International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Hydromagnetic Carreau Non-Newtonian Fluid Flow Over A Stretching Sheet with Suction and Blowing Effects

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Abstract
The Carreau fluid is a type of non-Newtonian fluid that exhibits shear-thinning behaviour, meaning its viscosity decreases under increasing shear stress. This property makes it useful in a variety of applications where fluid flow behaviour needs to be precisely controlled. In this article, non-Newtonian fluid flow over an elongating surface with vanishing mass flux boundary condition is discussed. Mathematical model with system of differential equations is solved by shooting method and important physical parameters are computed and analysed heat and mass transfer aspects. Brownian motion and thermophoresis effects are embedded in the governing equations. Comparative analysis of active and passive control of mass flux condition is discussed. It is observed that suction parameter reduces the velocity and temperature profiles.

Keywords: MHD, Carreau Rheological Model, Boundary layer flow, Shooting method.

1. INTRODUCTION.

Boundary layer flow of non-Newtonian fluids is quite different of that Newtonian fluids and due to widespread of applications[1] many researchers focused heat and mass transport of non-Newtonian fluids.Intially Sakiadis discussed viscous flow over three different geometries[2]–[4] Later many researcher considered different non-Newtonian model to explore various aspects of heat and mass properties.Hayat.t et al[5] explained about Soret and Dufour effect with Casson rheological model in stretched sheet flow. An exact solution to Casson non-Newtonian fluid flow over a pervious elongating surface is given Bhattacharya et al [6] .Mukhopadhyay et al [7] reported role of unsteady parameter in Casson non-Newtonian fluid flow over a stretching sheet. Carreau rheological model is one of the important non-Newtonian fluid flow models which is used to study both shear thinning and shear thickening scenarios. Many articles can be seen in literature exploring the features of Carreau rheological model based boundary layer flows over stretching shrinking surfaces under different physical conditions.Akbar.N et al[8] presented dual solutions for Carreau nanofluid stagnation point flow past a stretching sheet.Kodanadapani et al[9] reported emerging application of Carreau nanofluid in cancer treatment by considering peristatic fluid flow in symmetric channel with thermal radiation and magnetic field effects. Sulochana and Samrat [10] discussed radiative stagnation point flow behaviour of Carreau model with suction and injection effects.Hayat.T et al [11] examined the role of thermophoresis and Brownian motion on Carreau nanofluid past a stretched sheet and their results shows that temperature distribution rises with these two important nanofluid properties. Impact of nonlinear thermal radiation and convective boundary condition effects on Carreau model is simulated by Khan Masood et al [12] and their outcomes portrays that local Nusselt number diminishes with nonlinear radiation term. Eid Mohammed et al [13] presented non-Newtonian fluid flow in porous media with Carreau model. Besides these above cited articles on Carreau rheological models some more interesting numerical studies can be found in literature (See [12], [14]–[21]).

Suction-Injection is one of the most efficient technique in boundary layer flows which usually reduces friction losses near the walls in external flows and energy losses in internal flows such as channels and ducts etc.Gupta.P.S and Gupta A.S[22] studied role of suction on stretching sheet fluid flow problem. Later Dutta B.K [23] extended these type of viscous flows over moving surfaces with suction and blowing effects. Over the time many researchers consolidated the impact of suction and injection in laminarising turbulency in boundary layer.Kandaswamy et al[24] provided exact solution for fluid flow over a vertical stretching surface with suction-injection effect using scaling transformation method.Uprerti Himanshu and Pandey.A.K [25]studied viscous dissipative, radiative nanofluid flow with suction and blowing effect. Stagnation point flow embedded in porous medium is studied by Ely Mohammed H et al [26] and their results shows that momentum reduces with suction effect and porous effect. Role of Brownian motion and thermophoresis in flow over a pervious surface is analysed by Upreti et al [27] .Recently Sami Ullah Khan et al [28] presented electromagnetohydrodynamic flow over stretching surface using Carreau rheological model. In another study by Eid Mohammed et al [29] projects the role nano particle shape effect in nanofluid flow under suction and injection effect in boundary layer bio convective flow. Ado-Dahab et al [30] considered Casson rheology model and explained nanofluid flow over a permeable nonlinear elongating sheet under induced magnetic field. Most recently Sulochana and Savita [31] explained suction and injection role in nanofluid flow over stretching surface.

