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Influence of Thermal Radiation and Chemical Reaction on MHD Mixed Convection Casson Fluid Flow over a Nonlinear Stretching Sheet in a Porous Medium

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Abstract: This study investigates the influence of thermal radiation and chemical reaction on magnetohydrodynamic (MHD) mixed convection flow of a Casson fluid over a nonlinear stretching sheet embedded in a porous medium. The non-Newtonian behavior of the Casson fluid, combined with the effects of buoyancy forces, magnetic field, and porous medium resistance, is analyzed under nonlinear stretching conditions. The governing partial differential equations (PDEs) are transformed into a system of nonlinear ordinary differential equations (ODEs) using suitable similarity transformations. The resulting equations are solved numerically using the Runge-Kutta-Fehlberg (RKF) method with shooting technique. The impacts of key parameters such as the Casson fluid parameter, magnetic field strength, thermal radiation, chemical reaction rate, porosity, and nonlinear stretching exponent on velocity, temperature, and concentration profiles are discussed in detail. Additionally, the skin friction coefficient, Nusselt number, and Sherwood number are evaluated to assess the flow dynamics, heat transfer, and mass transfer characteristics. The results reveal that thermal radiation enhances temperature distribution while chemical reaction significantly alters concentration profiles. The findings provide valuable insights for industrial and engineering applications involving non-Newtonian fluid flows, thermal processing, and mass transfer control.

Keywords: *Casson fluid, MHD, mixed convection, thermal radiation, chemical reaction, porous medium, nonlinear stretching sheet*

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I.INTRODUCTION:

In engineering and industrial sectors, it is essential to grasp boundary layer phenomena that are linked with fluid movement and heat transmission which is caused by stretching of sheet. This field of research is broadly applicable, as it is employed in the extrusion, wire drawing, and refrigeration of large metallic plates, such as those used in electrolyte systems. The knowledge gained from the examination of these thermal phenomena and fluid dynamics is essential for the enhancement and optimization of a variety of industrial processes. Ishak et al. [1] investigate the heat transfer and stagnation point characteristics of a stretching sheet under a uniform magnetic field that is applied perpendicular to the sheet. Mukhopadhyay [2] explored the flow and heat transmission of MHD boundary layers over an exponentially stretching sheet that is surrounded in a thermally graded medium. Devi et al. [3] analyzed the impact of an oriented magnetic field and sloped outer velocity on non-Newtonian fluid flow over a stretching sheet with a heat source.

Numerous industrial operations are dependent on the production of sheeting materials, which encompasses both metal and polymer sheets. In particular, the drawing and stretching of segments extruded from a die at prescribed velocities are frequently necessary for technical operations involving polymers. Depending on the application, these strips may endure linear or nonlinear stretching. The importance of the study of nonlinear stretching surfaces has increased significantly, as these conditions more accurately reflect practical manufacturing scenarios in which surface velocity and temperature may fluctuate in a nonlinear manner as a result of heating or cooling effects. The optimization of the quality, uniformity, and mechanical properties of the final products in processes such as extrusion, coating, and film refrigeration is contingent upon an understanding of the behavior of fluid flow over nonlinear stretching surfaces. Ullah et al. [4] examined the MHD flow across the boundary layer over a nonlinear stretched sheet using the neural network technique. Poply et al. [5] conducted an analysis on the temperature-dependent fluid properties of MHD flow with heat transmission over a non-linearly stretching sheet.

