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Magnetohydrodynamics flow over a power law stretching sheet with viscous dissipation and chemical reaction effects

Gousia Begum
Department of mathematics, Department of UG and PG Studies in Mathematics
Government Degree (Autonomous) College, Kalaburagi, Karnataka, INDIA

Abstract

This study numerically examines the flow of a Casson nanofluid over a stretching sheet in the presence of a chemical reaction influenced by activation energy. The fluid motion is modelled using the governing boundary layer equations for momentum, energy, and concentration. These equations are transformed into a set of ordinary differential equations through similarity transformations and solved using MATLAB's built-in solver bvp4c. The effects of various flow parameters on velocity, temperature, and concentration profiles are analysed. Key physical quantities, including the Nusselt number and skin friction coefficient, are evaluated to assess the heat transfer rate and the frictional behaviour at the fluid–solid interface. The results reveal that increasing the activation energy parameter reduces the heat transfer rate, while the presence of a binary chemical reaction enhances the mass transfer rate.

Key words: MHD, Non-Newtonian fluid, non-linear stretching sheet, Activation energy.

1. Introduction

Non-Newtonian fluids are fluids whose flow behaviour does not follow Newton's law of viscosity, meaning their viscosity is not constant and can vary with shear rate, time, or applied stress. Unlike Newtonian fluids such as water and air, non-Newtonian fluids exhibit complex rheological characteristics, including shear-thinning, shear-thickening, viscoelasticity, and yield stress behaviour. Common examples include polymer solutions, suspensions, emulsions, blood, paints, and industrial slurries. Because of their widespread applications in engineering, biomedical, chemical, and food-processing industries, understanding the flow characteristics of non-Newtonian fluids is essential for accurately modelling and optimizing many practical processes. Among these Casson model is the most significant due to shear thinning feature. Blood, Ketchup, toothpaste, oils, greases, cosmetic fluids, slurries, polymeric fluids, paints are some non-Newtonian fluid examples. Amongst these models Casson fluid is the most significant one. Similarity Solutions for non-Newtonian fluids was proposed by [1] S.Y.LEE and W.F. AMES in the year 1966. Pearson et al. [2] studied different flow models for complex and non-Newtonian fluids past porous medium. Abel et al. [3] scrutinised magnetohydrodynamic heat transfer effect of viscoelastic fluid past a stretching sheet considering nonuniform thermal conductivity. Ellahi. R. [4] proposed an analytical solution of non-Newtonian fluid through a pipe with MHD effect and temperature dependent viscosity. Megahed and Ahmed M [5] together presented their study on heat transfer through vertical non-linear stretching surface considering thermal radiation and heat flux effect over non-Newtonian power-law fluid. Khalidas Das et al. [6] examined that radiative MHD melting heat transfer of Jeffrey nanofluid across stretching sheet by considering surface slip effect. Farooqa et al. [7] presented their study on MHD unsteady radiation effect on stagnation point flow past viscoelastic nanofluid. Kumar et al. [8] introduced the viscous dissipation and joule heating characteristics over Oldroyd B non-Newtonian fluid considering thermal radiation. Convective heat transfer over non-Newtonian fluid with different effects were proposed by [9]–[13]. Khan et al. [14] evaluated chemical reaction and radiation effects on non-Newtonian fluid considering suction effect on vertical stretching surface. Kumar et al. [15] numerically studied unsteady radiative slip effect over a non-Newtonian fluid across porous stretching sheet.

In nanofluids heat transfer through a stretching surface with MHD boundary layer flow has diverse applications in technological industrial processes such as glass fibres, geothermal extractions, paper production, extrusion of polymer sheets, hot rolling, glass fibre, extrusion of plastic sheets, cooling nuclear reactors, drawing of plastic films etc. The rate of heat transfer at the stretching surface strongly affects the mechanical properties of the final product. A 2D stretching surface in a quiescent fluid was first studied by Crane [16]. After this pioneering work, a flexible material Polyester can tolerate stretching of the filament surface during ejection. It is observed that during this process of ejection, surface velocity deviates from the state of uniform. This process of change in stretching rate is generally nonlinear. Such extensional polymeric flows behaviour grabbed the attention of researchers in mathematical and experimental rheology since the 1960s. K. Vajravelu and J.R. Cannon [17] **e**xtended their study on fluid flow across unsteady stretching sheet and obtained the results as interesting flow characteristics. Bhargava et al. [18] numerically investigated micropolar flow through nonlinear stretching surface. Cortell and Rafael [19] jointly investigated thermal radiation and viscous dissipation effects over nonlinear stretching sheet. Makinde and Aziz [20] together explored their study on conditions of convective boundary layer when a nanofluid past through a stretching sheet. The study of heat transfer over a steady non-linearly flat stretching sheet with laminar boundary conditions were proposed by Rana et al. [21]. Qayyum et al. [22] considered MHD third grade convective nonlinear nanofluid flow through variable thickness stretching sheet with aspects heat generation/absorption and chemical reaction. A similar study on Powell-Eyring nanofluid flow explored by Hayat et al. [23]**.** Prasannakumara et al. [24] carried out their investigation to find out effects of MHD radiative heat and mass transfer of Sisko nanofluid past nonlinear stretching surface with the influence of thermal radiation and chemical reaction. Magnetohydrodynamic heat transfer with variable effects over nonlinear stretching sheet were investigated by [25]-[26]**.**