In most of the articles cited above most of the authors considered Casson rheology model and a very few works are noticed with Carneau model. Some of the authors considered constant wall temperature and constant wall concentration boundary conditions while using Buingrno model [32] but no work on Carreau model with vanishing mass flux condition has been reported as per our knowledge .Hence the main aim of this present article is to analyse the Carreau nanofluid flow over stretching surface with suction and blowing effect with zero mass flux condition. Some of the existing studies in literature (See [8], [16], [19], [33]–[35]) are seems to be similar to this work ,but type of boundary conditions are completely different. So in this article we would like extend the work of Waqas .M et al [36] by incorporating suction-Injection effect.

2. Geometry of the fluid flow configuration.

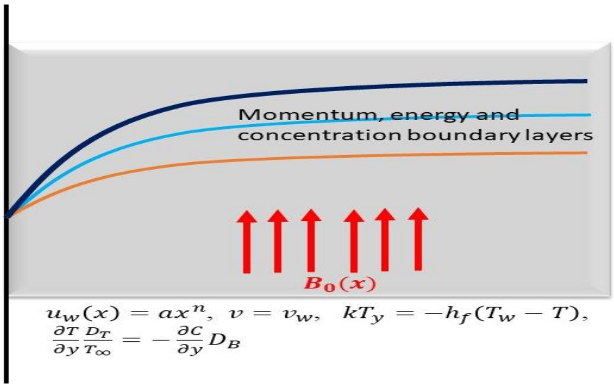

Figure-1: Physical representation of fluid flow .

Let us assume a two-dimensional laminar flow of incompressible electrically conducting shear thickening and shear thinning non-Newtonian fluid past a surface which is moving with nonlinear velocity $u(x) = ax^n$ with n being positive integer and a is stretching parameter. Fluid flows in x axis direction and transverse magnetic field $B_0(x)$ is applied perpendicular to the flow direction. Effect of induced magnetic field is neglected as current configuration is low Reynolds number flow problem. Representative geometric model is shown in Figure 1 and the boundary layer approximation for momentum, energy and concentration equations are:

2.1 Governing partial differential equations.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}= \vartheta\left[\frac{\partial^2 u}{\partial y^2}\right]\left\{\left[1+\Gamma^2\left(\frac{\partial u}{\partial y}\right)^2\right]^{\frac{n-1}{2}}+(n-1)\Gamma^2\left(\frac{\partial u}{\partial y}\right)^2\left[1+\Gamma^2\left(\frac{\partial u}{\partial y}\right)^2\right]^{\frac{n-3}{2}}\right\} - \frac{\sigma {B_0}^2}{\rho}u \qquad (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial y^2}\right)+\frac{(\rho c_p)_p}{(\rho c_p)_f}\left[D_B\left(\frac{\partial T}{\partial y}\frac{\partial C}{\partial y}\right)+\frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right]+\frac{Q_0}{(\rho c_p)_f}(T-T_\infty) \qquad (3)$$

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

and the boundary conditions at the surface and for free stream flow can be framed as:

$$\text{at } y=0: \quad u=u_w(x)=ax^n,\ v=v_w,\ \ T=T_w,\ \frac{\partial T}{\partial y}\frac{D_T}{T_\infty}+\frac{\partial C}{\partial y}D_B=0$$

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

2.2.Similarity variable and non-depersonalisation.

