

Unsteady Radiative Magnetohydrodynamic Flow Over a Chemically Reacting Porous Stretching Plate Considering the Soret Effect

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Abstract: The analysis of unsteady MHD flow over a porous stretching plate is critical for various engineering applications, particularly in systems involving chemical reactions and thermal radiation. This study explores the novel effects of heat and mass transfer in a two-dimensional unsteady magnetohydrodynamic (MHD) flow. This present work examines the effects of radiation and a transverse magnetic field on a chemically reacting fluid flowing over a stretched plate. The unsteady nature of the flow is associated with the time-dependent variations in stretching/extending velocity, temperature, and fluid concentration. The nonlinear governing boundary layer partial differential equations (PDEs) are transformed into a set of nonlinear ordinary differential equations (ODEs) using a similarity transformation, which are then numerically solved using the MATLAB bvp4c method. The flow, heat, and concentration profiles are quantitatively analysed through graphs for various problem parameters, including the unsteadiness parameter (A), Hartmann number (M), porosity parameter (Sp), radiation parameter (N), chemical reaction parameter (K), Soret number (Sr), Eckert number (Ec), Schmidt number (Sc), and Prandtl number (Pr). Additionally, the skin friction coefficient, Nusselt number (Nu), and Sherwood number (Sh) are numerically addressed and illustrated using graphs.

Introduction

In magnetic hydrodynamics, fluid mechanics and electromagnetic forces interact. Several flows experience turbulence damping, modification, and suppression. A magnetic field can modify the flow patterns of semiconductor single crystals to ensure homogeneous composition. This appears to be the most promising application of MHD. Researchers are interested in unsteady MHD laminar flow with heat and mass transfer along a chemically reacting stretching sheet moving at different speeds in a porous medium because it has many uses in geophysics, astrophysics, chemical engineering, and electronics. At first, Saikaidis [1] created the flow field on a constant-speed surface. He then examined fluid flow on a continuous flat surface [2]. Crane [3] studied boundary layer flow and heat transfer of a viscous fluid conducting electricity across a stretched sheet. With a similarity solution class, Banks [4] proposed and explored boundary layer flow equations prompted merely by a stretched surface. Many researchers study transverse magnetic fields and radiation because many natural occurrences and technology issues need MHD analysis. An extended flat surface caused 3-D flow, as Wang [5] investigated. Wang [5] discovered the precise solution of the Navier-Stokes equations. In the solution, a stretched flat surface caused three-dimensional fluid motion. A transverse magnetic field affects viscoelastic flow over a stretched sheet, according to Andersson [6]. The regulating non-linear boundary layer equation's accurate analytical solution showed that viscoelasticity affects flow as much as a magnetic field. Elbashbeshy [7] researched sequel of suction and injection on heat transmission across a stretched surface with varying and

homogeneous heat flux. Andersson et al. [8] studied liquid film heat transfer across a horizontal sheet. Ghaly [9], Raptis et al. [10] researched the radiation effect on MHD flow.

Using Homotopy perturbation, Ariel et al. [11] examined how axisymmetric stretching affects boundary layer flows. Elbashbeshy et al. [12] researched that heat source causes incompressible fluid to flow in an unstable boundary layer over a stretched surface. As time dependence of heat flux and surface expansion velocity, flow and temperature fields become unstable. Ahmad [13] examined heat transfer and boundary layer flow via a changing thermal conductivity plate. Ishak [14] studied heat transport and unsteady MHD laminar flow across a stretched plate. Ishak [15], and others examined heat radiation's impact on MHD flow issues on stretched sheets. A curved stretching/shrinking surface caused unstable viscous flow, according to Rosca et al. [16]. Choudhary et al. [17] looked at an unsteady two-dimensional flow over a stretched permeable surface of an electrically conducting fluid that is viscous and can't be compressed. They considered a constant strength transverse magnetic field. Beyond Ishak's work, Jhankal et al. [18] considered stretching plate in a porous material. Siri et al. [19] studied warmth transmission across a stretched surface under suction. The source effect and MHD flow over a vertical sheet were examined by Alarifi et al. [20]. Megahed et al. [21] studied MHD fluid flow along a stretched sheet in a porous medium, thermal radiation, and variable heat flux induces. Using a stretched cylinder, Reddy et al. [22] examined sequel of porous medium in MHD heat transfer fluid flow. Recently, Sarma and Sarma [23] researched on the flow of gyrotactic microorganisms in MHD flow.