The minimum amount of extra energy supplied to reactants to transform them into products under various chemical reactions is activation energy. The potential and kinetic energy existing in the molecules are of deemed importance to stretch, twist or break the bonds. Observation declares that activation energy is must for reactants to produce products. Once the reaction starts the activation energy becomes zero. The notation for activation energy is E_α and is denoted as Kcal/mol or K_j/mol. In the year 1889 Svanthe Arrhenius proposed activation energy. Applications of activation energy are more significant in hydrodynamics, oil emulsion, food processing, geothermal and chemical engineering. Considering the above interesting applications many investigators attracted towards activation energy. Anuradha and Yegammai [27] jointly worked on magnetohydrodynamic electrically conducting nanofluid past a steady 2D vertical plate with the aspects activation energy and binary chemical reaction. Kiran et al.

[28] analyzed stagnation-point Carreau fluid flow past a stretching surface considering effects of heat diffusion, chemical reaction and activation energy. Khan et al. [29] studied incompressible Carreau-Yasuda fluid flow over a stretchable sheet with porous medium. Chemical reaction and activation energy are accounted at the surface of sheet. A similar study of mixed convective radiative flow of Casson nanofluid through a stretching surface is accounted by khan et al. [30]. Stefan blowing effect proposed by Abdelmalek et al. [31]. Hayat et al. [32] scrutinized their work on magnetohydrodynamic flow of convective heat transfer over third grade nanofluid under the influence of activation energy, chemical reaction at the stretching surface. Impact of non-linear thermal radiation and activation energy over axisymmetric flow of Oldroyd-B fluid presented by Khan et al. [33]. Farhan et al. [34] inspected bioconvection effect over MHD Oldroyd-B fluid flow over thin film and Umair Khan et al. [35] inspected Dual solutions to obtain chemical reaction with an activation energy impact on comprising cross liquid flow over a moving edge. Shah et al[36]. numerically analysed the radiative magnetohydrodynamic flow of Casson nanofluid with entropy generation and activation energy aspects over an unsteady stretching surface with chemical mechanism. Dhlamini et a. l[37] investigated activation energy and higher chemical aspects on viscoelastic nanofluid. Dawar et al. [38] explored a model for Williamson nanofluid with activation energy. Kalaivanan et al. [39] analysed the active and passive control over second grade nanofluid in presence of activation energy. Jayadevamurthy et al. [40]. Impact of Marangoni Driven Boundary Layer Non-Newtonian fluid Flow of heat transfer and activation energy. Reddy et al. [41] studied the impact of Darcy-Forchheimer flow with Joule heating, Viscous dissipation and activation energy over a radially stretched sheet. Hayat et al. evaluated the rotationary hydromagnetic flow of nano liquid considering entropy and activation energy aspects along with convective flow and velocity slip conditions. Ullah et al. [42] investigated the effects of MHD mixed convective melting point flow of non-Newtonian fluid Prandtl–Eyring. Motivated by the above studies, the present research aims to analyse the electrically conducting magnetohydrodynamic Casson nanofluid flow over a nonlinear stretching sheet in the presence of activation energy and a chemical reaction using a statistical approach. The governing equations are initially formulated as a set of nonlinear partial differential equations. By applying suitable similarity transformations, these equations are reduced to nonlinear ordinary differential equations, which are then solved numerically using the **bvp4c** shooting technique.