The above governing equations are converted to non-dimensional form adopting the below similarity variables

$$\psi(x,y)=\sqrt{\frac{2\vartheta b}{m+1}}x^{\frac{m+1}{2}}f(\eta),\ \ \eta=y\sqrt{\frac{b(m+1)}{2\vartheta}}x^{\frac{m-1}{2}},\ \ \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty},\ \ \emptyset(\eta)=\frac{C-C_\infty}{C_\infty} \qquad (6)$$

Non-dimensional form of the governing equations (1) to (5) are

$$\left[1+nWe^2{f''}^2\right]\left[1+We^2{f''}^2\right]^{\frac{n-3}{2}}f'''+ff''-\frac{2}{m+1}\left[m{f'}^2+K_1f''\right]-Mf''=0 \qquad (8)$$

$$\frac{\theta''}{Pr}+Nb\theta'\phi'+Nt{\theta'}^2+f\theta'=0 \qquad (9)$$

$$\phi''+LePrf\phi'+\frac{Nt}{Nb}\theta''=0 \qquad (10)$$

The Boundary conditions are

$$f(\eta)=0,\ f'(\eta)=1,\ \theta'(\eta)=1,\ Nb\emptyset'(\eta)+Nt\theta'(\eta)=0,\ \text{at } \eta=0,$$

$$f'(\infty)\to 0,\ \theta(\infty)\to 0,\ \phi(\infty)\to 0 \qquad (11)$$

Here porosity parameter $K_1=\frac{\vartheta}{k(b{u_w}^{m-1})^{\frac{1}{m}}}$, $\lambda=\frac{Q_0}{(\rho c_p)_f(b{u_w}^{m-1})^{\frac{1}{m}}}$, $\lambda>0$ heat source and $\lambda<0$ heat sink parameter, Prandtl number $Pr=\frac{\vartheta}{\alpha}$, , Thermophoresis parameter $Nt=\frac{(\rho c_p)_p D_T(T_w-T_\infty)}{(\rho c_p)_f T_\infty \vartheta_f}$, Weissenberg number ${W_e}^2 = \frac{b^3(m+1)\Gamma^2}{2\vartheta}x^{3m-1}$, Lewis number $Le = \frac{\vartheta}{D_B}$, , Magnetic parameter $M = \frac{2\sigma {B_0}^2}{\rho(m+1)bx^{m-1}}$, Biot number $Bi = \frac{h_f}{x^{\frac{m-1}{2}}K\sqrt{\frac{b(m+1)}{2\vartheta}}}$, Brownian motion parameter $Nb = \frac{(\rho_{Cp})_p D_B(C_w - C_\infty)}{(\rho_{Cp})_f \vartheta_f}$.

3. Results and discussion.

The fluid flow governing equations (8)-(10) are solved in MATLAB software bvp4c which is one of the built in module used to obtain solutions of boundary value problems. The value of boundary layer thickness is fixed such that all boundary conditions are satisfied and with appropriate guessed values for missing boundary conditions solution can be obtained. In boundary layer flows, suction parameter has a significant effect on the velocity and temperature profiles. MATLAB Program code is verified in Table 1 with existing literature and satisfied with results.Figures 2 portrays the influence of boundary layer suction on momentum profile. It is observed that momentum and energy profiles diminish with suction parameter. The main reason for this diminishing nature in both velocity and temperature profiles could be suction removes low-momentum fluid from the boundary layer, reducing its thickness. A thinner boundary layer means the velocity gradient near the wall increases, leading to higher shear stress but lower overall velocity in the boundary. From these figures one can notice that boundary layer thickness declines for higher values of suction parameter (S).

Figure 3 shows the role of suction on energy profile and it is evident from this profile that higher values of suction parameter causing drastic reduction in energy profile. The physics behind this phenomenon can be explained as: A thinner thermal boundary layer means a steeper temperature gradient at the wall. This leads to an increase in the Nusselt number (Nu), which represents the heat transfer rate. More heat is conducted away from the surface due to the enhanced gradient. Effect of suction on concentration profile is shown in Figure 4 which has an increasing nature profile. Usually suction affects the concentration profile by modifying the species transport mechanisms within the boundary layer. While suction generally reduces the thickness of the concentration boundary layer, it can also increase the concentration of a solute at the wall under certain conditions.

