ISSN: 3068-2789

Research Article

Journal of All Physics Research and Applications

Soret and Dufour Effect on Radiating and Viscous Dissipating Casson Fluid Past a Non-Linearly Exponentially Stretching Sheet in the Presence of Variable Magnetic Field

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ABSTRACT
The current study focuses at examining the boundary layer flow of a Casson fluid over an exponentially permeable stretching surface with the existence of thermal radiation, magnetic field, viscous dissipation, Soret and Dufour effects. The partial non-linear differential equations of the continuity, motion and energy administering the flow of the problem are remodeled to the ordinary differential equations by making use of similarity transformation and figured out by utilizing MATLAB bvp4c package. On the velocity, temperature and concentration outlines, the consequences of distinct non-dimensional parameters mastering the flow are deliberated and sketched with the help of graphs. There is a comparison made among the results of the present study to those of the previous one which is seen to be in sound agreement. It is concluded that the Casson fluid gave better heat and mass transfer performance with the availability of the Soret and Dufour effects.

Keywords: Casson Fluid, Stretching Sheet, Soret and Dufour Effect, Viscous Dissipation, Thermal Radiation.

Received: May 13, 2026;
Accepted: May 20, 2026;
Published: May 27, 2026

Introduction

The non-Newtonian fluids have attracted the mindset of multitudinal researchers due to their numerous applications in the industry as comparable to the Newtonian fluids. Among the large number of non-Newtonian fluid models available, one of the most prominent is the Casson fluid model [1]. In the Casson fluid model, shear stress and strain have a non-linear relation. The Casson fluid is a plastic fluid yielding shear stress in the constitutive equations. The study of Casson fluid model has many usages like paints industry, manufacturing of medicines, synthetic lubricants and the flow of the blood. Due to the broad-spectrum of applications in the technology and industry, the theory of non-Newtonian fluid past a stretching surface has become a domain of effective research from last many years. Some of these applications include manufacturing of electronic chips, food stuffs, in paper industries, cooling processes, artificial fibers, glass blowing and many more. A wide range of scientists and researchers investigated the boundary layer flow over a stretching surface. The primary work on this work was initiated by Crane [2]. The boundary layer over a continuously stretching sheet with a power law surface velocity was revisited for a sheet of variable thickness by Fang et. al. Khan et. al explored the two-dimensional flow of MHD hyperbolic tangent fluid with nanoparticles towards a stretching surface [3,4]. Awaludin et. al numerically investigated the steady two-dimensional magnetohydrodynamic (MHD) boundary layer flow and heat transfer over a stretching/

Citation: Aastha Thakur, and Khem Chand (2026) Soret and Dufour Effect on Radiating and Viscous Dissipating Casson Fluid Past a Non-Linearly Exponentially Stretching Sheet in the Presence of Variable Magnetic Field. J All Phy Res Appli 2: 1-7.

shrinking permeable wedge [5]. The analysis on the thermal and mass diffusive MHD flow through a stretching sheet in the presence of chemically reactive solute under convective boundary conditions was made by Muni Venkatappa et. al. The Magnetohydrodynamics modules the advancement of the macroscopic behavior of fluids in the presence of ambient magnetic field and sights its application in engineering and technology like as in cooling of nuclear reactors, astronomy etc. [6]. The effect of MHD polar fluid over a semi stretched infinite vertical porous plate in the presence of heat source, temperature, magnetic field and thermal radiation was reported by Goud et. al. Yasmin et. al presented a comprehensive investigation of mass and heat transfer in magnetohydrodynamics (MHD) flow of an electrically conducting non-Newtonian micropolar fluid because of curved stretching sheet [7,8]. Along with, thermal radiation effects on heat and mass transfer over a stretching surface plays a vital role in Physics and Engineering having applications such as in missiles, aircrafts, combustion of fossil fuels and satellites etc. Ali et. al illustrated the thermal radiations and non-uniform heat flux impacts on magnetohydrodynamic hybrid nanofluid ($CuO\text{-}Fe_2O_3/H_2O$) flow along a stretching cylinder [9]. The extension of the lattice Boltzmann method for solving radiative transfer equation (RTE) in emitting, absorbing and non-scattering gaseous mixtures produced by combustion has been developed by Souai et. al. In fluids, we have two foremost effects specifically Soret and Dufour effects [10]. In Soret effect, thermal diffusion is the resultant of the presence of temperature gradient which regulates the thermal energy flow. The Dufour effect superintends the mass transfer inducing the diffusion-thermo effect. Despite of this that the magnitude of these two effects is very small, they have straight significance in the systems where the differences in density in the flow region exists like chemical processing, geoscience, hydrology, petrology etc. [11,12]. Numerous studies divulge that Soret effect, Dufour effect or the combination of both affect the free convection heat and mass transfer flow. Lagra et. al exhibited the combined Soret and Dufour effects on thermosolutal convection induced in a horizontal layer filled with a binary fluid and subject to constant heat and mass fluxes analytically and numerically [13]. The unsteady free convection heat and mass transfer flow in a vertical channel in the presence of Soret and Dufour effects was illustrated by Jha et. al. In the current study, the behavior of the flow, heat and mass transfer of a Casson fluid past an exponentially permeable stretching surface in the presence of thermal radiation, uniform magnetic field, viscous dissipation along with Soret and Dufour effects have been investigated [14]. The present results have been compared with the previous results existing in the literature. In the graphical presentations, the effects of various non-dimensional governing parameters on velocity, temperature and concentration profiles have been displayed. Also, under the comparison made in some chosen cases, the present results are found to be in good agreement with the existing results in the literature.

