Theoretical Study of Eyring-Powell Nanofluid Flow in Darcy-Forchheimer Porous Medium over a Radial Stretching Surface

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Abstract: This article investigates the flow dynamics of an Eyring-Powell nanofluid over a radially stretching surface. A revised zero-mass flux condition is applied, along with the effects of convective heat transfer and viscous dissipation. The influence of thermophoresis and Brownian motion is also considered. The mathematical formulation is developed under the boundary layer approximation, where the governing partial differential equations are transformed into a system of nonlinear ordinary differential equations using appropriate similarity transformations. These resulting equations are then solved numerically using the bvp4c. The study examines the velocity, temperature, and concentration profiles for various governing parameters, including the magnetic parameter, fluid parameter, Prandtl number, Biot number, and Eckert number. The findings reveal that variations in the fluid parameter have a significant impact on velocity, temperature, and concentration distributions.

1.Introduction

Fluids are primarily classified into Newtonian and non-Newtonian categories. Non-Newtonian fluids are commonly encountered in everyday life, with examples including toothpaste, ketchup, honey, mud, blood, paint, and shampoo. Over the past few years, these fluids have garnered significant attention from researchers and scientists due to their extensive applications in various industries, biological sciences, and manufacturing processes. Some notable applications include polymer solutions, nuclear fuel slurries, lubrication with heavy oils and greases, and blood flow.

The study of non-Newtonian fluid dynamics and heat transfer is particularly important in power engineering. These fluids are widely used in polymer solutions, paints, specialized lubricants, certain oils, clay coatings, colloidal suspensions, and cosmetic products. However, no single constitutive equation can comprehensively describe all the characteristics of non-Newtonian fluids. To address this, researchers have developed various mathematical models to study their complex behavior. Among these models, the Powell-Eyring fluid model stands out as a significant non-Newtonian model. First introduced by Powell and Eyring [1] in 1944, this model, although mathematically complex, offers distinct advantages over other fluid models, particularly in characterizing shear-thinning behavior. Additionally, it is derived from the kinetic theory of liquids rather than an empirical approach, making it more fundamentally grounded.

Several researchers have studied different aspects of Powell-Eyring fluid dynamics. Patel and Timol [2] examined its three-dimensional flow past a wedge. Jalil et al. [3] analyzed its heat transfer characteristics over a stretching sheet using Lie group analysis. Javed et al. [4] investigated the boundary layer flow of Powell-Eyring fluid induced by a stretching sheet, while Khader and Megahed [5] explored its unsteady flow and heat transfer with heat generation. Ara et al. [6] studied its boundary layer flow and heat transfer over an exponentially shrinking sheet. Recently, Akbar et al. [7] analyzed the two-dimensional flow of an incompressible Powell-Eyring fluid toward a stretching sheet under the influence of a magnetic field, concluding that increasing the magnetic field strength and Powell-Eyring fluid parameter enhances flow resistance. Malik et al. [8] conducted an analytical investigation into the heat transfer properties of Eyring-Powell fluid.

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The efficiency of a working fluid plays a critical role in various engineering and industrial applications, whether in motion or at rest. Traditionally, common heat transfer fluids such as oil, water, and ethylene glycol have been used. However, their thermal performance often falls short of meeting industrial cooling requirements.

To overcome this limitation, researchers have introduced an innovative approach—suspending tiny solid particles within these base fluids. Since solid materials possess significantly higher thermal conductivity than liquids, the addition of nanoparticles enhances heat transfer efficiency. Conventional heat transfer fluids struggle with low thermal conductivity, which limits their effectiveness. To address this issue, Choi and Eastman [9] pioneered the concept of incorporating solid nanoparticles into base fluids, leading to the development of nanofluids with superior thermal properties.

A nanofluid is a dilute suspension consisting of a base fluid and nanoparticles. In recent years, the significance of Nano fluids has grown considerably due to their wide-ranging industrial applications, including chemical processes, heating and cooling systems, power generation, and more. Following the pioneering work of Choi, Buongiorno [10] introduced a nanofluid model that incorporated the slip mechanism between the base fluid and nanoparticles. His study demonstrated that thermophoresis and Brownian motion have a significant impact on forced convection in nanofluids. The study of nanofluid flow over a stretching surface was initially conducted by Khan and Pop [11], who observed that the heat transfer rate decreases with increasing values of the Brownian motion parameter. Makinde and Aziz [12] extended this research by examining the effect of convective boundary conditions on the steady boundary layer flow of nanofluids. Further, Makinde et al. [13] investigated MHD stagnation point flow of nanofluids past a stretching surface and concluded that surface velocity increases with both the velocity ratio and Richardson number but decreases under the influence of a magnetic field. Wubshet et al. [14] numerically analyzed MHD stagnation point flow and heat transfer in nanofluids past a stretching surface, finding that velocity profiles increase with higher velocity ratio parameters. Mustafa et al. [15] applied the Homotopy Analysis Method to derive analytical solutions for stagnation point flow in nanofluids. Rana and Bhargava [16] used the Finite Element Method to analyze boundary layer flow caused by a nonlinearly stretching surface.

Following these foundational studies, researchers have extensively investigated nanofluid dynamics in various contexts [17–25]. Recent literature highlights the growing importance of nanofluids, with comprehensive reviews available in [26–30]. Prabhakar et al. [31] analyzed the effect of an aligned magnetic field on non-Newtonian nanofluid flow with zero normal nanoparticle flux at the surface. Additionally, Prabhakar et al. [32] explored the influence of nonlinear radiation on MHD flow of Maxwell fluid in the presence of nanoparticles past a stretching sheet.