Figure 5 shows the influence of magnetic field strength on velocity, accelerating magnetic parameter (M) values diminishes the fluid flow, the main reason for these phenomena is applied transverse magnetic field which originates resistance force known as Lorentz force which has the feature of reducing the fluid flow growth. Figure 6 displays the influence of magnetic field strength on temperature distribution and it is observed that temperature accelerates for higher values of magnetic parameter(M). The main reason for this behaviour can be increment to magnetic parameter (M) increases Lorentz force which results more drag force at the surface.

Brownian motion refers to the random movement of microscopic particles (such as nanoparticles) suspended in a fluid due to collisions with molecules. In boundary layer flows, Brownian motion plays a key role in heat transfer, particularly in nanofluids. Figure 7 and 8 are plotted with respect to Brownian motion parameter (Nb) for exploring temperature and concentration of the liquid and its boundary layer behaviour. From these figures it is clear that concentration profile diminishes whereas an enhanced temperature profile can be seen for Brownian motion parameter (Nb). Thermophoresis is the migration of particles in a fluid due to a temperature gradient. In boundary layer flows, small particles (such as nanoparticles, dust, or aerosols) move from hotter to colder regions due to temperature differences. Thermophoresis parameter (Nt) impact on concentration profile and temperature profile can be observed in Figure 9 and Figure-10. It is noticed that concentration and temperature boundary layer thickness increase with respect to Thermophoresis parameter (Nt).

Table-1: Comparison of Nusselt number, Skin friction coefficient when Pr=6.2, M=0=E, Nb=0.1=Nt for regular fluid without nano particles.

M	Ec	Skin friction coefficient		Nusselt number	
		Present results	Mabood et al[37]	Present results	Mabood et al[37]
	0.1	1.101066	1.10102	0.881962	0.88199
0	0.3	1.101066	1.10102	0.529432	0.52953
	0.1	1.309890	1.30989	0.810853	0.81055
0.5	0.3	1.309890	1.30989	0.338896	0.57564
	0.1	1.48912	1.48912	0.740577	0.74058
1	0.3	1.48912	1.48912	0.167893	0.16789

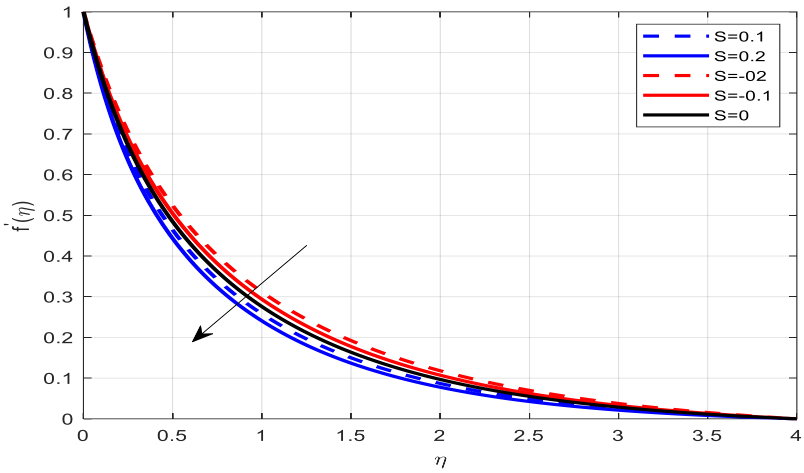

Figure-2: Impact of suction parameter on velocity.