Mathematical Formulation

The domain under the study is a steady, incompressible and dissipative MHD flow of a Casson fluid past a non-linearly exponentially stretching sheet coinciding with the plane y=0. The geometry of the flow is exhibited by Figure. 1. The flow of the fluid is restricted to the plane y>0. A variable magnetic field is implemented with the assumption that the induced magnetic field is small in comparison with the external magnetic field. In addition to this, the Soret and Dufour effects are considered. The wall is stretched keeping the origin fixed by the application of two equal and opposite forces along the x-axis.

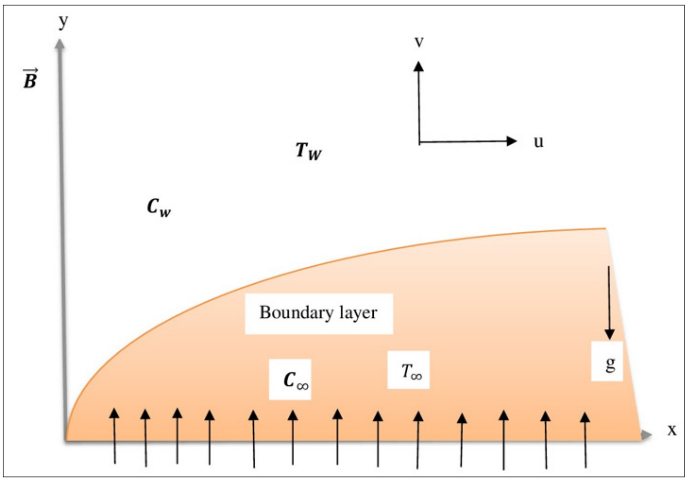

Figure 1: Physical configuration of the problem

For an isotropic and incompressible flow of a Casson fluid, the rheological equation of state is as follows: -

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

where $\pi = e_{ij}e_{ij}$ and e_{ij} are the $(i,j)^{th}$ component of the rate of deformation, π is the product of the component of deformation rate with itself, π_c is the critical value of this product based on the non-Newtonian model, μ_B is the plastic dynamic viscosity of the non-Newtonian fluid and p_y is the yield stress of the fluid.

The equations of continuity, momentum, energy and concentration governing this type of flow is given as [15]:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\left(1+\frac{1}{\gamma}\right)\frac{\partial^2 u}{\partial y^2}+g\beta_T(T-T_\infty)+g\beta_c(C-C_\infty)-\frac{\sigma B^2 u}{\rho}\ (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2}-\frac{\partial q_r}{\partial y}+\frac{\mu}{\rho c_p}\left(1+\frac{1}{\gamma}\right)\left(\frac{\partial u}{\partial y}\right)^2+D\frac{\partial^2 C}{\partial y^2}\ (3)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}+D\ \frac{\partial^2 T}{\partial y^2}\ (4)$$

here u and v are the components of velocity in the direction of x and y respectively, ν is the kinematic viscosity, ρ is the fluid density, $\gamma=\mu_B\sqrt{2\pi_c}/p_y$ is the Casson fluid parameter, g is the acceleration due to gravity, β_T is the coefficient of thermal expansion, β_c is the coefficient of concentration expansion, σ is the electrical conductivity, B= $B_0e^{\frac{Nx}{2L}}$ is the variable magnetic field, k is the thermal conductivity of the fluid, ρc_p is the heat capacitance of the fluid, q_r is the radiative heat flux, μ is the dynamic viscosity, D is the coefficient of mass diffusivity, C is the fluid concentration, N is the exponential parameter and $v(x)= v_0 e^{\frac{Nx}{2L}}$ is the parameter of suction/injection.

In accordance with the thermal radiation simulated using the Rosseland diffusion approximation, the radiative heat flux q_r is given by

$$q_r = \frac{-4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y} \quad (5)$$

where σ^* is the Stefan-Boltzmann constant and k^* is the Rosseland mean absorption coefficient.