The main novelty of this paper is to examine the unsteady flow of a chemically reacting fluid over a porous stretching plate, considering the Soret effect. The study aims to enhance our understanding of how magnetic fields, heat radiation, chemical processes, and species transport influence heat and mass transfer in fluids. The objective is to create a comprehensive mathematical model for the transient MHD flow over a porous stretching plate, incorporating thermal radiation, chemical reactions, and the Soret effect. To the best of the author's knowledge, no one has previously examined the combined effects of heat radiation, magnetic fields, the Soret effect, and chemical reactions using the boundary conditions utilized in this paper. Furthermore, since just a mild magnetic field is being considered, the Hall effect is not taken into consideration. Following the application of the similarity transformation, MATLAB bvp4c is used to create and solve nonlinear ordinary differential equations (ODEs) numerically. When compared to previous studies, the current results are also regarded as being rather excellent.

Mathematical Formulation

A 2-D MHD flow with an unstable, laminar boundary layer that goes over a porous, chemically reacting stretching plate that is exposed to heat radiation. The fluid is an incompressible, viscous fluid that conducts electricity. The external fluid's polarization of charges and Hall effect are disregarded. A transverse magnetic field B_0 is applied externally perpendicular to the x-axis in the direction of the positive z-axis. The direction of the stretching plate is taken as the x-axis and its perpendicular as the z-axis. The surface is extended with velocity $U_w = \frac{ax}{1-et}$ along x-axis, fixing the origin as shown in Fig. 1.

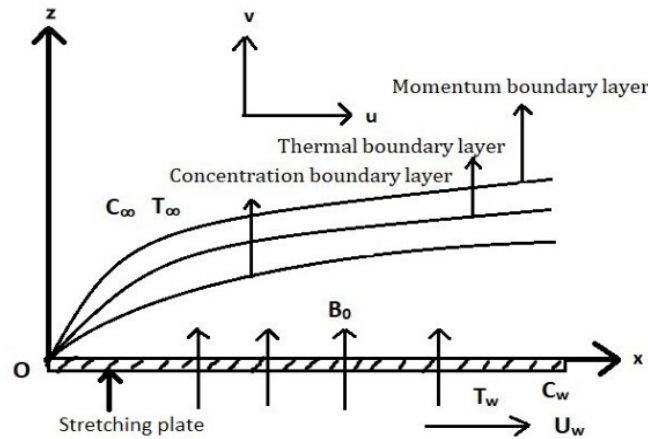


Fig.1. Graphical representation of the flow.

Using these criterion and Boussinesq's approximation, governing equations of continuity, momentum, energy and species concentration are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial z} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial z} = \nu \frac{\partial^2 u}{\partial z^2} - \frac{\sigma_e B_0^2 u}{\rho} - \frac{\nu u}{k_0} \quad (2)$$

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial z} = \alpha \frac{\partial^2 T}{\partial z^2} + \frac{\sigma_e B_0^2 u^2}{\rho c_p} - \frac{1}{\rho c_p} \frac{\partial q_r}{\partial z} \quad (3)$$

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial z} = D_M \frac{\partial^2 C}{\partial z^2} - K^*(C - C_\infty) + D_T \frac{\partial^2 T}{\partial z^2} \quad (4)$$

due to boundary circumstances [14]:

$$z = 0: \quad u = U_w, \quad v = 0, \quad T = T_w, \quad C = C_w \quad \text{and} \quad (5)$$

$$z \rightarrow \infty: \quad u \rightarrow 0, \quad T \rightarrow T_\infty, \quad C \rightarrow C_\infty \quad (6)$$

q_r [15] is described as follows

$$q_r = -\frac{4\sigma_1}{3k_1} \frac{\partial T^4}{\partial z} \quad (7)$$

where σ_1 indicates Stefan-Boltzmann constant and k_1 represents Rosseland mean absorption coefficient.