The radiation impact can be quite substantial at elevated operating temperatures. The development of pertinent equipment is significantly influenced by the understanding of radiation heat transfer, as numerous processes in engineering domains occur at high temperatures. Goud et al. [6] investigated the impact of radiation on the boundary layer flow of the MHD framework in an exponentially stretching sheet. Taneja et al. [7] investigated the fluid properties of an MHD free stream flow over a stretching sheet in the presence of radiation. Pramanik [8] has conducted research on the combined effects of thermal radiation and

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suction/blowing as heat transfer analysis in the boundary layer flow of a Casson fluid over an exponentially stretching sheet

Singh et al. [9] investigated the impact of radiation and the porosity parameter on the magnetohydrodynamic flow that results from the stretching of a sheet in porous media. Das et al. [10] examined the effects of mass transfer on free convective flow and heat transfer of a viscous, incompressible, and electrically conducting fluid flowing past a vertical porous plate embedded in a porous medium. Their study considered the influence of time-dependent permeability, oscillatory suction, a transverse magnetic field, and an internal heat source on the system's behavior. Ullah et al. [11] investigated the impact of Newtonian heating and slip scenario on the MHD flow of Casson fluid over a nonlinearly stretching sheet that is immersed in a porous medium. Swain et al. [12] have examined the impact of viscous dissipation and joule heating on the flow and heat transmission of MHD through a stretching sheet that is embedded in a porous medium.

Natural shifting and heat exchange have a wide range of applications in astrophysics, geophysics, cooling systems, tower cooling, and aerodynamics. Moreover, the properties of heat sources generated by fluids in motion are pertinent to chemical reactions. The transfer of heat and mass from a vertical plate inserted into a porous medium that is exposed to a transverse magnetic field with first-order chemical reaction is being investigated using a numerical technique by Makinde and Aziz [13] with convective boundary condition. The MHD flow of the boundary layer through a porous medium with an exponentially stretching surface, as well as the radiation effect and chemical reaction, were investigated by Ayesh and Salah [14]. Mahboobtosi et al. [15] examine the impact of a variety of parameters, such as chemical reactions, on the flow characteristics of MHD in a porous medium. Gopal et al. [16] performed a study on the dissipation of viscous and Joule's energy in a Casson fluid over a chemically reacting stretching sheet with an inclined magnetic field and multiple slides. The study conducted by Reddy et al. [17] examines the MHD boundary layer flow and heat transfer over a nonlinear stretching sheet with chemical reaction and suction/blowing. Sivasankaran et al. [18] have examined the convective boundary condition in a porous medium. Chemical reaction, radiation, and slip all contribute to the stagnation-point flow of MHD mixed convection.

Non-Newtonian fluids are extensively employed in industrial and engineering applications, including polymer processing, food industries, and biomedical systems, due to their intricate rheological behaviour. The Casson fluid model is particularly noteworthy among non-Newtonian fluids because of its capacity to characterize yield stress behaviour, which renders it applicable in the modelling of blood flow, chocolate production, and drilling muds. Inspired by the literature, no attempt has been made to examine the impact of thermal radiation and chemical reactions on the flow of MHD mixed convection Casson fluid over a nonlinear stretching sheet in a porous medium. The objective of the current study is to address this deficiency in the existing literature. The reduced ordinary differential equations are numerically solved using the Runge-Kutta-Fehlberg method with the gunshot method, and similarity solutions are obtained.

II. Mathematical Formulation

Consider the steady, laminar, two-dimensional boundary layer flow of an incompressible, electrically conducting viscous fluid over a nonlinear stretching sheet in the presence of a transverse magnetic field. The flow is further influenced by mixed convection, arising from the combined effects of buoyancy forces due to temperature and concentration differences. Additionally, thermal radiation is considered to better represent high-temperature industrial applications. A reactive species undergoing a first-order chemical reaction is considered within the boundary layer. The magnetic field is applied at a constant intensity along the y-axis, and the magnetic Reynolds number is assumed to be sufficiently small so that the induced magnetic field is negligible. The physical configuration and coordinate system are depicted in Figure 1.