Assuming the temperature differences within the flow as sufficiently small, equation (5) can be linearized by the expansion of T^4 into the Taylor series about T_∞ and neglecting higher order terms, we get $T^4 \cong 4T_\infty^3 T - 3T_\infty^4$ which converts equation (3) as:

$$\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2} - \frac{16\,\sigma\,T_\infty^3}{3\rho c_p\,k^*}\frac{\partial^2 T}{\partial y^2} + \frac{\mu}{\rho c_p}\left(1+\frac{1}{\gamma}\right)\left(\frac{\partial u}{\partial y}\right)^2 \quad (6)$$

Boundary Conditions

The concerned problem is subjected to the following conditions:-

at $y=0, u=U, v= -V(x), T= T_w, C= C_w$

as $y\to\infty, u\to 0, T\to T\_\infty, C\to C_\infty$ (7)

Here $U=U_0 e^{\frac{x}{L}}$ is the stretching velocity, $T_w= T_\infty + T_0 e^{\frac{x}{2L}}$ is the temperature at the sheet, U_0 and T_0 are the reference velocity and temperature, respectively. $V(x)= V_0 e^{\frac{x}{2L}}$ is the special type of velocity considered at the wall, (where V_0 is a constant, $V(x)>0$ is the suction velocity and $V(x)<0$ is the blowing velocity).

Method of Solution

The similarity variables applied to the problem are:

$$\eta = \sqrt{\frac{U_0}{2\nu L}}\, e^{\frac{Nx}{2L}}\, y,\ v = -\sqrt{\frac{\nu U_0}{2L}}\, e^{\frac{Nx}{2L}}\, N\{f(\eta) + \eta\, f'(\eta)\},\ u = U_0 e^{\frac{Nx}{L}} f'(\eta),$$

$$T = T_\infty + T_0 e^{\frac{2Nx}{L}}\,\theta,\ C = C_\infty + C_0 e^{\frac{2Nx}{L}}\,\phi \quad (8)$$

where T_∞ is the ambient fluid temperature, C_∞ is the ambient fluid concentration, L is the characteristic length and U_0 is the fluid velocity.

Upon the substitution of (8) in the equations (2), (4) and (6), the equations governing the problem reduces as: -

$$\left(1+\frac{1}{\gamma}\right) f'''(\eta) + N\,[f(\eta)f''(\eta) - 2\,f'^2(\eta)] + 2\,Gr\,\theta + 2\,Gc\,\phi - M\,f'(\eta) = 0 \quad (9)$$

$$\frac{1}{Pr}\left[\frac{4}{3}R_a - 1\right]\theta''(\eta) + N\,[4\,f'(\eta)\,\theta(\eta) - f(\eta)\theta'(\eta)] - Ec\,\left(1+\frac{1}{\gamma}\right)[f''(\eta)]^2 - Du\,\phi''(\eta) = 0 \quad (10)$$

$$\phi''(\eta) - N\,S_c\,[4\,f'(\eta)\,\phi\,(\eta) - f(\eta)\phi'(\eta)] + S_o\,S_c\,\theta''(\eta) = 0 \quad (11)$$

and the boundary conditions takes the form as: -

at $\eta = 0, f(\eta) = S, f'(\eta) = 1, \theta(\eta) = 1, \phi(\eta) = 1$

as $\eta \to \infty, f'(\eta) \to 0, \theta(\eta) \to 0, \phi(\eta) \to 0$ (12)

where the prime denotes the differentiation with respect to η, $S = \frac{v_0}{\sqrt{U_0 \nu / 2L}}$ >0 or <0 is the suction or blowing parameter, $M= \frac{2\,\sigma\,B_0^2\,L}{\rho U_0}$ is the magnetic field parameter, N is the exponential parameter, $Gr = \frac{g\,\beta_T\,L\,T_0}{U_0^2}$ is the thermal Grashof number, $Gc = \frac{g\,\beta_c\,L\,C_0}{U_0^2}$ is the concentration Grashof number,

$Pr = \frac{\mu\,c_p}{k}$ is the Prandtl number, $R = \frac{4\,\sigma\,T_\infty^3}{k\,k^*}$ is the Radiation parameter,

$Ec = Ec = \frac{U_0^2}{L\,\rho c_p}$ is the Eckert number, $Sc = \frac{\nu}{D}$ is the Schmidt number,

$So = \frac{D\,T_0}{\nu C_0}$ is the Soret number and $Du = \frac{D\,C_0}{\nu\,T_0}$ is the Dufour number.

The equations (9) to (11) along with the boundary conditions (12) are solved by converting them to an initial value problem by setting:

$f = y(1), f' = y(2), f'' = y(3)$

$\theta = y(4),\ \theta' = y(5)$

$\phi = y(6),\ \phi' = y(7).$

The system of non-linear ordinary differential equations (9) to (11) with the interrelated boundary conditions are computationally solved by the use of bvp4c MATLAB package. All computations were carried out by solving these equations with the help of collocation method that bvp4c uses.