Assuming internal flow temperature difference is negligible, T^4 can be shown by Taylor series expansion about T_∞ , while disregarding higher-order phrases as,

$$T^4 = 4T_\infty^3 T - 3T_\infty^4 \quad (8)$$

Assuming, stretching velocity $U_w(x, t)$, surface temperature and concentration as $T_w(x, t)$ and $C_w(x, t)$:

$$U_w = \frac{ax}{1-et}, \quad T_w = T_\infty + \frac{bx}{1-et}, \quad C_w = C_\infty + \frac{dx}{1-et} \quad (9)$$

With stream function ψ such that $u = \psi_z$ and $v = -\psi_x$, the continuity equation (1) is attained.

The similarity variables and nondimensional quantities below translate the nonlinear PDEs Eq. 2-Eq. 4 into nonlinear ODEs:

$$\eta = \sqrt{\frac{a}{v(1-et)}}z, \quad \psi = \sqrt{\frac{av}{(1-et)}}f(\eta)x, \quad \theta(x) = \frac{T - T_\infty}{T_w - T_\infty}$$

$$\phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty}, A = \frac{e}{a}, M = \frac{\sigma_e B_0^2(1-et)}{\rho a}, S_p = \frac{v(1-et)}{k_0 a},$$

$$Ec = \frac{a^2 x}{b C_p(1-et)}, Sc = \frac{v}{D_M}, \alpha = \frac{\kappa}{\rho C_p}, K = \frac{K^*(1-et)}{a},$$

$$Sr = \frac{D_T(T_w - T_\infty)}{D_M(C_w - C_\infty)}, N = \frac{\kappa k_1}{4\sigma_1 T_\infty^3}, \lambda = \frac{4 + 3N}{3N}, Pr = \frac{\mu C_p}{\kappa}$$

The translated nonlinear ODEs are:

$$f''' + ff'' - f'^2 - Mf' - S_p f' - A\left(f' + \frac{1}{2}\eta f''\right) = 0 \quad (10)$$

$$\frac{\lambda}{Pr}\theta'' + MEcf'^2 + f\theta' - \theta f' - A\left(\theta + \frac{1}{2}\eta\theta'\right) = 0 \quad (11)$$

$$\phi'' + Sr\theta'' - ScK\phi + Scf\phi' - Sc\phi f' - ScA\left(\phi + \frac{1}{2}\eta\phi'\right) = 0 \quad (12)$$

Also, modified initial and boundary circumstances are:

$$f(0) = 0, f'(0) = 1, \theta(0) = 1, \phi(0) = 1 \text{ and} \quad (13)$$

$$f'(\infty) \rightarrow 0, \theta(\infty) \rightarrow 0, \phi(\infty) \rightarrow 0 \quad (14)$$

The coefficient of skin friction (τ), the Nusselt number (Nu), and the Sherwood number (Sh) are all stated in their non-dimensional forms.

$$Re_x^{\frac{1}{2}} C_f = f''(0), Re_x^{-\frac{1}{2}} Nu_x = -\theta'(0) \text{ and } Re_x^{-\frac{1}{2}} Sh_x = -\phi'(0) \quad (15)$$

Method of Solution

The MATLAB solver bvp4c performs the evaluation of linear or nonlinear boundary value systems. This method is algorithm-based and differs from the shooting method. Using the boundary conditions into consideration at each step, it can efficiently calculate the approximate value of $z(x)$ for every x in $[a, b]$. This method exchanges boundary conditions at ∞ for those at a location that logically resolves the problem at hand. The finite difference-based solver bvp4c transforms Eqs. 10,11,12 as follows:

$$f = z_1, f' = z_1' = z_2, f'' = z_2' = z_3, \theta = z_4, \theta' = z_4' = z_5, \phi = z_6, \phi' = z_6' = z_7 \quad (16)$$

$$z_3' = -z_1 z_3 + z_2^2 + M z_2 + S_p z_2 + A\left(z_2 + \frac{1}{2}\eta z_3\right) \quad (17)$$

$$z_5' = \frac{Pr}{\lambda} \left[-MEcz_2^2 - z_1z_5 + z_4z_2 + A \left(z_4 + \frac{1}{2}\eta z_5 \right) \right] \quad (18)$$

$$z_7' = -Sr z_5' + Sc \left[Kz_6 - z_1z_7 + z_6z_2 + A \left(z_6 + \frac{1}{2}\eta z_7 \right) \right] \quad (19)$$

Also, initial and boundary circumstances Eq. 13 and Eqn. 14 are translated as described:

$$z_1(0) = 0, z_2(0) = 1, z_4(0) = 1, z_6(0) = 1 \quad (20)$$

$$z_2(\infty) = 0, z_4(\infty) = 0, z_6(\infty) = 0 \quad (21)$$

MATLAB solver bvp4c computes the converted results numerically.