2. Mathematical model

Consider a steady two dimensional thermally radiative MHD flow of non-Newtonian Casson nanofluid across nonlinear stretching sheet. The sheet is overextended with the exponential velocity as $u_w(x)$=ax^n with origin fixed, where n is a nonlinear stretching parameter and a is a constant. The wall temperature $T = T_w(x) = T_\infty + Ax^n$, where A>0. where T_∞ ambient temperature and C_∞ ambient concentration respectively. The flow is along x-axis $(y > 0)$ and y is normal to it as shown in figure1. $B_0(x)$ is magnetic field applied normal to the stretching sheet whereas electric field is not considered for low magnetic Reynolds number.

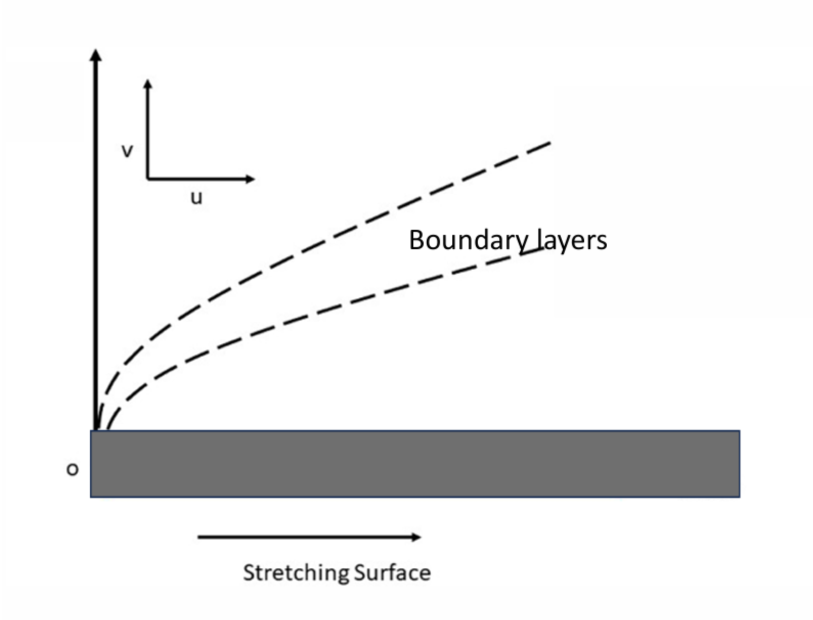

Figure 1. Physical model of the problem

The rheological equation for the Casson fluid model is [43],[44], [45]

$$\tau_{ij} = \begin{cases} 2\left(\mu_B + \frac{P_i}{\sqrt{2\pi}}\right) e_{ij,} & \pi > \pi_c \\ 2\left(\mu_B + \frac{P_i}{\sqrt{2\pi}}\right) e_{ij,} & \pi < \pi_c \,, \end{cases}$$

Where $\pi = e_{ij}\ e_{ij.}$

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{\mu_f}{\rho_f}\left[1 + \frac{1}{\beta}\right]\left[\frac{\partial^2 u}{\partial y^2}\right] - \frac{\sigma_f {B_0}^2(x)}{\rho_f} u \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\left(\frac{\partial^2 T}{\partial y^2}\right) + \frac{1}{(\rho c p)_f}\frac{\partial q_r}{\partial y} + \frac{(\rho c p)_p}{(\rho c p)_f}\left[D_B\left(\frac{\partial T}{\partial y}\frac{\partial C}{\partial y}\right) + \frac{D_T}{T_\infty}\left(\frac{\partial T}{\partial y}\right)^2\right] + \frac{v}{Cp}\left[1 + \frac{1}{\beta}\right]\left(\frac{\partial u}{\partial y}\right)^2 \tag{3}$$

$$\left[T^4 \cong 4T^3T - 3T^4, q_r = -\frac{4\sigma_e}{3K_R}\frac{\partial {T_\infty}^4}{\partial y}\right]$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_B\left(\frac{\partial^2 C}{\partial y^2}\right) + \frac{D_T}{T_\infty}\left(\frac{\partial^2 T}{\partial y^2}\right) + {k_r}^2(C - C_\infty)\left(\frac{T}{T_\infty}\right)^{n_0} e^{\left[\frac{-E_a}{K_0 T}\right]} \tag{4}$$

Boundary conditions are

$$u = ax^n,\ v = v_w \quad T = T_w(x) = T_\infty + Ax^n$$

$$\frac{\partial T}{\partial y}\frac{D_T}{T_\infty} + \frac{\partial C}{\partial y}D_B = 0\ at\ y = 0,$$

$$u \to 0, C \to C_\infty,\ T \to T_\infty \text{ as } y \to \infty \tag{5}$$

where u, v are velocity components in x, y directions respectively. $\mu = \rho_{nf}$ kinematic viscosity, ρ_f nanofluid density, σ_{nf} electric conductivity of nanofluid, B_0 magnetic force. T fluid temperature.