Most studies in the literature have focused on flow induced by a stretching surface. However, in many practical applications, the stretching surface is not necessarily two-dimensional, as it can be stretched in different ways. In this context, Ariel [33] examined the flow of a second-grade fluid over a radially stretching sheet, obtaining both numerical and analytical solutions for the axisymmetric flow. Later, Ariel [34] extended this work by investigating the axisymmetric slip flow of a fluid past a stretching surface. Sajid et al. [35] derived analytical series solutions for unsteady axisymmetric flow over a non-linearly stretching sheet using the Homotopy Analysis Method. Sahoo [36] studied the effect of partial slip on the axisymmetric flow of an electrically conducting non-Newtonian second-grade liquid over a radially stretching sheet. The findings indicated that as the slip parameter increases, more fluid is allowed to slip past the sheet.

Recent studies [37–39] have explored the flow and heat transfer characteristics of viscous fluids over a radially stretching sheet under various thermo-physical conditions. Khan et al. [40] investigated the MHD axisymmetric flow of a non-Newtonian Sisko liquid over a radially stretching surface, incorporating convective boundary conditions at the wall. Their study provided both numerical and analytical solutions. Additionally, Hayat et al. [41] examined the MHD axisymmetric stagnation point flow of Jeffrey fluid, considering the effects of Joule heating and viscous dissipation.

In the above studies flow and heat transfer over a stretching sheet is confined to viscous fluids. Therefore, the purpose of this present study is to discuss the axisymmetric flow of non-Newtonian Darcy-Forchheimer Eyring-Powell fluid with nanoparticles over a radially stretching surface with the effect of viscous dissipation.

2. Mathematical formulation

Consider a steady two dimensional(r, z) convective boundary layer flow of Darcy-Forchheimer Powell-Eyring nanofluid past a radially stretching sheet placed at $z = 0$. The flow is generated due to radially stretched surface with a velocity $u = u_w = ar$, where a is real number and fluid resides in the region $z \geq 0$. The sheet is kept at constant temperature T_w and T_∞, C_∞ is the ambient temperature and nanoparticle volume fraction respectively with $T_w > T_\infty$. Further considered the different external effects like thermal radiation, porous medium, magnetic field and viscous dissipation, Under the above assumptions the relevant governing equations of flow are as follows

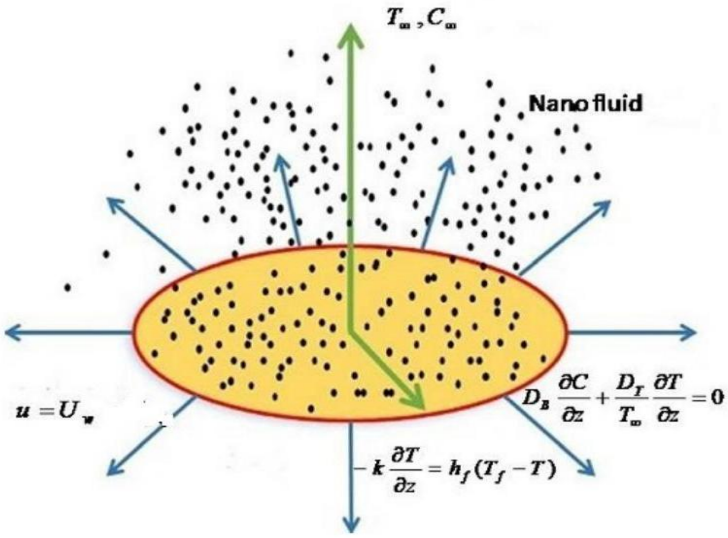

Fig. 1. Flow Configuration.

$$\frac{\partial u}{\partial r}+\frac{u}{r}+\frac{\partial w}{\partial r}=0 \quad (1)$$

$$u\frac{\partial u}{\partial r}+w\frac{\partial u}{\partial z}=\left(\upsilon+\frac{1}{\rho\beta d}\right)\frac{\partial^2 u}{\partial z^2}-\frac{1}{2\rho\beta d^3}\left[\left(\frac{\partial u}{\partial z}\right)^2\frac{\partial^2 u}{\partial z^2}\right]-\frac{\sigma B_0^2 u}{\rho}-\frac{\nu}{K}u-Fu^2 \quad (2)$$

$$u\frac{\partial T}{\partial r}+w\frac{\partial T}{\partial z}=\ \alpha\frac{\partial^2 T}{\partial z^2}+\tau\left[D_B\frac{\partial C}{\partial z}\frac{\partial T}{\partial z}+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial z}\right)^2\right]+\frac{1}{\rho c_p}\left[\left(\nu+\frac{1}{\rho\beta d}\right)\left(\frac{\partial u}{\partial z}\right)^2-\frac{1}{6\rho\beta d^3}\left(\frac{\partial u}{\partial z}\right)^4\right] \quad (3)$$

$$u\frac{\partial C}{\partial r}+v\frac{\partial C}{\partial z}=D_B\frac{\partial^2 C}{\partial z^2}+\frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial z^2} \quad (4)$$

The corresponding boundary conditions are

$$u=U_{\hat{w}}, w=0, -k\frac{\partial T}{\partial r}=h_f\left(T_f-T\right),\ D_B\frac{\partial C}{\partial z}+D_T\frac{\partial T}{\partial z}=0, at\ z=0 \quad (5a)$$

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

Here *u* and *w* are the velocity components along *r*-and *z*-directions respectively, α is thermal diffusivity, σ is electrical conductivity, υ is the kinematic viscosity, ρ is the density of the base fluid, D_B is the Brownian diffusion coefficient and D_T is the thermophoresis diffusion coefficient, $\tau=\frac{(\rho c)_p}{(\rho c)_f}$ is the ratio of nanoparticle heat capacity and the base fluid heat capacity.

