corrections for the estimated boundary values. The process is repeated iteratively many times until convergence and accuracy are occurred.

4. Discussion

In this section, both the tangential and normal velocities, temperature and nano-particles concentration for different values of the problem physical parameters are analyzed in details and depicted graphically. Mathematica package Ver.10.1 is used to obtain the numerical values of these physical quantities. The coefficients of skin-friction and both heat transfer and mass transfer are tabulated to obtain the effect of the above parameters in details.The following values of pertinent parameters are taken as follows

$n = 2, M = 0.5, \mathrm{Da} = 1, \mathrm{E1} = 1, \frac{\partial p}{\partial x} = -10, \mathrm{Re} = 0.5, \mathrm{Fs} = 0.4, \mathrm{We} = 0.5, \mathrm{Pr} = 1, \mathrm{R} = 1, \mathrm{Ec} = 3.5, \mathrm{Q0} = 1, \mathrm{Sc} = 2.5, \mathrm{Bi} = 0.5,\ \mathrm{Nt} = 1.5, \mathrm{Nb} = 2.5, \mathrm{m} = 2,\ \delta = 0.8.$

Pr	M	Bi	$-\theta'(0)$in the present work	$-\theta'(0)$in the work of Eldabe et al. [11]
1	1	0.5	1.20705	1.19268
2	1	0.5	1.89802	1.94141
3	1	0.5	2.80445	2.79731
3	0.6	0.5	1.29605	1.34502
3	0.8	0.5	1.31918	1.33632
3	1	0.5	1.24717	1.25013
3	1	0.2	0.87026	
3	1	0.1	0.76004	

Table (1)

Weissenberg number yields from the ratio between the elastic forces to the viscous forces. Morever, it usually measures the relation of stress relaxation time of the fluid and a specific process time, i.e. Weissenberg number may help to increase the fluid motion. Figures (1) and (2) display the variations of the normal velocity f versus the dimensionless coordinate $\eta$for different values of Weissenberg number We and the magnetic field parameterM, respectively. It is noted from these figures that the normal velocity increases with the increase of We; this is due to the above definition of Weissenberg number, while it decreases as M increases.Inaddition, f increases with η for large values of We, and small values of M, till a definite value $\eta = \eta 0$ (represents the maximum value of f) and it decreases afterwards. This maximum value of f increases by increasing We, while it decreases by increasing M.theresult in figure (2) is due to the fact that the effect of the magnetic field on electrically conductive fluid generates a drag force and develops the force which is known as Lorents force, and it makes to decrease the motion of fluid.Fig. (3) shows the variation of the normalvelocity f with $\eta$for various values of Darcy number Da. It is seen from Fig.(3), that the normal velocity decreases with the increasing of Da in the interval $\eta \in$ [0, 0.85]; otherwise, it increases by increasing Da. Therefore, the behavior of f in the interval $\eta \in$ [0, 0.85] is opposite to its behavior in the interval y ∈ [0.85, 1.2].

The variations of the tangential velocity*f'* with the dimensionless coordinate η forvarious values of the dimensionless power-law index *n*and Reynolds number *Re*are shown in Figs. (4) and (5), respectively, The graphical results ofFigs. (4) and (5),indicate that the tangential velocity increases with increasing in the parametern, while it decreases by increasing the parameter Re, respectively.Furthermore, It is observed that for smallvalues of *n* and large values of*Re*, the relation between *f'* and $\eta$is a parabola with down vertex, i.e.*f'*decreases with ηtill a definite value $\eta = \eta_0$, (represents the minimum value of *f'*) and it increasesafterwards. This absolute minimum value of *f'* increases by increasing *Re*, while it decreases by increasing *n*. The following explains the result in Fig. (5); Reynolds number is defined as the rate of inertia forces to viscous forces in a fluid, this will lead to a resisitance in fluid flow as Reynols number increases. Morever, this result is in agreement with those which are presented by [27].