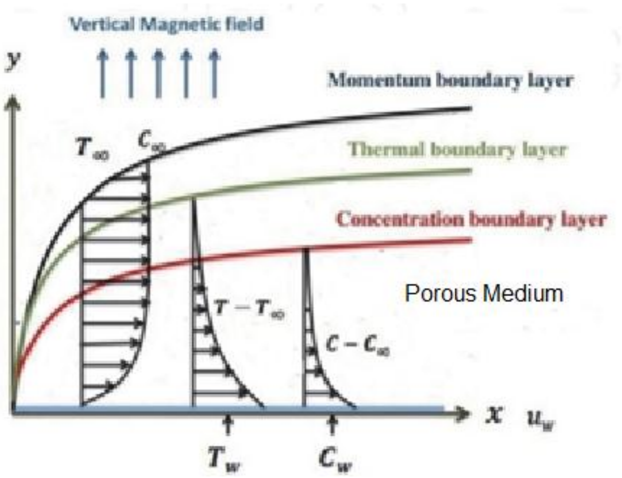

Fig. 1 Physical model of the problem

Governing Equation:

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

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

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho c_p}\frac{\partial q_r}{\partial y} \qquad (3)$$

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$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-k_c(C-C_\infty) \qquad (4)$$

u and v indicate the velocity elements in x and y direction respectively, ν is kinematic viscosity, σ is the electrical conductivity, β is the Casson parameter, ρ is the fluid density, g is the gravitational force due to acceleration, β_T is the volumetric coefficient of thermal expansion, β_C is the coefficient of concentration expansion, k is the heat conductivity of the fluid, q_r is the radiative heat flux, D is the mass diffusivity and k_c is chemical reaction parameter, B is the magnetic intensity, K is the permeability coefficient of porous medium

The boundary conditions are:

$$u=cx^n,\ v=0,\ T=T_w,\ C=C_w \quad at \quad y=0 \qquad (5)$$

$$u\to 0,\quad T\to T_\infty \quad C\to C_\infty \quad at \quad y\to\infty \qquad (6)$$

Using the similarity transformation

$$\psi=\sqrt{\frac{2\nu a}{(n+1)}}x^{\frac{n+1}{2}}f(\eta),\quad \eta=\sqrt{\frac{a(n+1)}{2\nu}}yx^{\frac{n-1}{2}},\quad \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty},\quad \varphi(\eta)=\frac{C-C_\infty}{C_w-C_\infty}$$

$$u=\frac{\partial\psi}{\partial y},\qquad v=-\frac{\partial\psi}{\partial x}$$

and the Rosseland approximation for radiation, the radiative heat flux q_r is simplified as

$$q_r=-\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y} \qquad (7)$$

Where σ^* and k^* are the Stefan-Boltzmann constant and the mean absorption coefficient respectively. It is supposed that the temperature differences with the flow are sufficiently small s.t. the term T^4 can be press out as a linear function of temperature. Hence, expanding T^4 in a Taylor series through T_∞ and neglecting higher-order terms, we obtain $T^4=4T_\infty{}^3T-3T_\infty{}^4$

$$\frac{\partial T^4}{\partial y}=4T_\infty{}^3\frac{\partial T}{\partial y} \qquad (8)$$

The governing equation (1)- (4) then reduce to using similarity variables and equation (8)

$$\left(1+\frac{1}{\beta}\right)f'''+ff''-\frac{2}{n+1}\left(n(f')^2+\left(M+\frac{1}{Da}\right)f'-Gr\theta-Gm\phi\right)=0 \qquad (9)$$

$$\left(1+\frac{4}{3}R\right)\theta''+Prf\theta'=0 \qquad (10)$$

$$\phi''+Sc(f\phi'-C_r\phi)=0 \qquad (11)$$

The transformed boundary condition is

$$\eta=0,\quad f=0,\quad f'=1,\quad \phi=1,\quad \theta=1 \qquad (12)$$

$$\eta\to\infty,\quad f=0,\quad f'=0,\quad \theta=0,\quad \phi=0 \qquad (13)$$

The key thermophysical parameters are defined by:

$$Da=\frac{K_0 a}{\nu},\quad M=\frac{\sigma B_0{}^2}{\rho a},\quad Gr=\frac{g\beta_T T_0}{a^2},\quad Gm=\frac{g\beta_C C_0}{a^2},\quad R=\frac{4\sigma^* T_\infty{}^3}{kk^*},\quad Pr=\frac{\nu\rho c_p}{k}$$

$$\alpha=\frac{k}{\rho c_p},\quad Sc=\frac{\nu}{D},\quad C_r=\frac{2k_c x}{(n+1)u}$$