In $\alpha(\rho c)_f = K$ where $\alpha -$ Thermal diffusivity, K−thermal conductivity, c−heat capacity.

In $q_r = -\frac{4\sigma_e}{3K_R}\frac{\partial T^4}{\partial y}$, q_r −radiative heat flux, K_R −mean absorption coefficient, σ_e−Stefan Boltzman constant.

$D_B -$ Brownian motion, D_T −Thermophoresis, K_r −rate of chemical reaction, $E_\alpha -$ activation energy, $n_0 -$ fitted rate constant,

In order to transform the above governing equations to non-dimensional form, considering the below similarity variables,

$$u = ax^n f'(\eta),\ v = -ax^{\frac{n-1}{2}}\sqrt{\frac{\vartheta}{a}}\left(\frac{n+1}{2}f(\eta) + \frac{n-1}{2}\eta f'(\eta)\right)$$

$$\eta = \sqrt{\frac{a}{\vartheta}}x^{\frac{n-1}{2}}y,\ \theta(\eta) = \frac{T-T_\infty}{T_w-T_\infty},\ \emptyset(\eta) = \frac{C-C_\infty}{C_w-C_\infty}$$
(6)

By using above non dimensional transformation (6) equations (1) to (5) can be obtained as

$$\left(1+\frac{1}{\beta}\right)f''' - nf'^2 + \frac{n+1}{2}ff'' - Mf' = 0$$
(7)

$$\left(1+\frac{4}{3}N_r\right)\frac{1}{\Pr}\theta'' + \frac{n+1}{2}f\theta' - nf'\theta + Nb\theta'\phi' + Nt\theta'^2 + \left(1+\frac{1}{\beta}\right)Ecf''^2 = 0$$
(8)

$$\phi'' + \frac{n+1}{2}Scf\phi' + \frac{Nb}{Nt}\theta'' - \sigma_1 Sc\emptyset(1+\delta\theta)^{n_0}e^{\left(\frac{-E}{(1+\delta\theta)}\right)} = 0$$
(9)

The Boundary conditions are

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

$$f'(\infty) \to 0, \theta(\infty) \to 0, \emptyset(\infty) \to 0 \ \text{ as } \eta \to \infty$$
(10)

$p_r = \frac{\vartheta}{\alpha}$ is the Prandtl Number, $Sc = \frac{\vartheta}{D_B}$ is the Schmidt number, $Nb = \frac{(\rho_C)_p D_B(C_w-C_\infty)}{(\rho_C)_f\vartheta}$ is the Brownian motion parameter, $Nt = \frac{(\rho_C)_p D_T(T_w-T_\infty)}{(\rho_C)_f T_\infty\vartheta}$ is the Thermophoresis parameter,

$Ec = \frac{{u_w}^2}{(T_w-T_\infty)Cp}$ is the Eckert number, $\sigma_1 = \frac{{k_r}^2}{ax^{n-1}}$ reaction rate constant, $E = \frac{E_a}{k_0 T}$ non-dimensional activation energy, $N_r = \frac{16\sigma_e {T_\infty}^3}{3K_R K}$ Thermal radiation parameter, $M = \frac{\sigma_f {B_0}^2(x)}{a\rho_f}$ Magnetic field parameter, $\delta = \frac{T_w-T_\infty}{T_\infty}$ is the relative temperature variable.