Validation

This work's procedure is accurate and precise, as shown in Table 1. The bvp4c approach is utilised to validate the results of Ishak [15] by disregarding A, M, Sp, Ec, Sr, Sc, and K and taking $N_1 = 1/N$. The present investigation's computed findings are identical to the preceding outcome, demonstrating that the technique is dependable.

Table 1. Comparison with Ishak's [15] earlier outcomes.

N_1	M	Pr	$\theta'(0)$ Ishak (2011)	$\theta'(0)$ Present result
0	0	1	-0.9458	-0.9458
		2	-1.4715	-1.4715
		3	-1.8691	-1.8691
1	1	1	-0.8611	-0.8611
	0	1	-0.5312	-0.5312

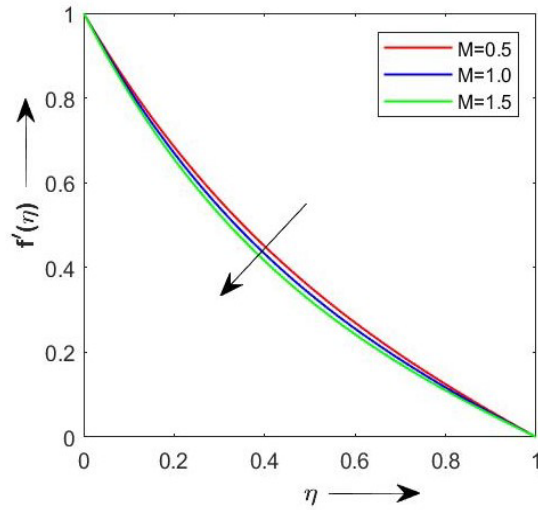
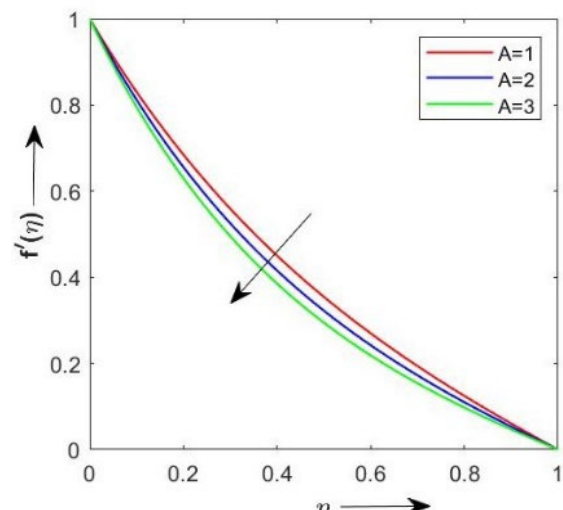
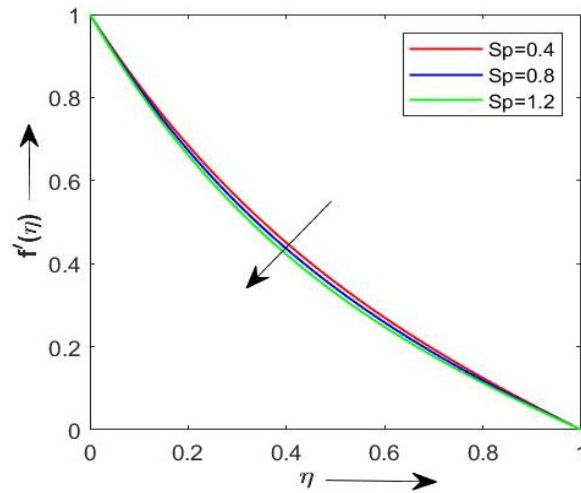
Additionally, Table 2 provides a verified illustration of the precision and correctness of the methodology used in this work. To compare the findings of Nazari et al. [24], Ismail et al. [25], and Sarma and Sarma [26] with the modification of Pr, the bvp4c approach is used in this instance by disregarding M, Ec, K, Sp, A, and Sc and using $\lambda=1$. The process is dependable since the computed results of the current research are the same as the previous result.

Table 2. Comparison with earlier findings of Nazari et al. [24], Ismail et al. [25], Sarma and Sarma [26].