Figs. (6) and (7) show the behavior of the temperature distributionθ with the dimensionless coordinate η for various values of the thermophoresis parameter Ntand Brownian motion parameter Nb, respectively. It has been seen from these figures that the temperature increases with the increases of Nt, while it decreases as Nbincreases. It is also noted that for each value of both Nt and Nb, there exists a minimum value of θwhich its absolute value increases by increasing Nb and decreases by increasing Nt, and all minimum values occur at $\eta = 0.25$.Brownian motion is an inherent flow of particles dangled in a fluid. This random transition agrees with the fact that the temperature decreases with Brownian motion parameter. So, the result in Fig. (7) agrees with the physical excpectation, and is in agreement with those which are presented by [28, 29]. The effect of Ec on the temperature distribution θas a function of the dimensionless coordinate $\eta$is shown in Fig. (8). It is found that the temperature distribution increases by increasing Ec in the interval $\eta \in [0.5, 1.2]$; otherwise it decreases by increasing Ec.Fig. (9) illustrates the effect of Bi on the temperature distribution θas a function of the dimensionless coordinate η. It is found that in the interval of the coordinate $\eta \in [0.18, 1.2]$, the behavior of $\theta$for various values of Bi is exactly similar to the behavior of $\theta$for various values ofNb given in Fig. (7). It is also noted, from Fig. (9) that in the interval of the radial coordinate $\eta \in [0.18, 1.2]$, the behavior of $\theta$is an inversed manner of its behavior in the interval$\eta \in [0, 0.18]$, except that the curves are quitely close to each other in the second interval. Eq. (13) evaluates how the nanoparticles concentration distribution φ changes with the dimensioless coordinateη. The effects of both Biot number *Bi* and the local electric parameter E_1on the the nanoparticles concentration distribution φ are given in figures (10) and (11), respectively. It is found that the nanoparticles concentrationincreases by increasing *Bi*, but it decreases by increasing E_1. Furthermore, the nanoparticles concentrationis always positive and for large values of Bi and small values of E_1, it increases with ηtill a maximum value of η, after which it decreases.The effects of Brownian motion parameter Nb on the nanoparticles concentrationφ which is a function of η are given in Fig. (12). It is found that the nanoparticles concentration decreases by increasing *Nb* in the interval $\eta\in$ [0, 0.55]; otherwise it increases by increasing η. So, the behavior of g in the interval $\eta\in$ [0, 0.55], is an inversed manner of its behavior in the interval $\eta\in$ [0.55, 1.2], and in the first interval, there is a maximum value of φholds at η =0.19. Figure (13) illustrates the effect of the pressure gradient$\frac{\partial p}{\partial x}$ on the nanoparticles concentrationφas a function of η. It is found that, the behavior of $\varphi$for various values of $\frac{\partial p}{\partial x}$is an inversed manner to the behavior of g for various values of *Nb* given in Figure (12). It is also noted from Fig. (13) that the nanoparticles concentrationis always positive. Moreover, the relation between $\varphi$and η is a parabolic, i.e. as η increases, φ increases till a maximum value after which it decreases.

Table (1) presents a comparison between the numerical results of present study and those obtained by Eldabe et al. [18] for skin friction$f''(0)$, Nusselt number $-\theta'(0)$ and Sherwood number $-f'(0)$ for various values of both E1 and Ha. It is clear from table (1) that an increase in the local electric parameter E1 gives an increase in the skin-friction, but both Nusselt number and Sherwood number decreases or increases. Moreover, as Hartman number Ha increases, the values of $f''(0)$and Sh increase but decreases the dimensionless quantity Nu. Finally, It can be concluded from table (1) that the present results are in a good agreement with those obtained by Eldabe et al. [19]