We introduce the following similarity transformations

$$\eta=z\sqrt{\frac{a}{\upsilon}}, u=ar^2 f'(\eta),\ w=-2\sqrt{a\upsilon}f(\eta), \theta=\frac{T-T_\infty}{T_w-T_\infty}, \phi=\frac{C-C_\infty}{C_\infty} \quad (6)$$

Using transformations (6), equations (2)-(4) takes the form as:

$$(1+\varepsilon)f'''+2ff''-\delta\varepsilon f''^2 f'''-(1+Fr)f'^2-(M+\lambda)f'=0 \quad (7)$$

$$\theta''+2Prf\theta'+PrNb\theta'\phi'+PrNt\theta^2+PrEc\left((1+\epsilon)f''^2-\frac{\varepsilon\delta}{3}f''^4\right)=0 \quad (8)$$

$$\phi''+Le\ Pr\ f\phi'+\frac{Nt}{Nb}\theta''=0, \quad (9)$$

Subject to the boundary conditions

$$f(0)=0, f'(0)=1, \theta(0)=1, Nb\phi'(0)+Nt\theta'(0)=0\ at\ \eta=0 \quad (10a)$$

$$f'(\infty)=0, \theta(\infty)=0, \phi(\infty)=0. \quad (10b)$$

where $\epsilon=\frac{1}{\rho\beta d}, \delta=\frac{a^3 r^2}{2\nu c^2}$ are fluid parameters, $Fr=\frac{C_b}{\sqrt{K}}$ is inertia Coefficient, $M=\frac{2\sigma B_0^2}{c\rho}$ magnetic parameter, $\Pr=\frac{\nu}{\alpha}$ is Prandtl number, $Nt=\frac{\tau D_T(T_W-T_\infty)}{T_\infty\alpha}$ thermophoresis parameter, $\gamma=\sqrt{\frac{v}{a}}\frac{h_f}{k}$ is the Biot number, $Nb=\frac{\tau D_B C_\infty}{\alpha}$ is the Brownian motion parameter, $\lambda=\frac{\nu}{Ka}$ is local porosity parameter, and $Le=\frac{\alpha}{D_B}$ the Lewis number,

The physical quantities of interest are skin friction coefficient and local Nusselt number which are defined as:

$$Re_r^{-1/2} C_{f_x} = (1+\epsilon) f''(0) - \frac{\delta\epsilon}{3} f''(0)^3 \quad (11)$$

$$(Re_r)^{\frac{-1}{2}} Nu_x = -\theta'(0), \quad (12)$$

3. Results and discussion:

In this portion the impact of various physical parameters like fluid parameters ε and δ, , thermophoresis parameter Nt, Brownian motion parameter Nb, Prandtl number Pr, Lewis number Le and Eckert number Ec on velocity profile $f'(\eta)$, temperature profile $\theta(\eta)$ and concentration profile $\varphi(\eta)$ discussed graphically. Further the results were validated from previous data of Makinde [46]and AS. Butt [45] and which are in excellent agreement.

Fig.2 represents the characteristics of fluid parameter ε on velocity, temperature and concentration profile for various values of ε . It is noticed from the figure that an increase in fluid parameter ε enhances the velocity of fluid. This is happened due to the higher values of fluid parameter ε (ε = $1/\mu\beta c$) viscosity of fluid μ decreases as a result of this fluid velocity increases. It is also observed that boundary layer gets thicker for larger values of ε. The graph also reveals that temperature and thermal boundary layer thickness reduced when the fluid parameter ε enhanced. Physically for large values of fluid parameter ε viscosity of fluid reduced and less heat is generated due to frictional forces. Hence, the temperature profile decreases.

Table-1:Comparison of $f''(0)$ and variations of M, when $\lambda = 0$, $Fr = 0, \delta = 0, \epsilon = 0$

M	Makinde[46]	AS.Butt[45]	Present results
0.0	-1.17372	-1.17372	-1.173720882
0.5	-1.36581	-1.36581	-1.365814496
1.0	-1.53571	-1.53571	-1.535710521
2.0	-1.83049	-1.83049	-1.830489675
3.0	-2.08484	-2.08484	-2.084846568

Fig.3 reflects the influence of fluid parameter δ on velocity profile for larger values of δ. It is evident that from the figure that velocity profile decreases by raising the values of fluid parameter δ. This is happened due to the increment in viscosity of fluid by enhancing the value of δ. Further it is observed that fluid velocity and momentum boundary layer thickness decrease for higher values of δ.

Fig-4 depicts the impact of magnetic parameter M on $f'(\eta)$, $\theta(\eta)$ and $\varphi(\eta)$ profiles. As we increase magnetic parameter M Lorentz force increases. Since it is resistive force to the fluid particles therefore velocity declines but temperature and concentration of fluid raises. Variation of λ on $f'(\eta)$, $\theta(\eta)$ and $\varphi(\eta)$ is exhibited in Fig-5. It is noticed that velocity is decreased with the effect of λ, temperature and concentration of fluid raises. Variation of Fr on $f'(\eta)$, $\theta(\eta)$ and $\varphi(\eta)$ is exhibited in Fig-6. Larger Fr indicates decline in velocity $f'(\eta)$ and escalates in temperature $\theta(\eta)$. Increase in Inertia Co-efficient Fr has resulted in the thermal boundary layer becoming thicker and fluid could not move freely.