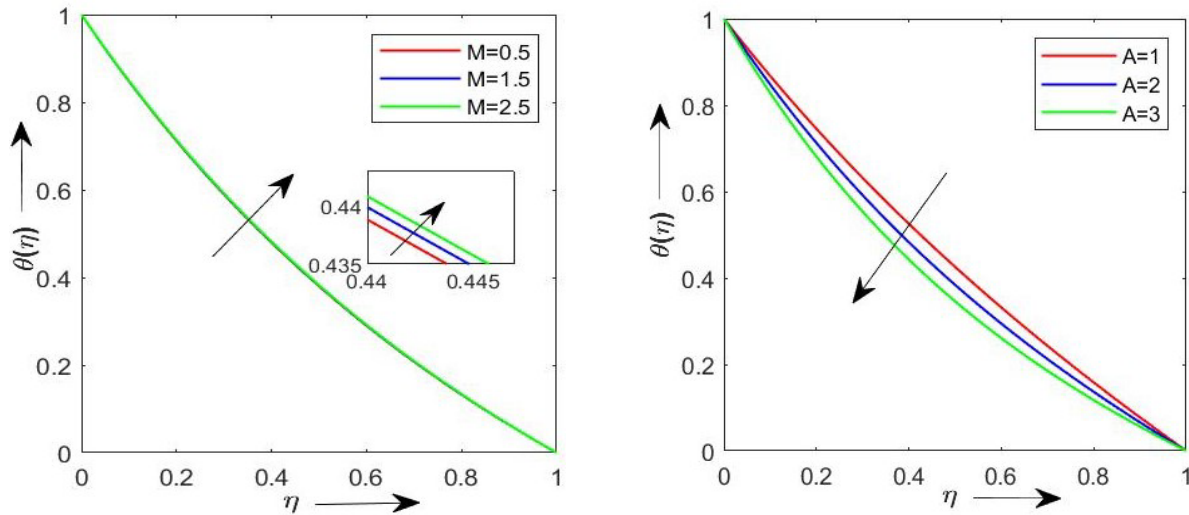
Pr	$\theta'(0)$ (Nazari et al., 2018)	$\theta'(0)$ (Ismail et al., 2021)	$\theta'(0)$ (Sarma and Sarma, 2024)	$\theta'(0)$ (Present result)
1	-0.9547	-0.9548	-0.9548	-0.9548
2	-1.4714	-1.4715	-1.4715	-1.4715
3	-1.8691	-1.8691	-1.8691	-1.8691

Results and Discussions

Using the above assumptions, the problem can be solved numerically, and the graphs in Figs. 2-15 show how velocity, temperature, and concentration change for several parameters such as A, N, Ec, Pr, Sr, Sc, M, SP, and K, while the other parameters are constant.

(a) Velocity profile with the variation of M .(b) Velocity profile with the variation of A .(c) Velocity profile with the variation of S_p .**Fig. 2.**

Figures 2 (a), (b) and (c) shows the flow variation with M , A , and S_p values. The velocity profile falls as M and A rises and progressively as S_p rises. As the surface distance increases, we observe a decrease in velocity, reaching the boundary condition at ∞ . Negative τ values cause the solid surface to provide a drag force on the fluid. Drag constantly hinders fluid flow. As S_p increases, the velocity profile drops, allowing for pure Darcy flow.



(a) Temperature profile with the variation of M . (b) Temperature profile with the variation of A .

Fig. 3.

Figure 3 (a) and (b) show the temperature profile fluctuations for M and A . As M and A change, temperatures rise and fall. The Lorentz force created by the magnetic field pushes against the flow of the fluid, which causes more viscous loss. The temperature rises near the stretching sheet because of this extra loss, which turns motion energy into heat. Also, when the unsteady goes up, it means that the effects change more quickly over time, which usually speeds up the flow and makes the thermal boundary layer thinner. This makes it easier for heat to move away from the sheet through convection, which lowers the temperature profile.