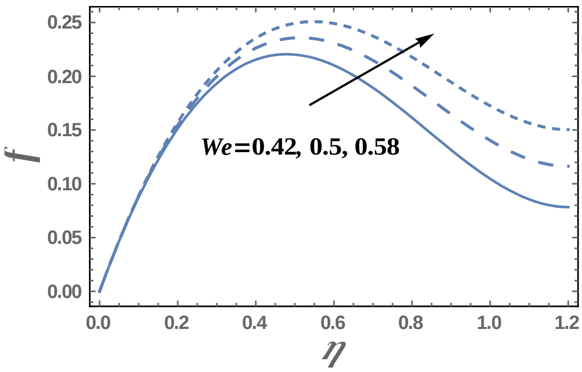

Figure 1: The normal velocity$f$ is sketched towards η under the impact of *We*

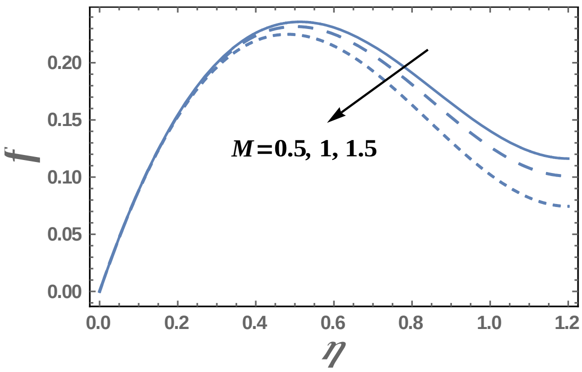

Figure 2: The normal velocity f is sketched towards η under the impact of *M*

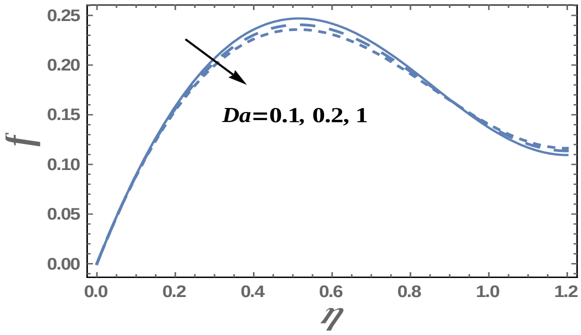

Figure 3: The normal velocity *f* is sketched towards η under the impact of *Da*

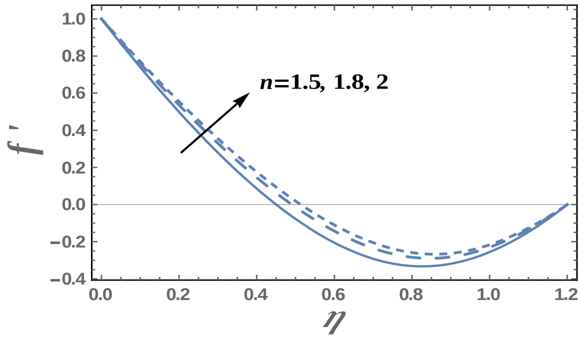

Figure 4: The tangential velocity f' is sketched towards η under the impact of *n*

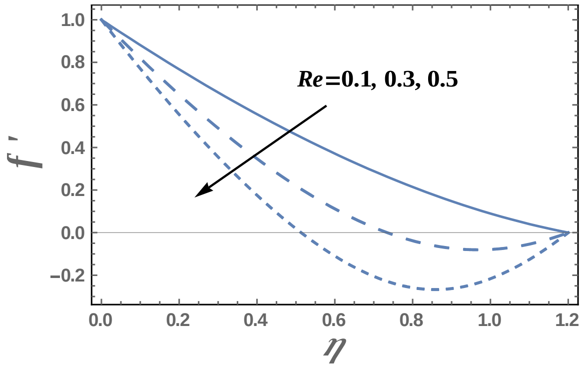

Figure 5: The tangential velocity f' is sketched towards η under the impact of *Re*