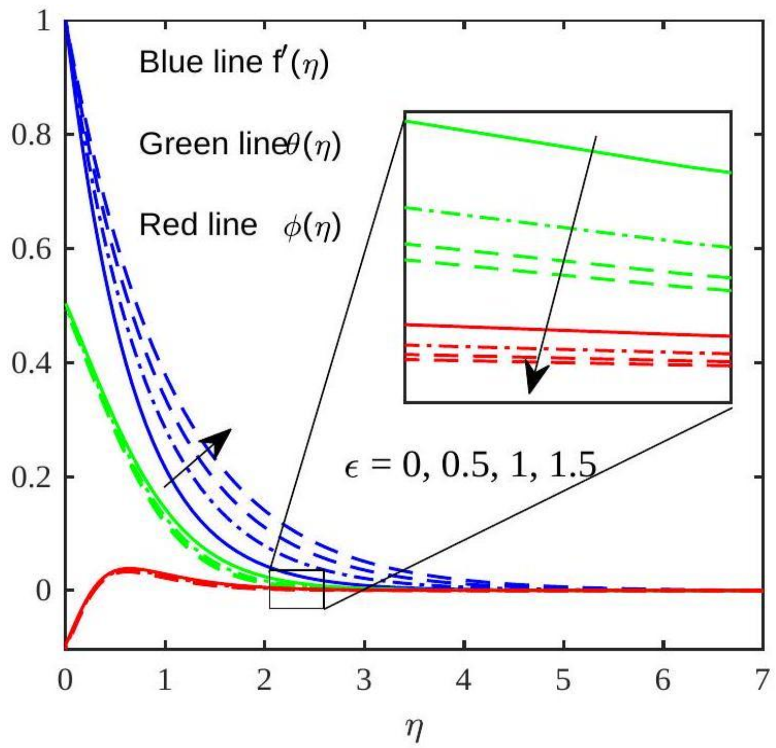

Fig. 2. Variations of ϵ on $f'(\eta), \phi(\eta)$ and $\theta(\eta)$.

Figure.7 is captured to discuss the influence of Biot number γ on temperature and concentration profile. It is perceived that there is an increment in both temperature and concentration profiles with the effect of Biot number γ. From this figure we can observe that enhancement in the Biot number enhances the heat transfer coefficient, which is responsible in increment of temperature profile.

Characteristics of thermophoresis parameter Nt on temperature and concentration profile is depicted in Fig-8. It is noticed that for higher thermophoresis parameter more particles are pulled away from hot surface to cold surface which results in enhancement of temperature and concentration profile for large values of Nt.

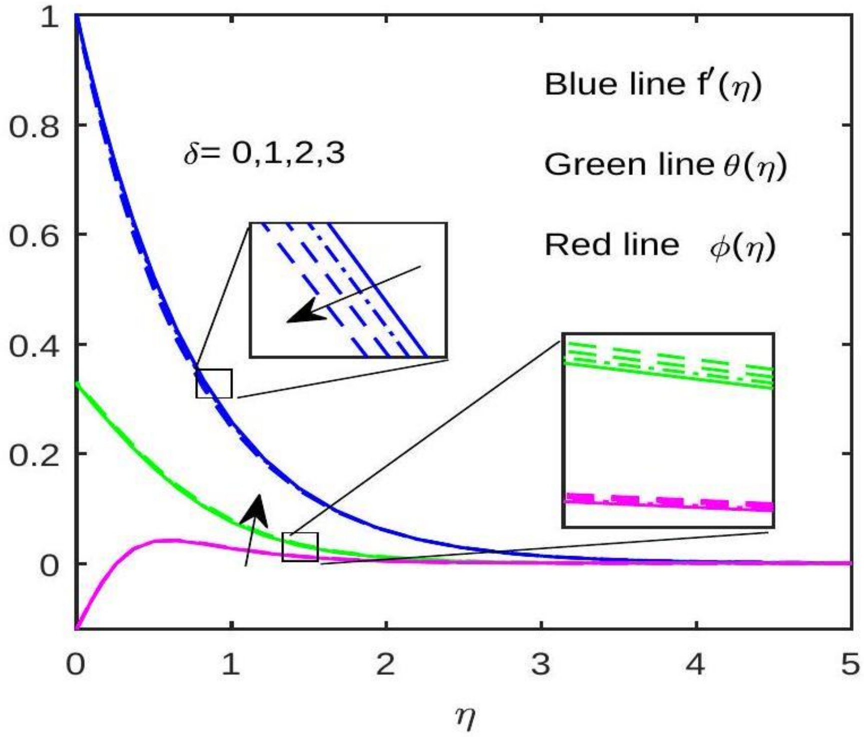

Fig. 3. Variations of δ on f', θ and ϕ.