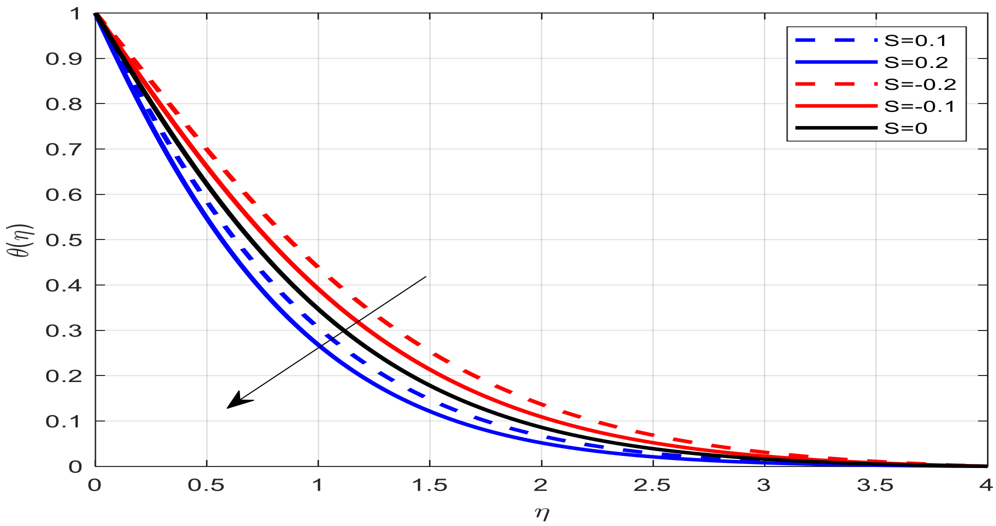

Figure-3: Impact of suction on energy profile.

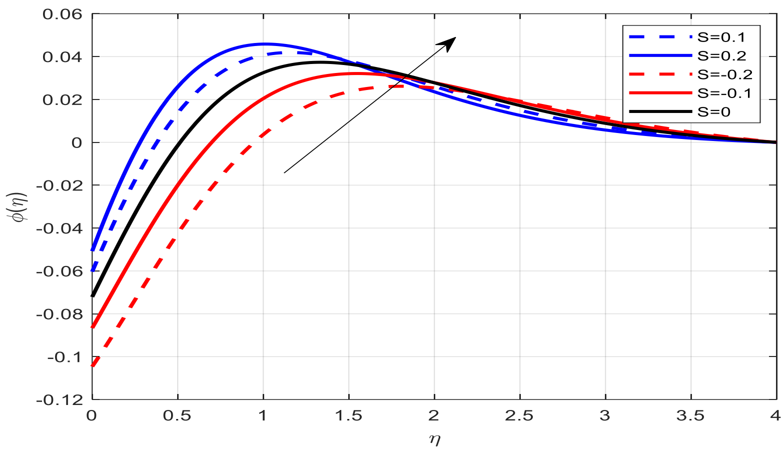

Figure-4: Impact of suction on concentration profile.

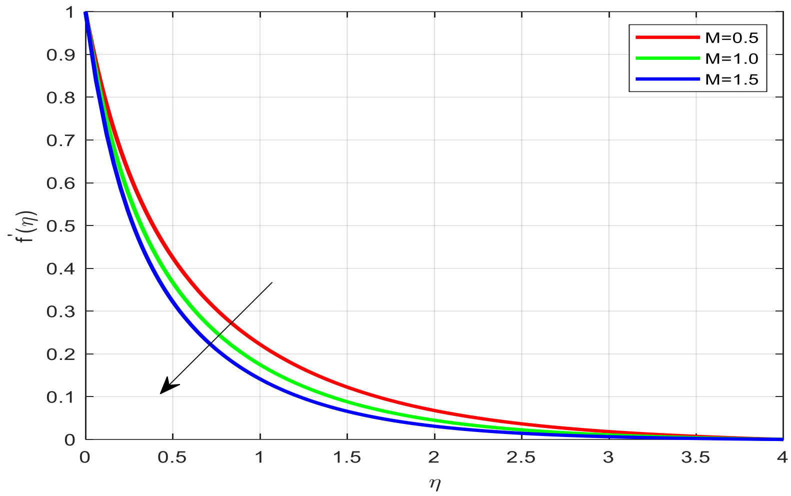

Figure-5: Impact of magnetic field on velocity.