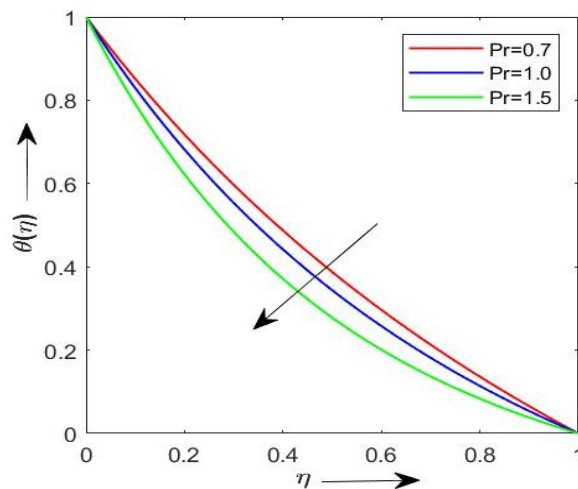


Fig. 4. Temperature profile with the variation of Pr .

Figure 4 shows Pr 's temperature impact. Increasing Pr lowers temperature, demonstrating a link between velocity and thermal boundary layer thickness. Thermal diffusivity dominates, and for large Pr values, the thermal boundary layer is narrower than the velocity boundary layer. As the distance from the surface increases, the temperature drops to zero in the zone of unrestricted stream flow.

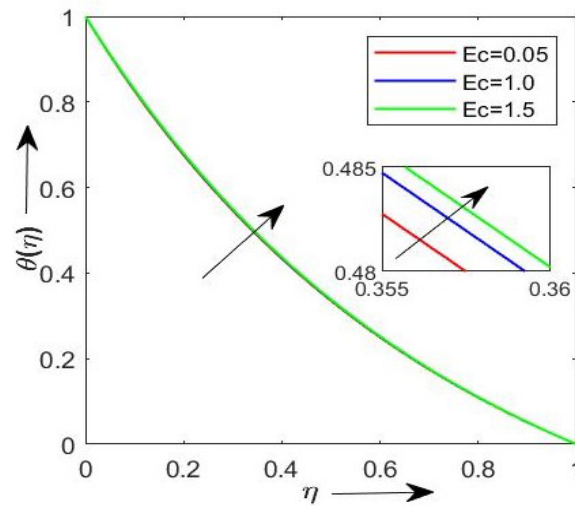


Fig. 5. Temperature profile with the variation of Ec .

Figure 5 shows the Eckert number (Ec)'s sequel on heat profiles. As Eckert number grows, fluid temperature rises, indicating a decrease in enthalpy and a rise in kinetic energy.

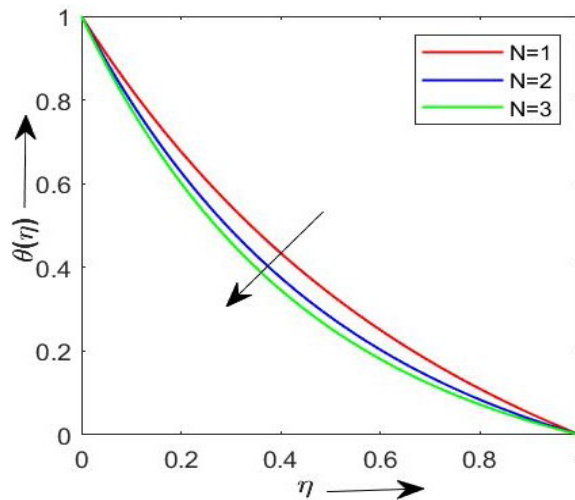


Fig. 6. Temperature profile with the variation of N .

Figure 6 demonstrates the influence of N on temperature. It is discovered that as N escalates, the fluid's temperature lowers. The system loses more heat through radiative transfer as N goes up. This lowers the thermal energy near the stretching sheet. As a result, the temperature profile drops and the thermal boundary layer gets thinner because of this better heat escape.