Results & Discussions

In the results acquired, the effect of various non-dimensional governing parameters specifically Magnetic parameter (M), thermal Grashof number (Gr), concentration Grashof number (Gc), exponential parameter (N), Prandtl number (Pr), Radiation parameter (R), Eckert number (Ec), Casson fluid parameter (γ), Dufour number (Du), Soret number (S_o) and Schmidt number (S_c) on the flow, temperature and concentration profiles has been shown.

Effect on Velocity Distribution

In Figure. 2, the velocity profile for Magnetic parameter (M) is presented. Velocity is found to decrease with the increasing M. The reason for this is that rise in M marks the strengthening of the Lorentz force, thereby reducing the magnitude of the velocity. The effect of thermal Grashof number (Gr) on the velocity profile is depicted in Figure. 3, describing that an increase in Gr enhances the velocity profile. The thermal Grashof number denotes the relative effect of the thermal buoyancy force to the viscous hydrodynamic force in the boundary layer. It is observable that there is an upgradation in the velocity due to the amplification of thermal buoyancy force. In Figure. 4, the effect of concentration Grash of number (Gc) is displayed. It is inferred that the velocity profile increases with an increase in the concentration Grashof number (Gc). The concentration Grashof number gives the ratio of the species buoyancy force to the viscous hydrodynamic force. As expected, the fluid velocity elevates. The variation of the dimensionless velocity distribution for distinct values of exponential parameter (N) is shown in Figure. 5. It is noticeable that an increase in N declines the velocity of the fluid. This might occur due to the reduction in the wall temperature throughout the boundary layer for the positive values of the exponential parameter which means that the transfer of heat takes place from the wall to the ambient fluid causing the particles to move away from the wall.

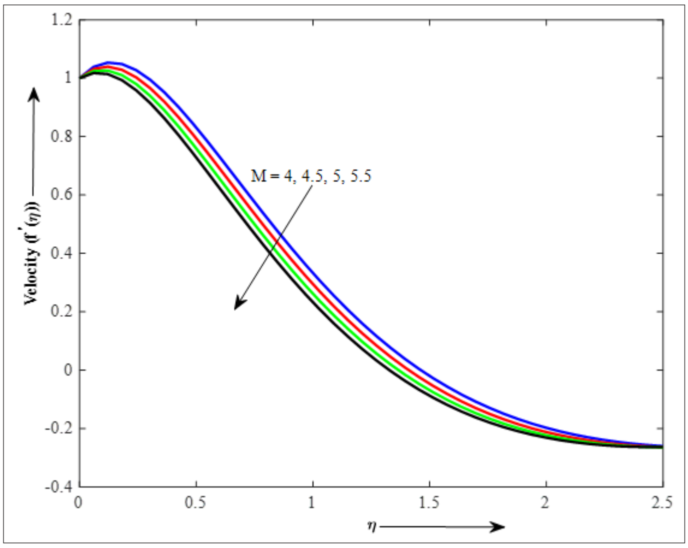

Figure 2: Velocity profile for different *M* when *Gr*=2, *Gc*=3, *Ec*=0.7, *Du*=20, S_c=6, S_o=15, *Pr*=7, *R*=1, *γ*=0.9, *N*=0.1.

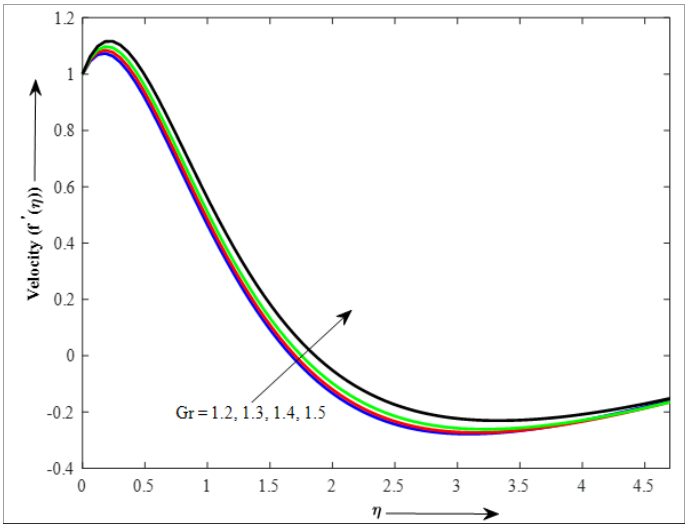

Figure 3: Velocity profile for different *Gr* when *Gc*=3, *M*=3, *Ec*=0.7, *Du*=20, S_c=6, S_o=15, *Pr*=7, *R*=1, *γ*=0.9, *N*=0.1