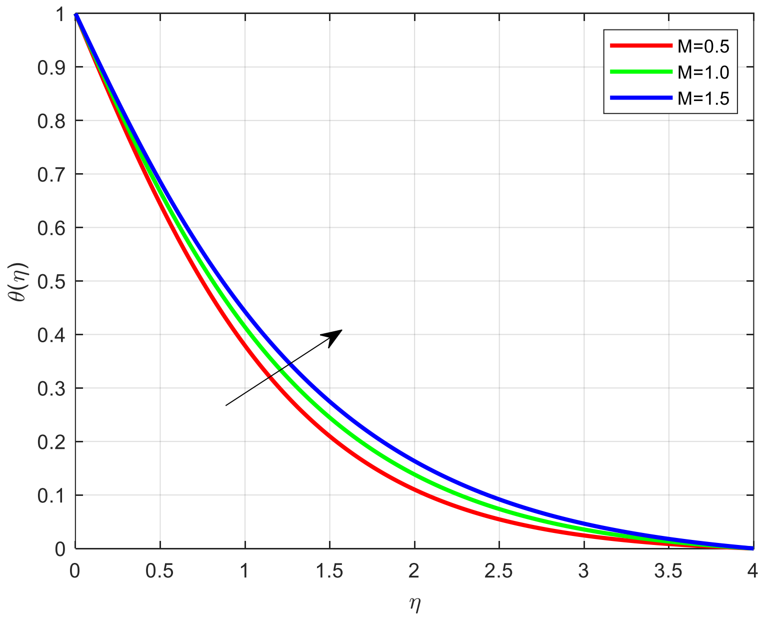

Figure-6: Impact of magnetic field on temperature.

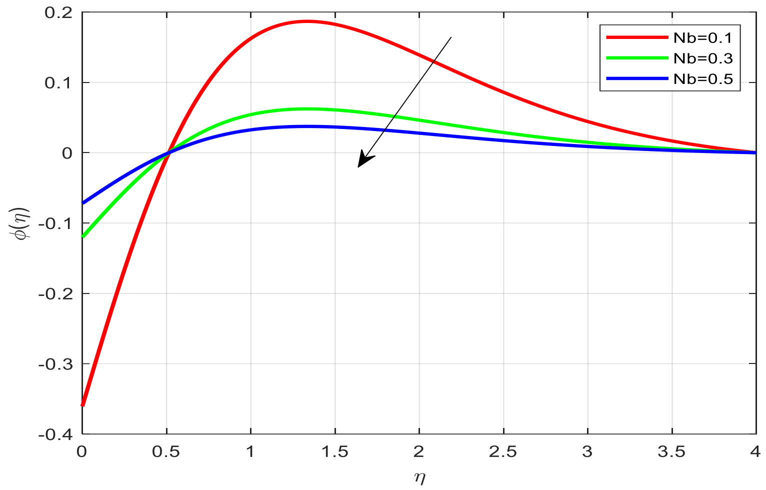

Figure-7: Impact of Brownian motion on concentration profile.

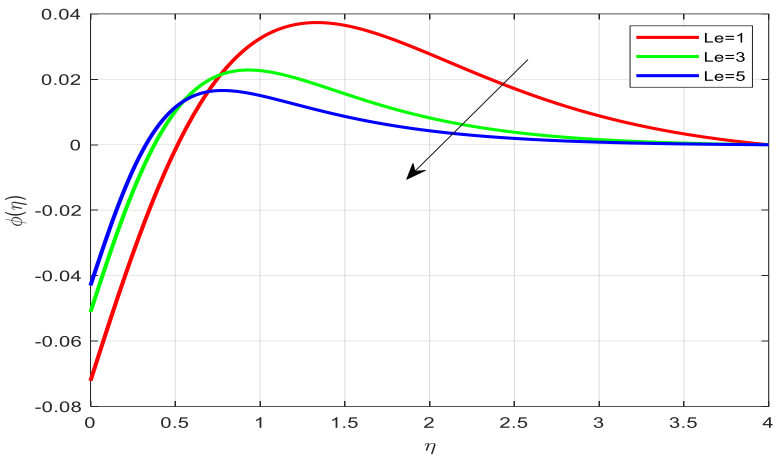

Figure-8 : Impact of Lewis number on concentration profile.