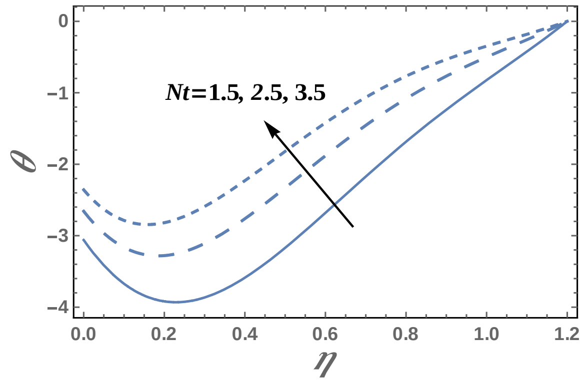

Figure 6: The temperature θ is sketched towards η under the impact of *Nt*

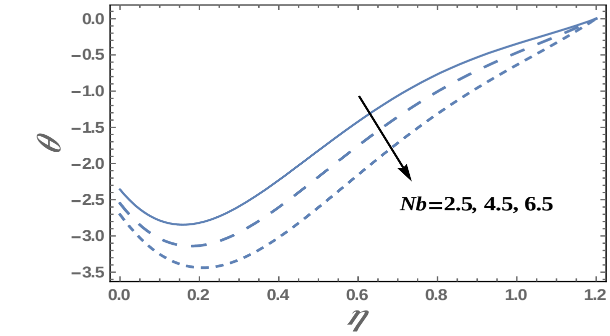

Figure 7: The temperature θ is sketched towards η under the impact of *Nb*

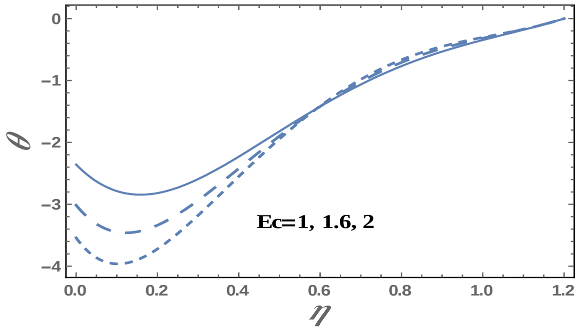

Figure 8: The temperature θ is sketched towards η under the impact of *Ec*

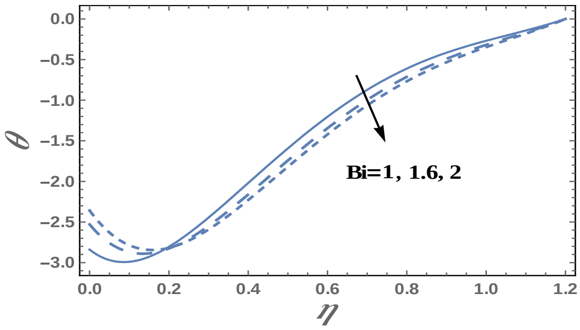

Figure 9: The temperature θ is sketched towards η under the impact of *Bi*

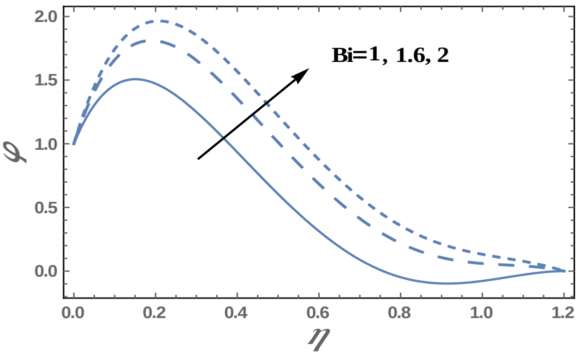

Figure 10: The thenanoparticles concentration φ is sketched towards η under the impact of *Bi*

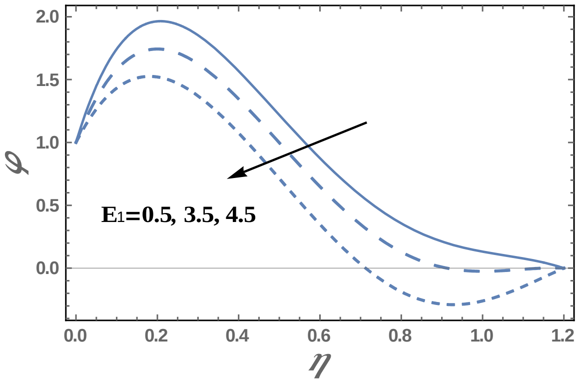

Figure 11: The thenanoparticles concentration φ is sketched towards η under the impact of E_1

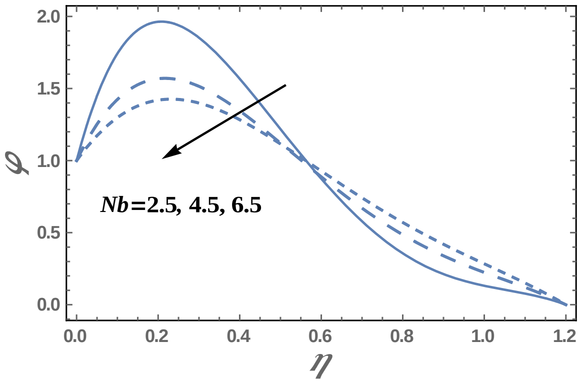

Figure 12: The nanoparticles concentration φ is sketched towards η under the impact of Nb

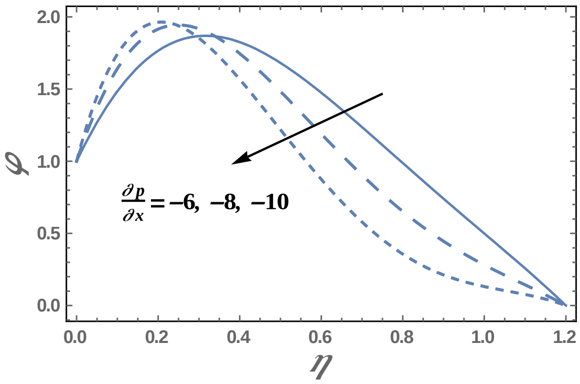

Figure 13: The thenanoparticles concentration φ is sketched towards η under the impact of $\frac{\partial p}{\partial x}$

5.Conclusion

This problem is an extension of Eldabe et al. [11] to include bothnon-Darcian and non-Newtonian nanofluid, viscous dissipation effects. The highly non-linear partial differential equations of velocity,temperature and nanoparticles concentrationare converted into non-linear ordinary differential equation by using suitable similarity transformations. This system of equations is solved numerically by applying Rung-Kutta-Merson-method with a Newton iteration in a shooting and matching technique. The ready analysis can render as a model which may support in comprehension the mechanics of chemical and physiological flows [30-33]. The obtained results can be outlined as follows.

1. By increasing$n$ *and We* and Fs,both the normal and tangential velocites increase while they decrease as E_1, M, and *Re* increase.
2. The normal velocity becomes greater with increasing the dimensionless coordinate η and reaches maximum at η =0.52, after which, it decreases, but the tangential velocity has an opposite manner, i.e. it has a minimum value.
3. The temperature distribution increases as Da, δ, Nt and Re increase, while it decreases or increases as Bi, Ec, n, Pr, R, Sc and We increase.
4. The temperature becomes lower with increasing the dimensionless coordinate η and reaches minimum at η=0.16, after which, it increases.
5. The nanoparticles concentration has an opposite behavior with respect to the temperature behavior except that it increases as Bi, n,, Sc and We increase.

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