3. Results and Discussion

This section deals with the results presented by considering the impact of various parameters on momentum, temperature and concentration profiles during Casson nanofluid past a nonlinear stretching sheet with magnetic field. The dimensionless governing equations (7) - (9) are solved using shooting technique. To determine the values of dimensionless parameters we have considered the following ranges of physical parameters. $0 \leq M \leq 3$, $1 \leq \beta \leq 5$, . $0 \leq K \leq 3$, $2 \leq n \leq 4$, $0 \leq E \leq 4$, $0 \leq \sigma_1 \leq 2$, $-0.1 \leq F_w \leq 0.2$. Figure 1 describes the physical model of the nanofluid flow. Figure 2 displays Variation of temperature θ concerns η with numerous values of β. It is observed that there is a decrease in temperature as casson parameter increases and $\eta \to \infty$. Variation of velocity f' concerning η with numerous values of β is as shown in figure 3 and it is clear that reduction in velocity profile takes place for higher values of β. Figure 4 represents the influence of velocity f' concerning η with numerous values of n and we noticed that with increase in n and η velocity decreases. Figure 5 shows the Magnetic field effect (M) on velocity profile. For increasing magnetic parameter M, velocity decreases. Figure 6 shows the distribution of velocity profile f' concerning η with numerous values of chemical reaction K. It is observed that decrease in velocity for increase in small values of K. Variation in velocity profile f' concerning η with numerous values of $\mathrm{F_w}$ is observed in figure 7 and noticed that velocity decreases with rising of $\mathrm{F_w}$. Figure 8 portrays temperature variation θ concerning η for different n values and we have observed that increase in viscosity parameter n results in increase in temperature. Figure 9 shows influence of temperature θ with variable values of M concerning η and noticed that temperature increases with rise in magnetic parameter M. Figure 10 depicts the variation of temperature θ concerning η with numerous values of $\mathrm{F_w}$. We noticed that declination in temperature is seen for smaller rise in $\mathrm{F_w}$. Temperature variation for different values of E concerning η is observed in figure 11 and results declared that for decrease in parameter E, temperature profile also decreases. The effect of viscosity parameter n on concentration profile is studied in figure12 and noticed that concentration profile decreases for arising values of σ_1 and smaller increase in η. In figure 13 concentration profile increases for rising values of n. Figure14 shows distribution of concentration ϕ against η with numerous values of $\mathrm{F_w}$. we can see that for smaller increase in $\mathrm{F_w}$ values result in increase in chemical reaction. Variation in concentration profile for increasing values of E is observed in figure 15. We noticed that for higher values of E, concentration increases.

5. Conclusion

In this numerical investigation, the flow behaviour of a Casson nanofluid over a stretching surface in the presence of a chemical reaction influenced by activation energy is analysed. The study focuses on examining how various physical and flow parameters affect the velocity, temperature, and concentration distributions within the boundary layer. The numerical results reveal several important observations. It is found that an increase in the activation energy parameter leads to a reduction in the heat transfer rate, indicating a suppressing effect on thermal transport. The Casson parameter significantly decreases the fluid velocity, reflecting the enhanced resistance to flow due to non-Newtonian effects. An increase in the Eckert number results in a rise in fluid temperature, highlighting the role of viscous dissipation in the thermal behaviour of the system. Furthermore, the presence of a binary chemical reaction enhances the mass transfer rate, while an increase in the Schmidt number causes a reduction in mass transfer due to lower molecular diffusivity.