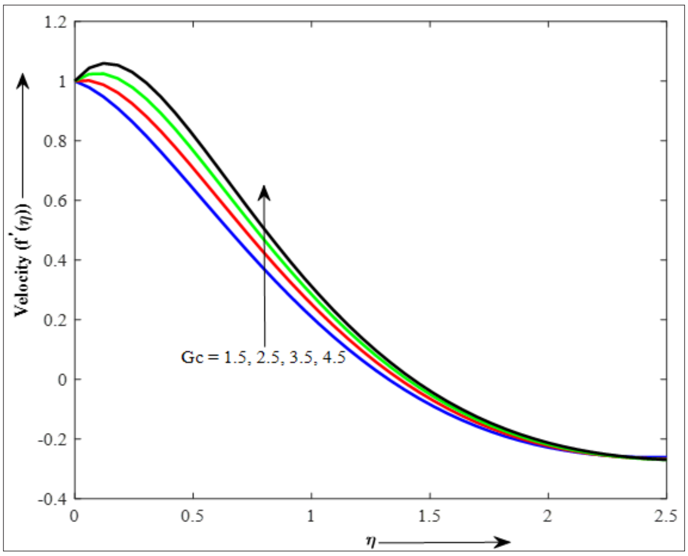

Figure 4: Velocity profile for different *Gc* when *Gr*=1.2, *M*=4, *Ec*=0.7, *Du*=20, S_c=6, S_o=15, *Pr*=7, *R*=1, *γ*=0.9, *N*=0.1

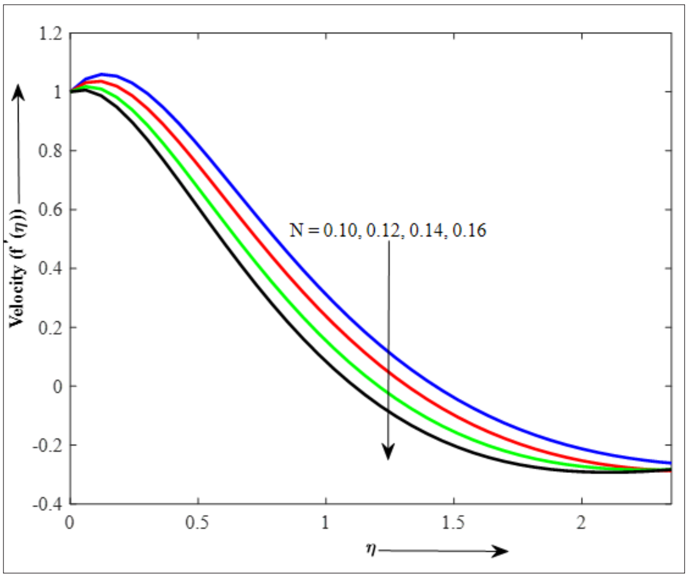

Figure 5: Velocity profile for different *N* when *Gr*=1.2, *M*=4, *Ec*=0.7, *Du*=20, S_c=6, S_o=15, *Pr*=7, *R*=1, *γ*=0.9, *Gc*=4.5

Effect on Temperature Distribution

Figure. 6 shows the temperature behavior of the Casson fluid with variation in the values of the Eckert number (*Ec*). It was confirmed that the temperature rises up with the uplifting values of Ec. An increase in Eckert number accounts to the conversion of the kinetic energy into the internal energy by the work that is done in opposition to the viscous fluid stresses. The influence of Casson parameter (*γ*) on the temperature profile is exhibited in Figure. 7. It is remarked that an increase in γ brings down the temperature profile of the flow. The reason being that increase in γ intends to the decrement in the yield stress and consequently there is a shrinkage in the thickness of the thermal boundary layer. Figure. 8 reveals the impact of Dufour number (*Du*) on the dimensionless temperature profile. An upsurge in the temperature profile of the fluid with the increasing values of Dufour number recounts that the thermal boundary layer thickens. In Figure. 9, the consequence of radiation parameter (R) on the temperature profile is considered. Higher values of thermal radiation parameter supply more heat to the working fluid causing an upliftment in the temperature and the thermal boundary layer thickens. Figure. 10 manifests the alteration in the temperature profile for different values of the Prandtl number (*Pr*). It is perceived that the temperature profile drops with the rising values of the Prandtl number. The Prandtl number is the ratio of momentum diffusivity to the thermal diffusivity. An increase in the Prandtl number reduces the thermal boundary layer thickness and hence the temperature falls down.