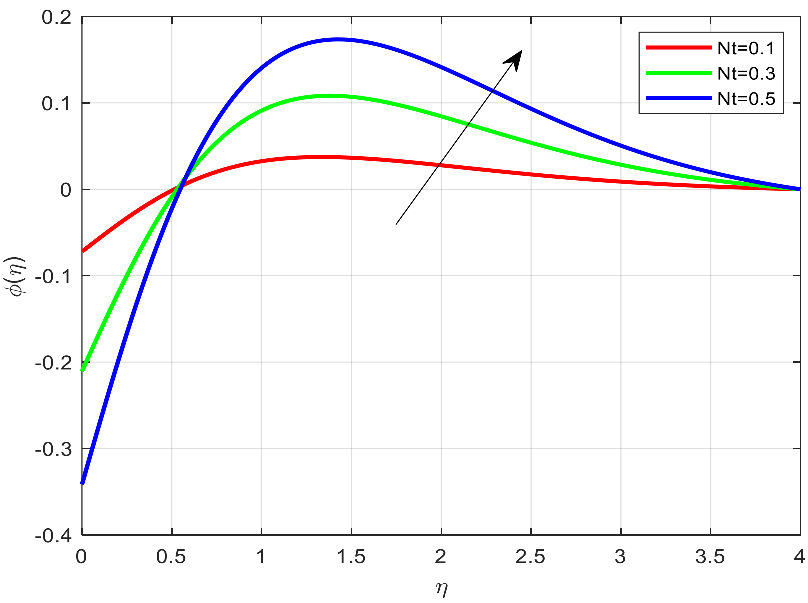

Figure-9:Impact of thermophoresis on concentration profile.

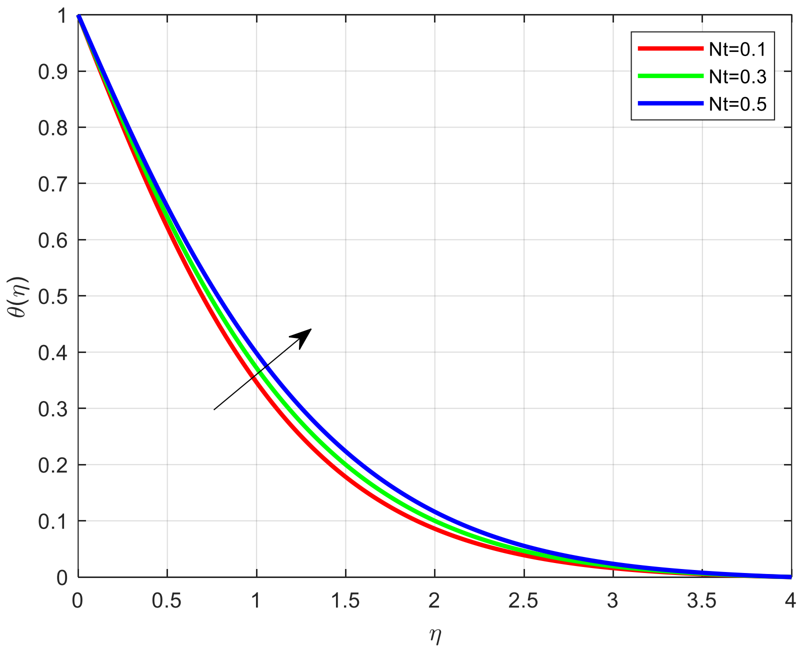

Figure-10: Impact of thermophoresis on energy profile.

4. Conclusions.

This current research explores magnetohydrodynamics Carreau non-Newtonian fluid flow past a moving surface is investigated numerically with suction and blowing effects. Some of the important observation made from this present study are as follows:

- Momentum profile diminishes for higher magnetic field strength whereas an enhanced temperature distribution is noticed for magnetic parameter.
- Suction parameter results in decreased velocity and temperature profiles.
- Concentration of nanofluid is diminished for Lewis number and Brownian motion.
- Thermophoresis results in increased energy and concentration distribution and boundary layer thickness.

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