Here $\beta, n, M, Da, Gr, Gm, R, Pr, Sc, C_r$ denotes the Casson parameter, non-linearity parameter, magnetic parameter, Darcy number, porous parameter, , thermal Grashof number, mass Grashof number, radiation parameter, Prandtl number, Schmidt number, chemical reaction parameter,

III. Numerical Procedure

The ODE's (9) to (11) are non-linear, and the RKF method numerically solved the resulting governing equations according to conditions (12) and (13). The key element of the RKF method to find out the solutions of governing equations, as explained below:

- The Runge Kutta Fehlberg Method is a method for numerically solving ordinary differential equations arising in mathematical modeling.
- The RKF method is one way to solve the problem. At each step, different approximation solutions are made and compared. If two answers are close, then an approximation is accepted.
- If two answers do not agree to a specified accuracy, then step is reduced, and if answers agree to a specified accuracy, then step is increased.

IV. Results and Discussion

Figure 2 illustrates the variation in velocity profiles for different values of the Casson parameter β. It is evident from the figure that an increase in β leads to a notable decrease in the velocity of the fluid. Physically, the Casson parameter characterizes the non-Newtonian behavior of the fluid; higher values of β correspond to a fluid with increased yield stress and stronger resistance to deformation. In the context of Casson fluids, which are commonly used to model materials such as blood, inks, and certain food products, the parameter β essentially quantifies the degree of deviation from Newtonian behavior. As β increases, the fluid exhibits more pronounced pseudo-plastic characteristics, requiring a higher threshold stress to initiate flow. This enhanced resistance diminishes the velocity of the fluid layers throughout the domain.

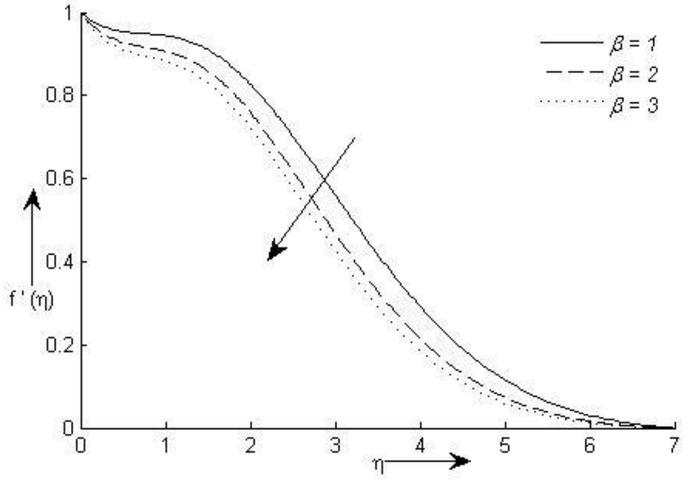

Fig. 2 Velocity for β

From an engineering perspective, the ability to control fluid motion via manipulation of the Casson parameter has practical significance. In processes where suppression of fluid motion is desirable, such as in damping systems, coating technologies, and biomedical applications like controlling blood flow in artificial organs, the use of fluids with higher non-Newtonian characteristics can be advantageous. The observed trend in Figure 2 confirms that increasing non-Newtonian effects act to retard the fluid motion, offering a mechanism for passive flow control in a range of industrial and biomedical applications. Thus, the study of how the Casson parameter influences velocity profiles not only deepen the theoretical understanding of non-Newtonian fluid dynamics but also aids in the design and optimization of systems where precise regulation of fluid behaviour is critical.

Figure 3 illustrates the variation in velocity profiles for different values of the non-linear stretching parameter n. It is observed from the figure that an increase in n initially results in a reduction in the fluid velocity near the stretching surface. However, beyond a certain distance from the surface, a phase-like transition occurs where the velocity begins to increase with increasing n.