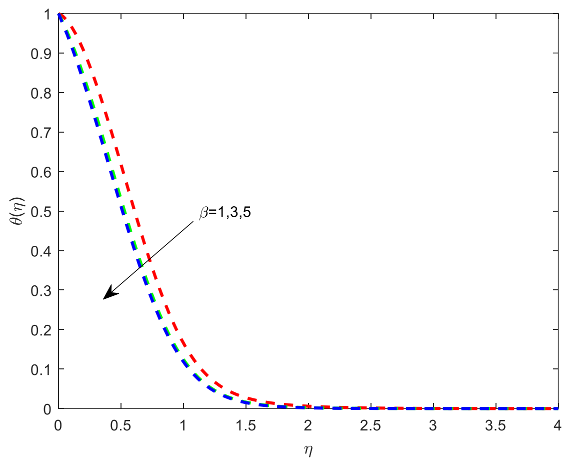

Figure2. Distribution of temperature θ concerns η for numerous values of β

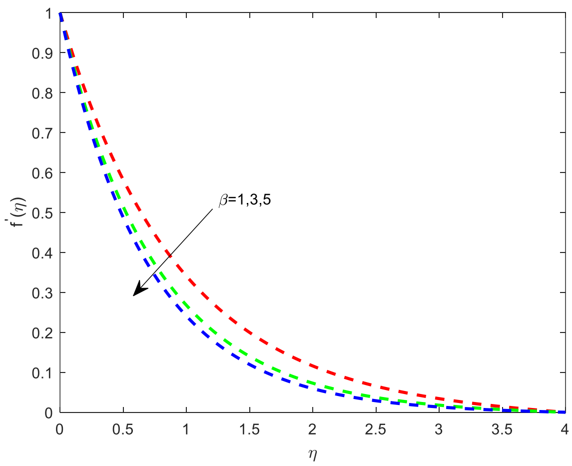

Figure 3. Distribution of velocity f' concerns η for numerous values of β

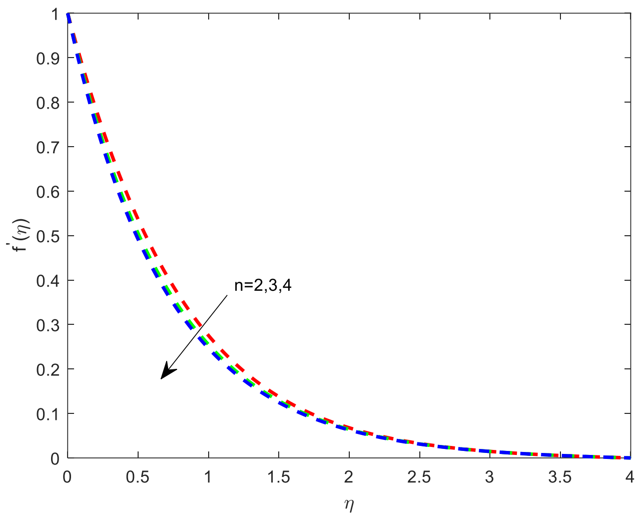

Figure 4. Distribution of velocity f' concerning η for numerous values of n

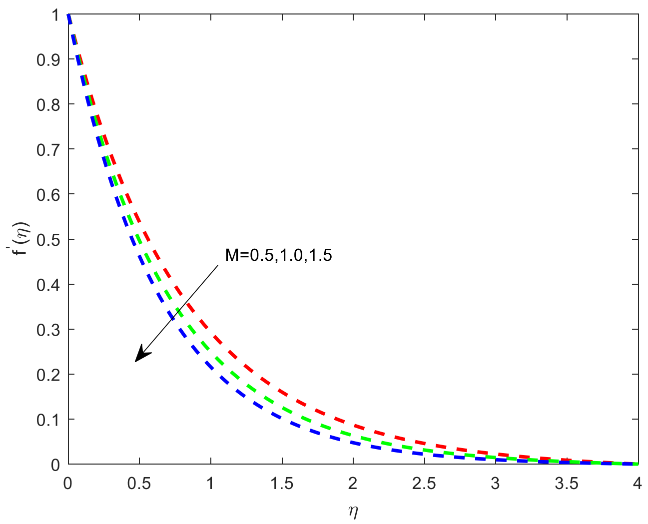

Figure 5. Distribution of velocity f' concerning η for numerous values of M

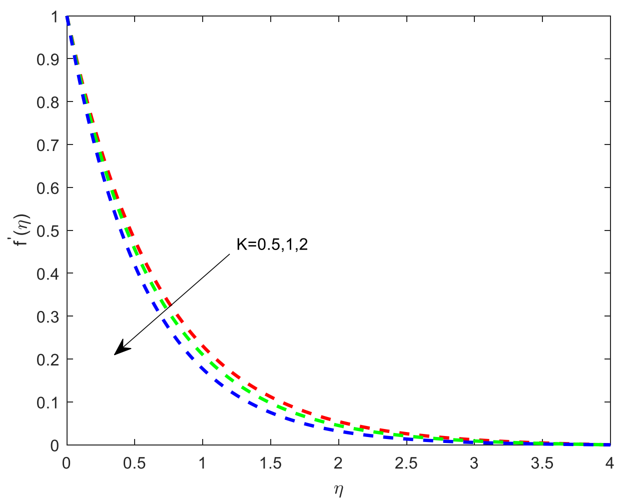

Figure 6. Distribution of velocity f' concerning η for numerous values of K

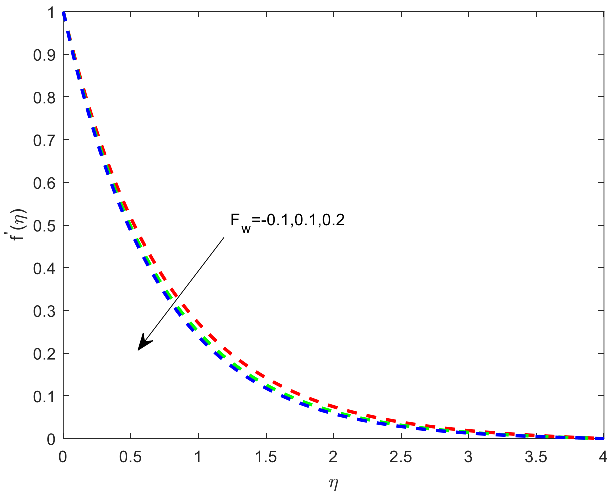

Figure 7. Distribution of velocity f' concerning η for numerous values of $\mathrm{F_w}$