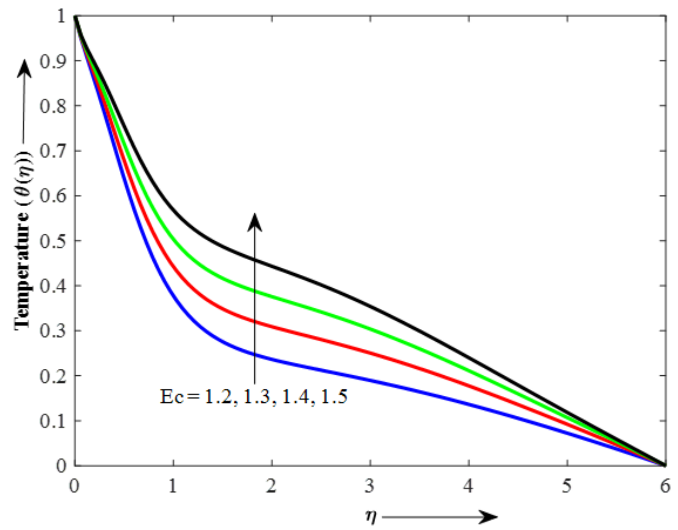

Figure 6: Temperature profile for different *Ec* when N=0.1, Gr=1.2, Gc=4.5, M=4, Du=20, S_c=6, S_o=15, Pr=7, R=1, γ=0.9

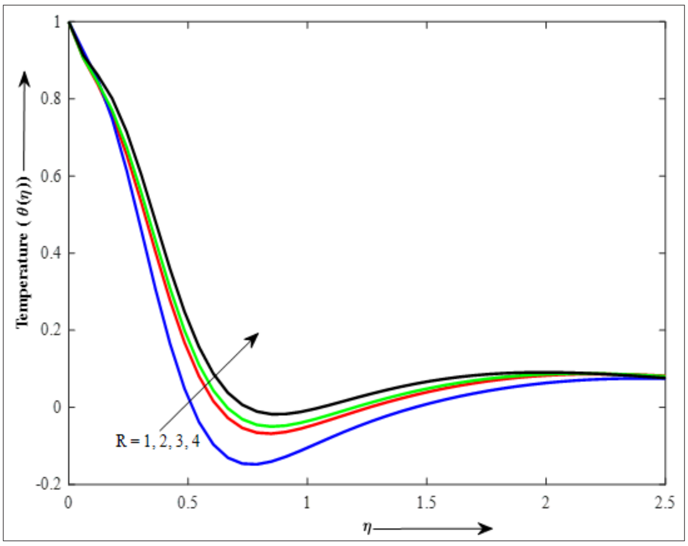

Figure 9: Temperature profile for different *R* when N=0.1, Gr=5, Gc=7, M=4, Ec=1.5, Du=2, S_c=6, S_o=4, Pr=7, γ=0.9

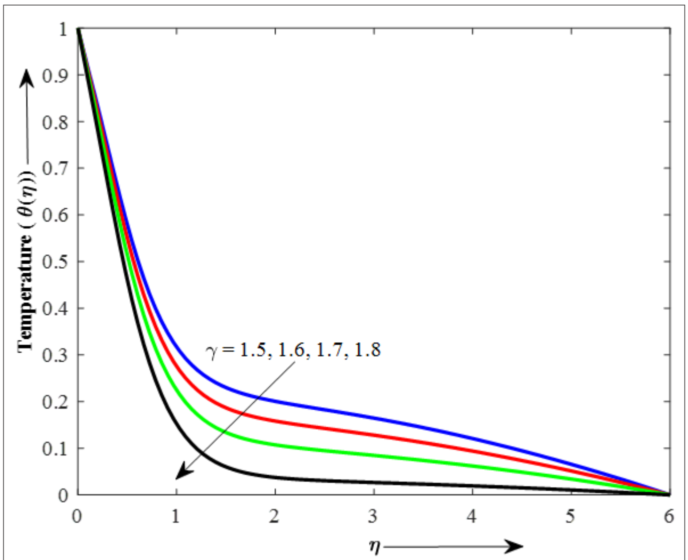

Figure 7: Temperature profile for different γ when N=0.1, Gr=1.2, Gc=4.5, M=4, Du=20, S_c=6, S_o=15, Pr=7, R=1, Ec=1.5

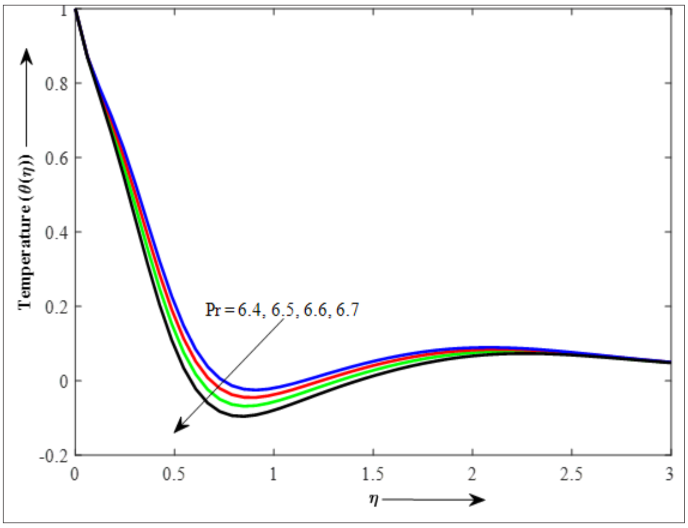

Figure 10: Temperature profile for different Prwhen N=0.1, Gr=5, Gc=7, M=4, Ec=1.5, Du=2, S_c=6, S_o=4, R=1, γ=0.9