This behaviour can be attributed to the influence of non-linear stretching on the momentum boundary layer structure. The non-linear stretching parameter n governs the rate at which the surface is stretched along the flow direction, with higher values of n indicating a more pronounced non-linear stretching behaviour. Physically, this intensified non-linearity enhances the shear forces near the wall, which suppresses the fluid motion in the immediate vicinity of the surface due to increased frictional resistance. Consequently, the velocity decreases in the near-wall region for higher values of n.

However, as the distance from the surface increases, the influence of surface stretching weakens while the inertial effects of the fluid motion become more dominant. This causes the velocity profiles to rise beyond a certain point in the boundary layer, as the retarding effects of non-linear stretching diminish and the fluid accelerates in response to the momentum diffusion away from the wall. The point at which this shift occurs moves farther from the surface with increasing n, indicating a redistribution of momentum within the boundary layer.

From an engineering perspective, this dual behavior of the velocity profiles with respect to the non-linear stretching parameter holds considerable importance. In applications such as polymer extrusion, metal drawing, and continuous casting processes, where stretching sheets are employed, controlling the stretching rate non-linearly can be used to regulate the thickness of the boundary layer and optimize the desired surface finish and product quality. Moreover, in thermal and mass transfer operations involving non-Newtonian or complex fluids, adjusting the non-linear stretching parameter allows for tailored control over fluid flow characteristics near and away from the surface, enhancing process efficiency and stability.

Thus, the observed trend in Figure 3 not only enriches the theoretical understanding of boundary layer flows over non-linearly stretching surfaces but also offers valuable insights for the practical design and operation of industrial processes involving complex fluid-surface interactions.

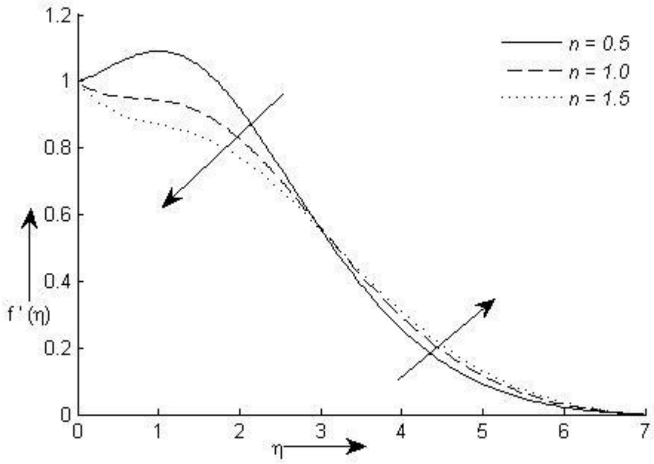

Fig. 3 Velocity for n

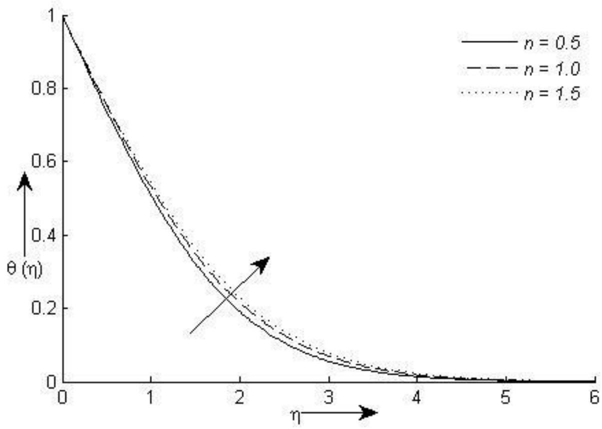

Fig. 4 Temperature for n

Figure 4 depicts the variation in temperature profiles for different values of the non-linear parameter n. It is evident from the figure that an increase in n leads to a corresponding increase in the fluid temperature throughout the boundary layer. This behaviour can be physically interpreted by considering the effect of non-linear stretching on the thermal boundary layer. As n increases, the stretching rate of the surface becomes more intense in a non-linear fashion. This enhanced stretching action generates additional frictional heating due to increased shear forces within the fluid, which contributes to a rise in the local fluid temperature, especially near the wall region.