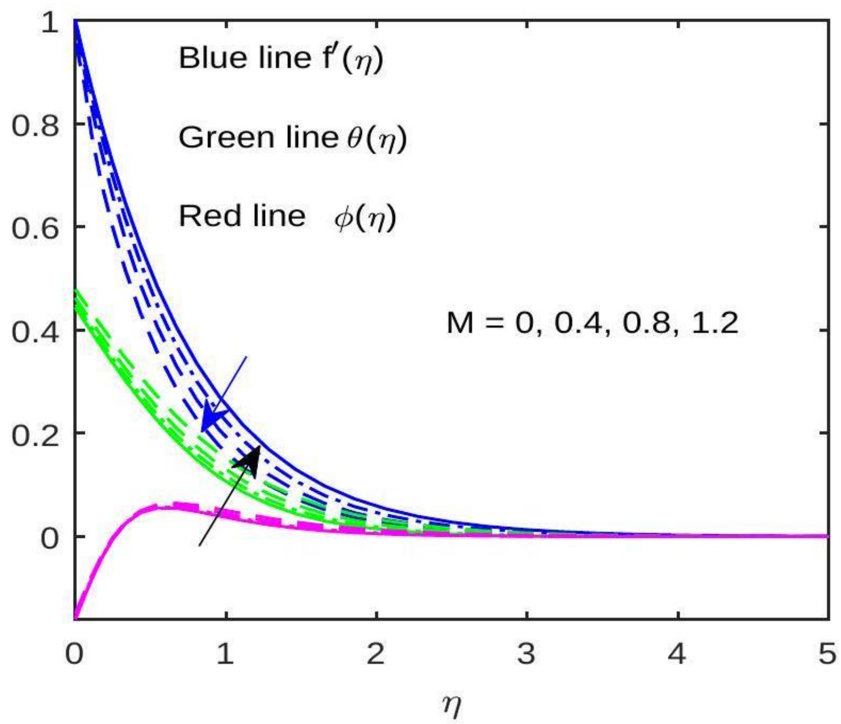

Fig. 4. Variations of M on f', θ and ϕ.

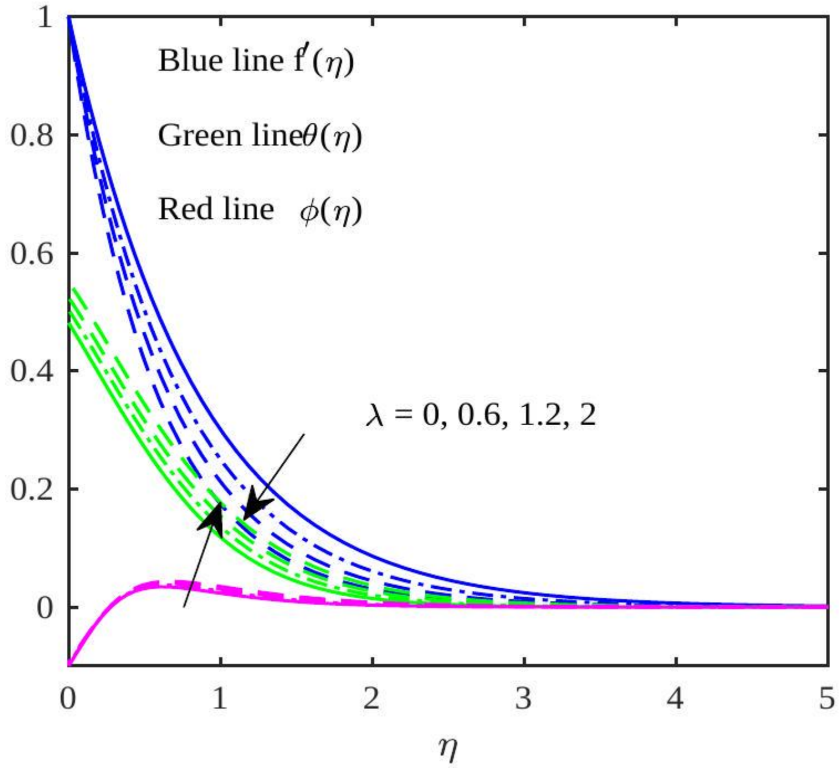

Fig. 5. Variations of λ on f', θ and ϕ.

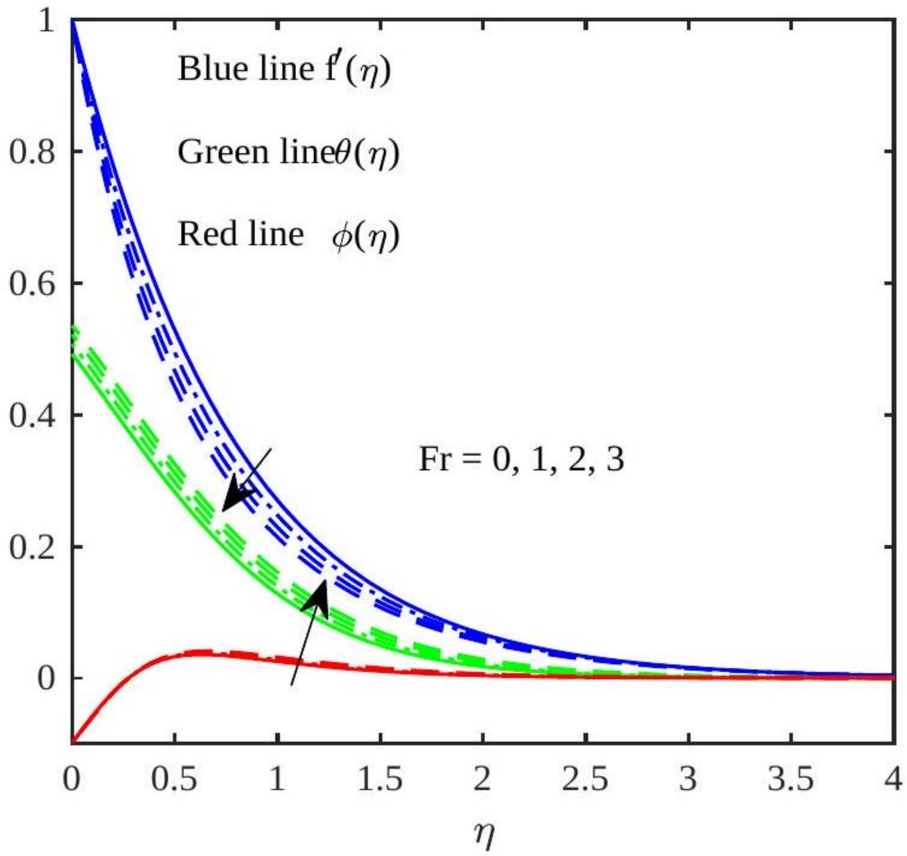

Fig. 6. Variations of Fr on $f'(\eta)$, $\theta(\eta)$ and $\phi(\eta)$.