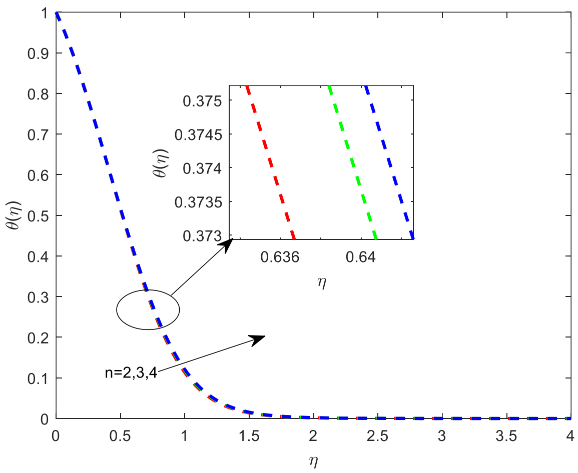

Figure 8. Distribution of temperature θ concerning η for numerous values of n

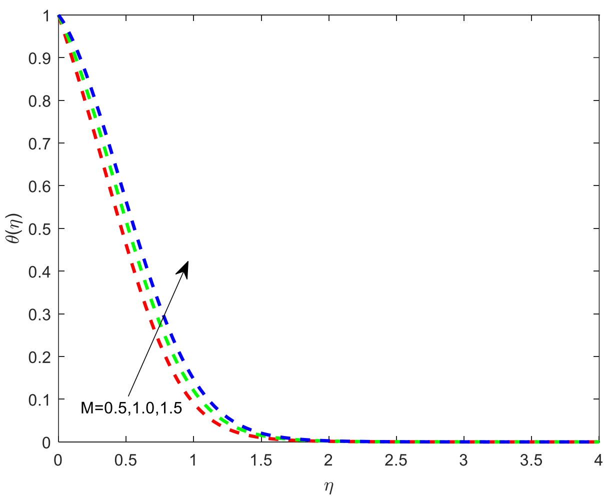

Figure 9. Distribution of temperature θ concerning η for numerous values of M

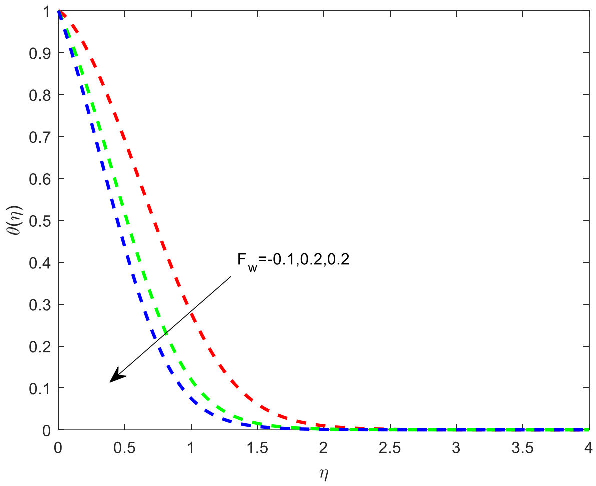

Figure 10. Distribution of temperature θ concerning η for numerous values of F_w

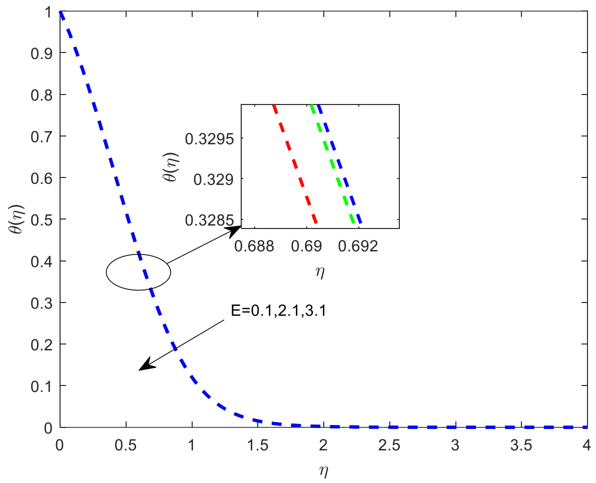

Figure 11. Distribution of temperature θ concerning η for numerous values of E

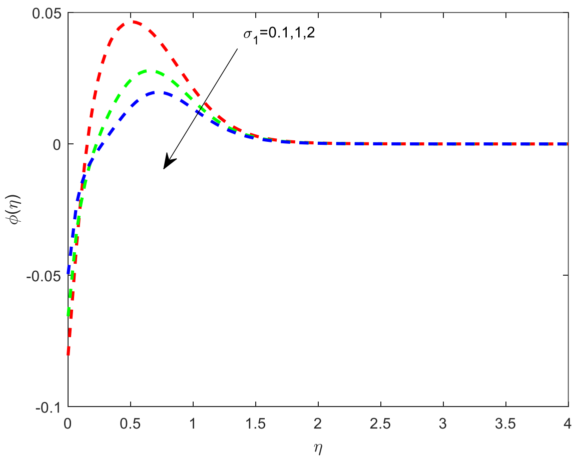