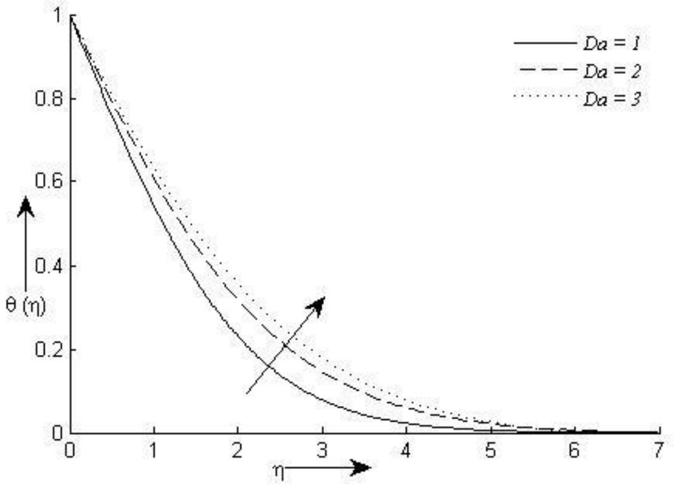

Fig. 5 Temperature for Da

Figures 5 and 6 illustrate the variations in temperature and concentration profiles, respectively, for different values of the Darcy number (Da). It is clearly observed from these figures that as the Darcy number increases, both the temperature and concentration profiles exhibit a corresponding increase throughout the boundary layer region.

Physically, the Darcy number is a dimensionless parameter that characterizes the permeability of the porous medium through which the fluid flows. A higher Darcy number indicates a more permeable medium, which facilitates enhanced fluid movement within the porous structure. As Da increases, the resistance offered by the porous medium to the fluid motion decreases, allowing more vigorous penetration and transport of thermal and solutal energy within the boundary layer.

The increase in temperature with higher Darcy numbers can be attributed to the fact that a more permeable medium permits greater fluid motion, which in turn enhances convective heat transfer within the system. The intensified convective movement enables more efficient transport and accumulation of thermal energy in the fluid, leading to elevated temperature profiles.

Similarly, the concentration profiles also rise with increasing Da, as the enhanced permeability promotes improved mass transport within the porous medium. The reduced flow resistance allows for easier diffusion and convection of species within the fluid, thereby increasing the concentration levels throughout the boundary layer.

From an engineering perspective, this behavior has considerable implications for thermal and mass transfer systems involving porous media, such as in geothermal engineering, filtration processes, chemical reactors, and biomedical applications like tissue engineering and controlled drug delivery. By adjusting the permeability of the medium (i.e., varying the Darcy number), one can regulate the temperature and concentration distributions to optimize process performance and material properties.