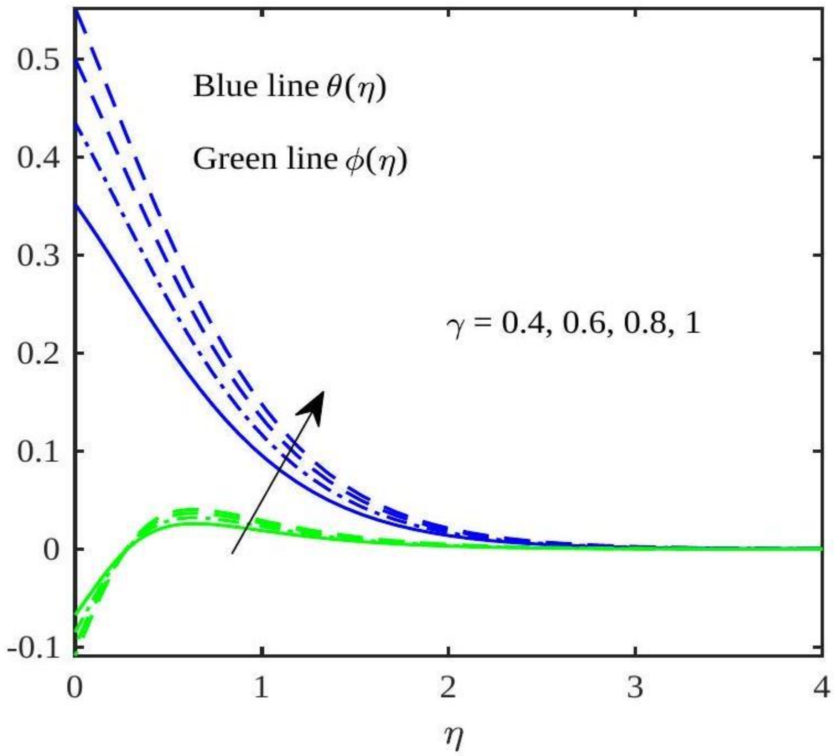

Fig. 7. Variations of γ on $\phi(\eta)$.

Fig-9. is drawn to depict the variation of temperature and concentration profile for distinct values of Brownian motion parameter Nb. As the Brownian motion parameter Nb increases the fluid particles frequently hit with each other which generate more heat so it enhances the temperature but inverse nature is observed in the case of concentration profile. Therefore, for the large values of Nb leads to decrement in concentration profile.

Impact of Prandtl number Pr on temperature profile is explored in Figure-10. As we increase Prandtl number Pr, thermal conductivity of fluid reduced it leads to decreases temperature profile. Hence temperature profile is a decreasing function of Prandtl number Pr.

Fig-11. is plotted to observe the nature of concentration profile with respect to Lewis Number *Le.* From the figure it is clear that concentration profile reduced with uplifting the Lewis number Le. Physically Le is depends on Brownian diffusivity, for large values of Lewis number Le causes weaker Brownian diffusivity. As a consequence of this reduction in concentration profile occurs. Fig-12 represents the variation of skin friction for different values of λ and Fr. It is clear from the figure that skin friction decreases with the values of λ and Fr reverse trend is observe for ϵ. Figures 13-14 shows that Nusselt number is reduced with the effect of λ and Fr but increased with the influence of Ec and γ.

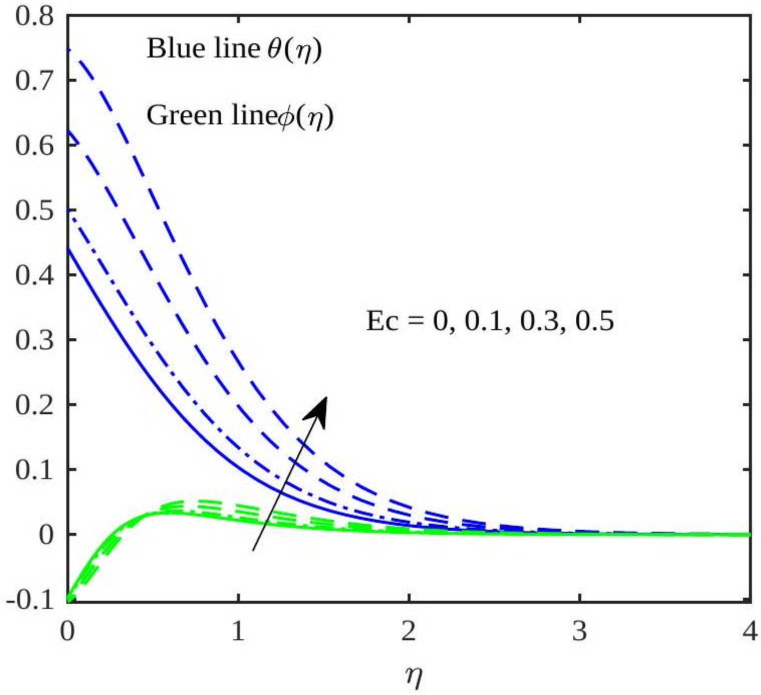

Fig. 8. Variations of Ec on $f'(\eta)$ and $\theta(\eta)$.