Figure 12. Distribution of concentration ϕ concerning η for numerous values of σ_1

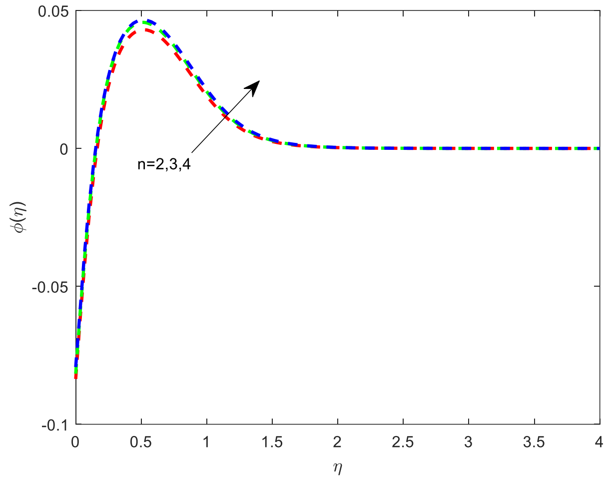

Figure 13. Distribution of concentration ϕ concerning η for numerous values of n

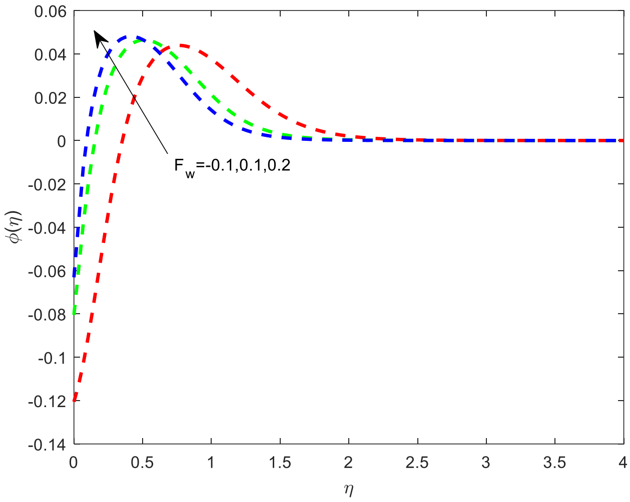

Figure 14. Distribution of concentration ϕ concerning η for numerous values of F_w

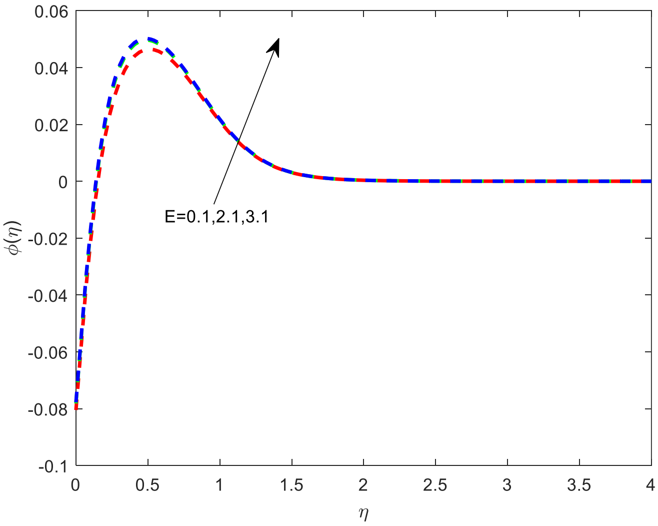

Figure 15. Distribution of concentration ϕ concerning η for numerous values of E

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