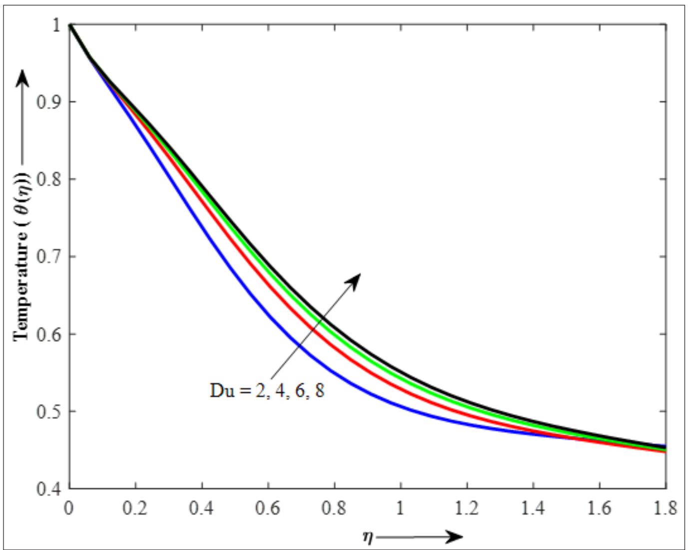

Figure 8: Temperature profile for different *Du* when N=0.1, Gr=1.2, Gc=4.5, M=4, Ec=1.5, S_c=6, S_o=15, Pr=7, R=1, γ=0.9

Effect on Concentration Distribution

Figure. 11 demonstrates the dimensionless concentration profile with the variation of Schmidt number. The concentration profile decreases as well as we increase the value of the Schmidt number. The increase in the Schmidt number corresponds to a weaker solute diffusivity allowing a shallower penetration of the solutal effect. As an outcome, the concentration decreases with an increase in Sc. In Figure. 12, the concentration profile behavior with different values of Soret number (S_o) is anticipated. A surge in the Soret parameter was found to heighten the fluid's concentration. In the Soret phenomenon, the concentration distribution is affected by the temperature gradient. Larger values of Soret number corresponds to the higher temperature gradient resulting in the higher convective flow. Hence, increasing the concentration distribution.

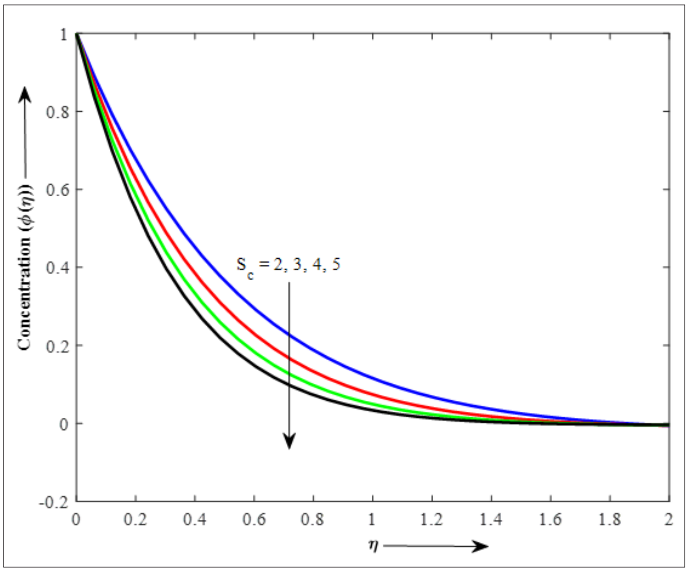

Figure 11: Concentration profile for different S_c when N=0.1, Gr=1.2, Gc=4.5, M=4, Ec=1.5, Du=20, S_o=15, Pr=7, R=1, γ=0.9

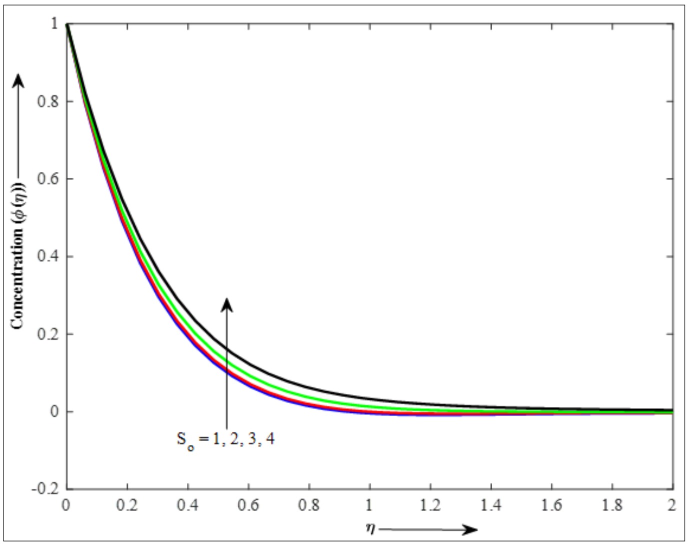

Figure 12: Concentration profile for different S_o when N=0.1, Gr=6, Gc=7, M=4, Ec=1.5, Du=20, Pr=7, R=1, S_c=6, γ=0.9