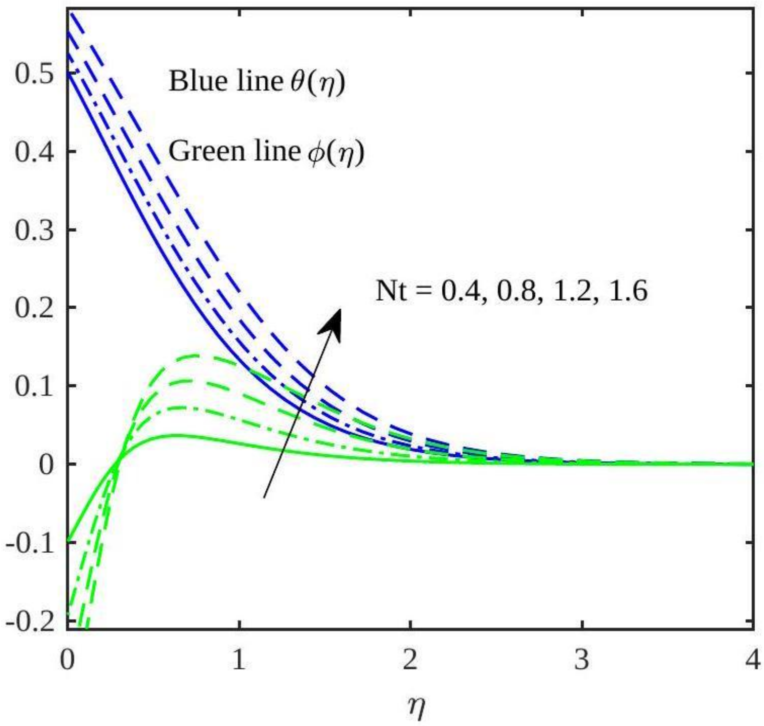

Fig. 9. Variations of Nt on $\phi(\eta)$ and $\theta(\eta)$.

Conclusions

Significant outcomes from this study are as follows.

- Increase in magnetic field M, leads to occurrence of Lorentz force, due to this effect it decelerates the velocity profiles.

- An increment in fluid parameter increases fluid velocity whereas temperature and concentration profile decreases.
- Temperature profile enhanced with an increment in Biot number and Eckert number.
- As the thermophoresis parameter Nt increases both temperature and concentration profile increases.
- Concentration profile reduced with the effect of Lewis number Le.
- Temperature and concentration profiles are enhanced for higher values of λ and Fr.
- Heat transfer rate is enhanced via γ and reverse trend is seen via λ and Fr.

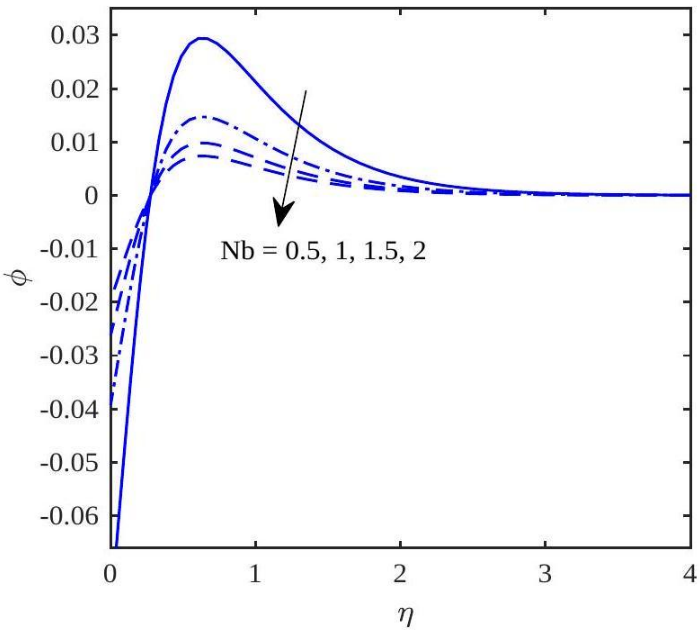

Fig. 10. Variations of Nb on $\phi(\eta)$.

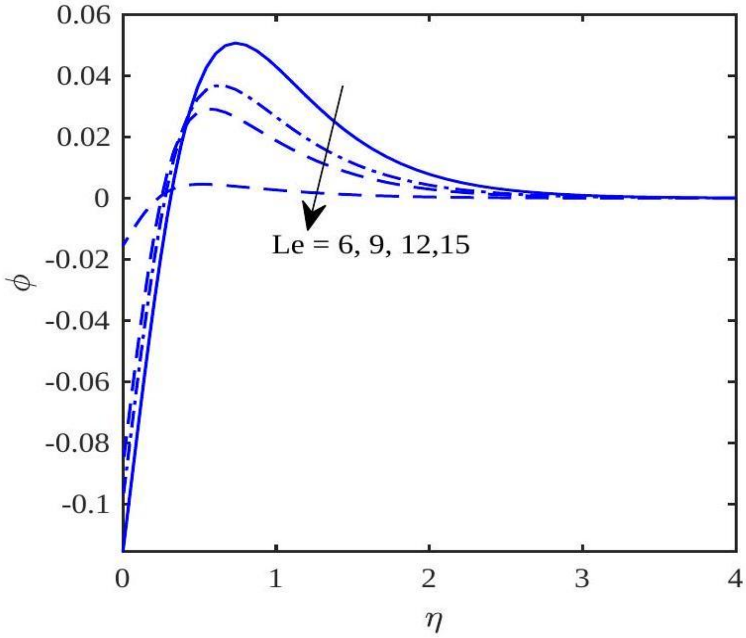

Fig. 11. Variations of Le on $\phi(\eta)$.