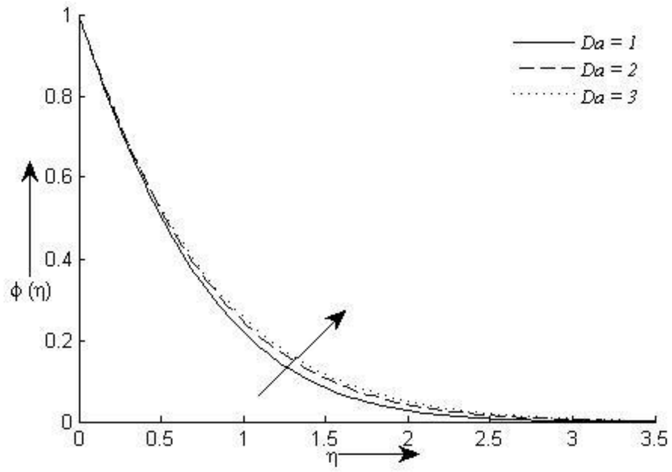

Fig. 6 Concentration for Da

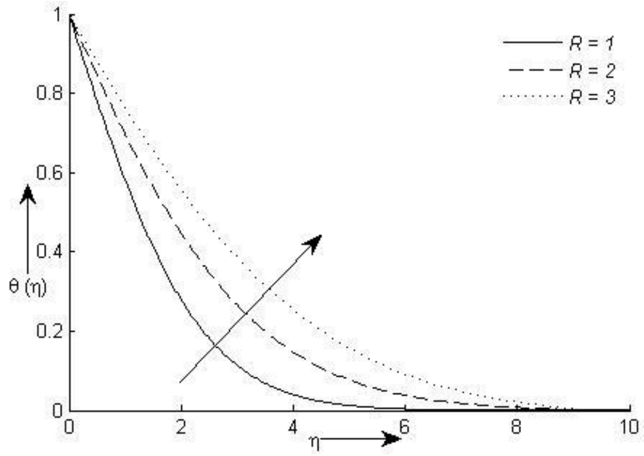

Fig. 7 Temperature for R

Figure 7 illustrates the variation in temperature profiles for different values of the radiation parameter R. It is evident from the figure that an increase in the radiation parameter leads to a significant rise in the fluid temperature throughout the boundary layer.

Physically, the radiation parameter R quantifies the relative contribution of thermal radiation to the overall heat transfer process within the fluid. As R increases, the radiative heat flux becomes more prominent, effectively enhancing the thermal energy supplied to the fluid. This additional heat input raises the thermal energy content in the boundary layer, resulting in elevated temperature profiles.

The presence of thermal radiation is particularly influential in high-temperature processes or environments where radiative heat transfer can rival or surpass conductive and convective mechanisms. The increase in temperature with higher radiation parameter values also contributes to the thickening of the thermal boundary layer, as the rate of heat diffusion to the surrounding fluid is reduced due to the elevated radiative heating near the surface.

From an engineering and manufacturing perspective, this behaviour has significant implications. In processes such as glass production, metal forging, polymer extrusion, and materials processing at elevated temperatures, radiative heat transfer plays a crucial role in determining the thermal environment. The ability to predict and control temperature distribution by manipulating the radiation parameter allows for improved thermal management, enhanced material quality, and optimized process efficiency. For example, increasing radiative heating can be used to maintain desired temperature levels without excessively increasing convective heat inputs, thereby achieving energy savings and uniform thermal profiles.

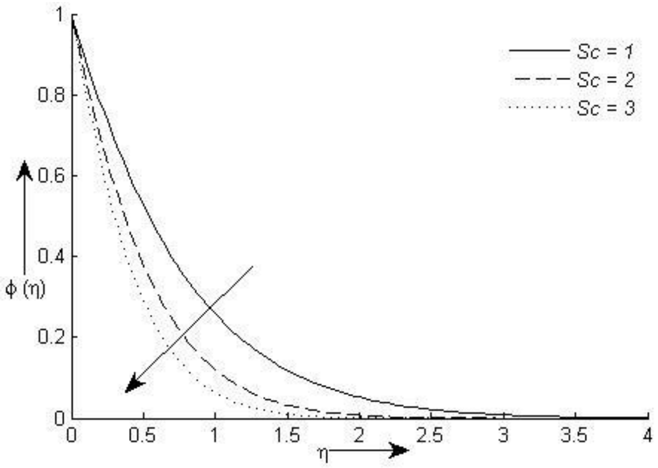

Fig. 8 Concentration for Sc

Figure 8 presents the variation in concentration profiles for different values of the Schmidt number (Sc). It is clearly observed from the figure that an increase in the Schmidt number leads to a noticeable decrease in the concentration distribution within the boundary layer.