Comparison of the Results

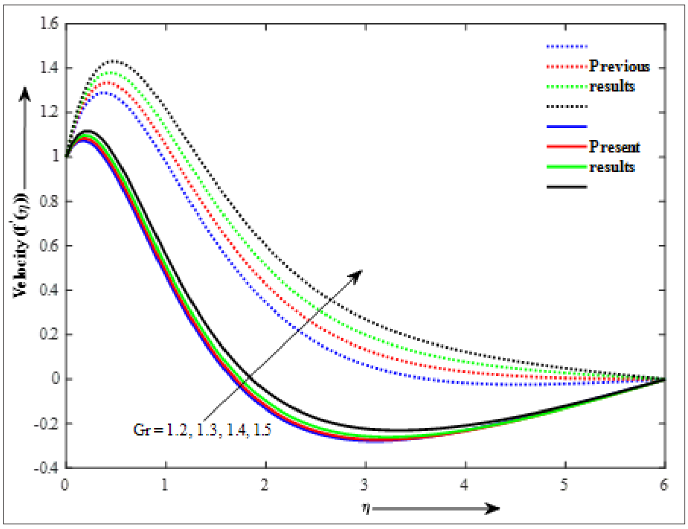

Figure 13: Comparison of velocity for Gr in the absence of S_o and Du

To appraise the validity and accuracy of the results obtained, the numerical values of the velocity and temperature profile for various values of Grashof number (Gr) and Eckert number (Ec) in the absence of Soret and Dufour effects are compared with the available results for which the outcome is displayed in Figures. (13 and 14) [16]. The results are found to be in the excellent agreement with the earlier published results.

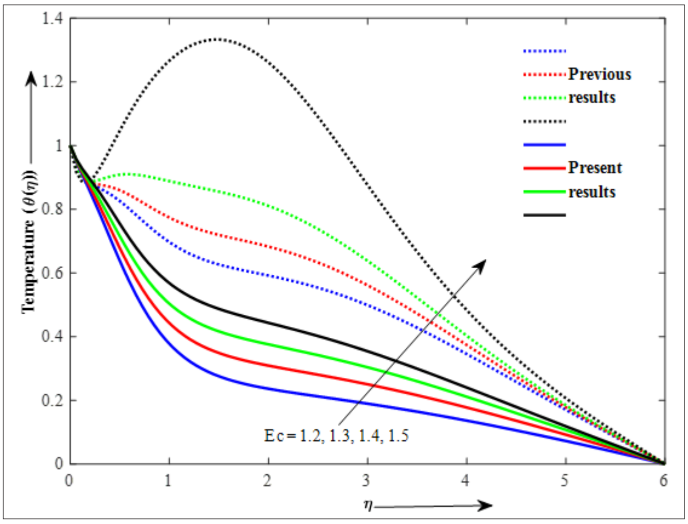

Figure 14: Comparison of temperature for Ec in the absence of S_o and Du

Conclusions

In this investigation, the numerical solutions for Casson fluid over an exponentially permeable stretching surface amalgamated with Soret and Dufour effects have been obtained. A comparison with the previously obtained results in the absence of these effects has been done. The effects of several non-dimensional parameters involved in the problem have been examined on the velocity, temperature and concentration profiles.

The conclusions of the present investigation are as follows: -

- For enlarging values of M (Magnetic field parameter) and N (exponential parameter), the velocity field undergoes diminution.
- A reverse trend is exhibited in the velocity field for growing values of Gr (thermal Grashof number) and Gc (concentration Grashof number).
- An augmenting behavior is noticed by the thermal field for enhancing values of Ec (Eckert number),R (Radiation parameter) and Du (Dufour number). Increase in the temperature distribution with increment in the values of Du exhibits the enhancement in the heat transfer rate of the Casson fluid.
- An opposite behavior is marked by the thermal field on amplifying γ (Casson fluid parameter) and Pr (Prandtl number).
- The concentration field shows an increasing behavior on escalating values of S_o (Soret number) while a reverse impact for the fluctuation in S_c (Schmidt number).
- Casson fluid indicated better heat and mass transfer performance with the blending of Soret and Dufour effects.

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