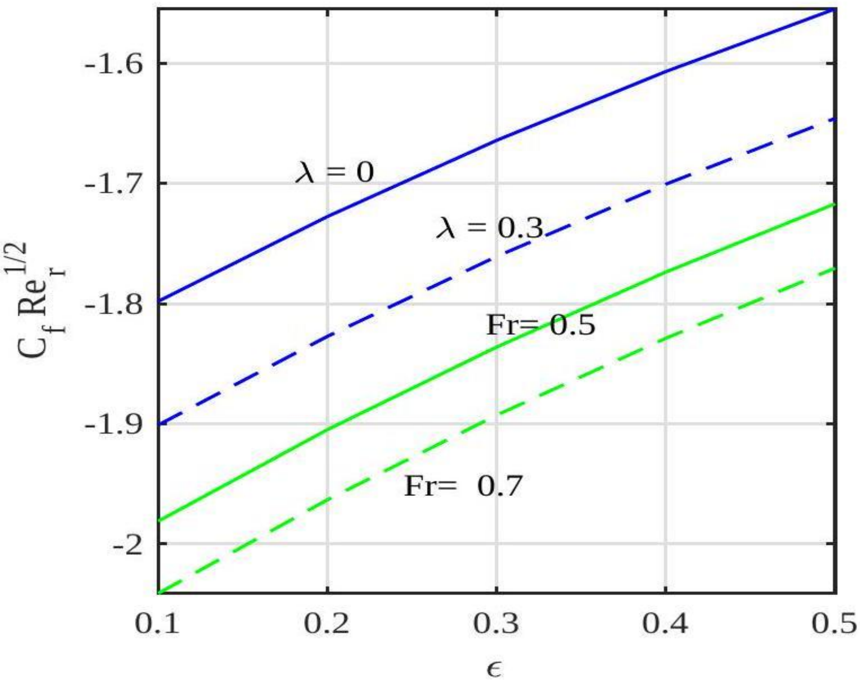

Fig. 12. Variations Skin friction for different values of β and Fr.

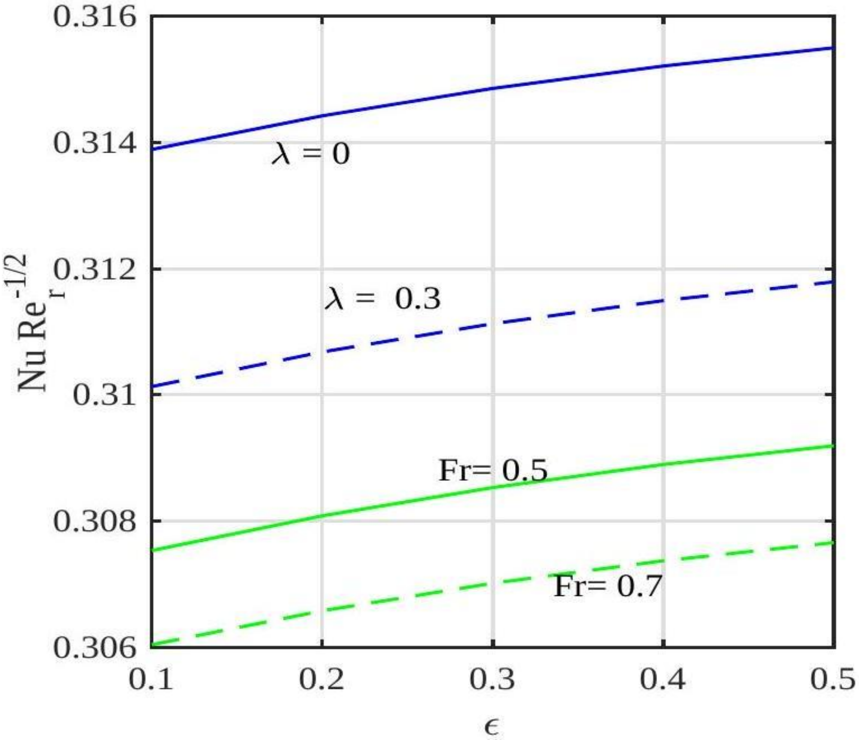

Fig. 13. Variations Nusselt number for different values of ϵ, λ and Fr.

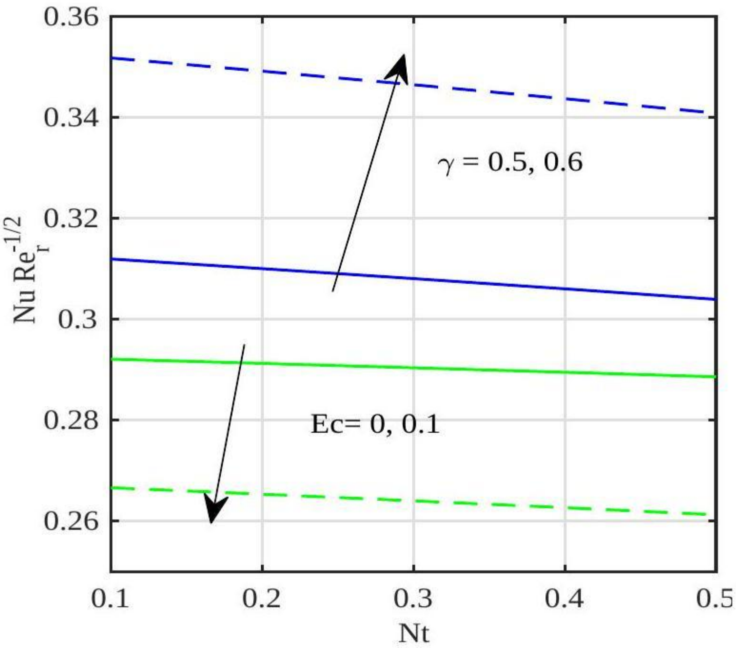

Fig. 14. Variations Nusselt number for different values of Nt, γ and Ec.

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