Physically, the Schmidt number is a dimensionless parameter that represents the ratio of momentum diffusivity (kinematic viscosity) to mass diffusivity. A higher value of Sc indicates lower mass diffusivity relative to the momentum diffusivity of the fluid. As Sc increases, the capacity of the fluid to diffuse mass (or species) diminishes, thereby restricting the transport of concentration away from the surface. This reduced mass diffusivity causes a thinning of the concentration boundary layer and a corresponding decrease in concentration profiles throughout the domain.

The physical implication of this behaviour is significant in processes where precise control over mass transfer rates is required. For instance, in chemical engineering operations such as catalytic reactors, separation processes, and coating technologies, adjusting the Schmidt number through variation of fluid properties or operating conditions can regulate the diffusion rates of reactants or solutes. A higher Schmidt number can be used to limit the spread of species within the fluid, maintaining higher concentrations near the surface while suppressing diffusion into the bulk. Moreover, this trend is relevant in environmental and biological applications, including pollutant dispersion in air and water bodies, controlled drug delivery, and tissue engineering, where controlling the spread of solutes is essential for achieving desired outcomes.

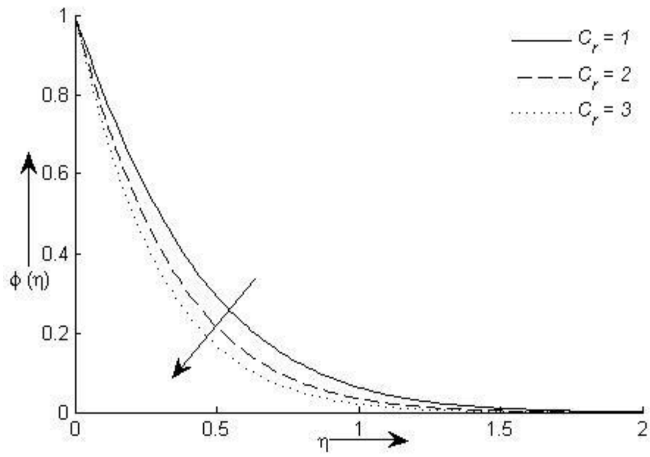

Fig. 9 Concentration for C_r

Figure 9 displays the variation in concentration profiles for different values of the chemical reaction parameter C_r. It is clear from the figure that as the chemical reaction parameter increases, the concentration of the species within the boundary layer decreases significantly.

The chemical reaction parameter C_r characterizes the rate of a homogeneous chemical reaction occurring within the fluid. A higher value of C_r indicates a more intense or rapid chemical reaction that consumes the reactive species. As the reaction rate increases, more solute is depleted from the fluid due to chemical transformation, leading to a reduction in the concentration of the species throughout the boundary layer.

Physically, this behaviour signifies that the reactive nature of the fluid plays a major role in mass transport phenomena. An increase in the reaction rate enhances the consumption of the diffusing species, thereby thinning the concentration boundary layer and reducing the overall solutal content in the system.

This observation has important implications in industrial and environmental processes where chemical reactions are coupled with convective-diffusive transport. For instance, in catalytic reactors, combustion systems, or pollutant degradation scenarios, controlling the chemical reaction rate directly influences the concentration profiles and, therefore, the efficiency of the process. Similarly, in biomedical and pharmaceutical applications, such as drug metabolism and biochemical transport in tissues, the effect of reaction kinetics on solute distribution is critical to system performance and safety.

IV.CONCLUSION

The present study is to find out numerical solution of MHD mixed convection of Casson fluid over a non-linear stretching sheet in a porous medium with chemical reaction and heat radiation. The RKF method has been applied to find out the impact of various physical conditions. The graph represents the performance of dimensionless velocity, temperature, and concentration profiles over the different dimensionless parameters. The important outline of this study is explained below:

- The velocity decreases with increases in β.
- The velocity decreases near the wall and increases away from the surface as nonlinearity increases.
- The concentration and temperature increase with an increase in Da
- The temperature increases with increasing the nonlinearity and radiation parameter.
- The concentration within the boundary layer decreases as Sc and C_r increases.

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