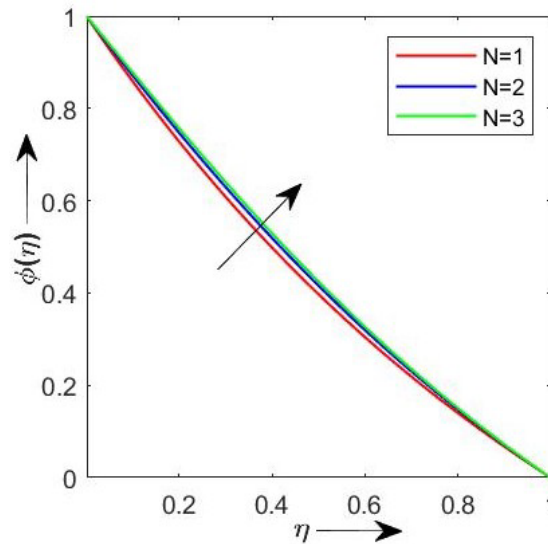
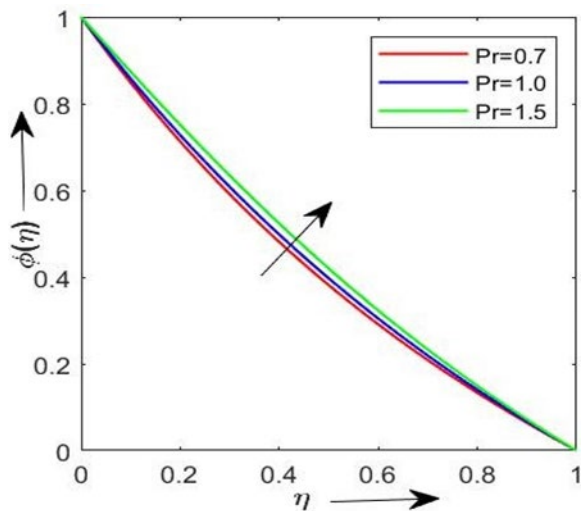
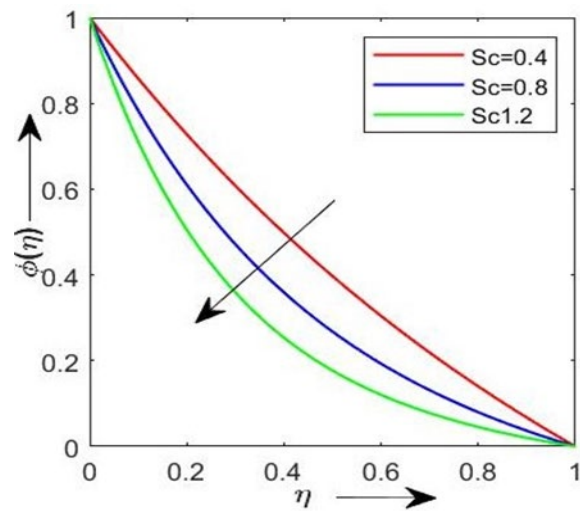


Fig. 7. Concentration Profile with the variation of N .

Figure 7 demonstrates the sequel of N on concentration. As N grows, fluid concentration increases, increasing concentration boundary layer thickness. As the radiation parameter goes up, the temperature drops near the stretching sheet. This slows down the rate of thermal diffusion, which can indirectly speed up mass transfer by lowering thermal gradients. This lets the concentration profile get higher because the spread of species is stronger than the effects of temperature.



(a) Concentration profile with the variation of Pr .



(b) Concentration profile with the variation of Sc .

Fig. 8.

Figure 8(a) and (b) demonstrates the sequel of Pr and Sc respectively on the concentration profiles. As Pr escalates, fluid's concentration escalates and decreases with the increase in Sc . It represents the relative thickness of velocity boundary layer compared to solute boundary layer. Since the concentration profile shrinks as the Schmidt number rises, this suggests that velocity boundary layer is wider than concentration boundary layer.

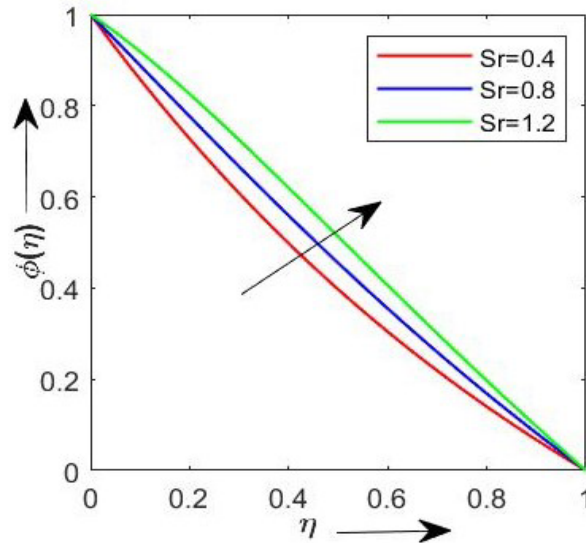
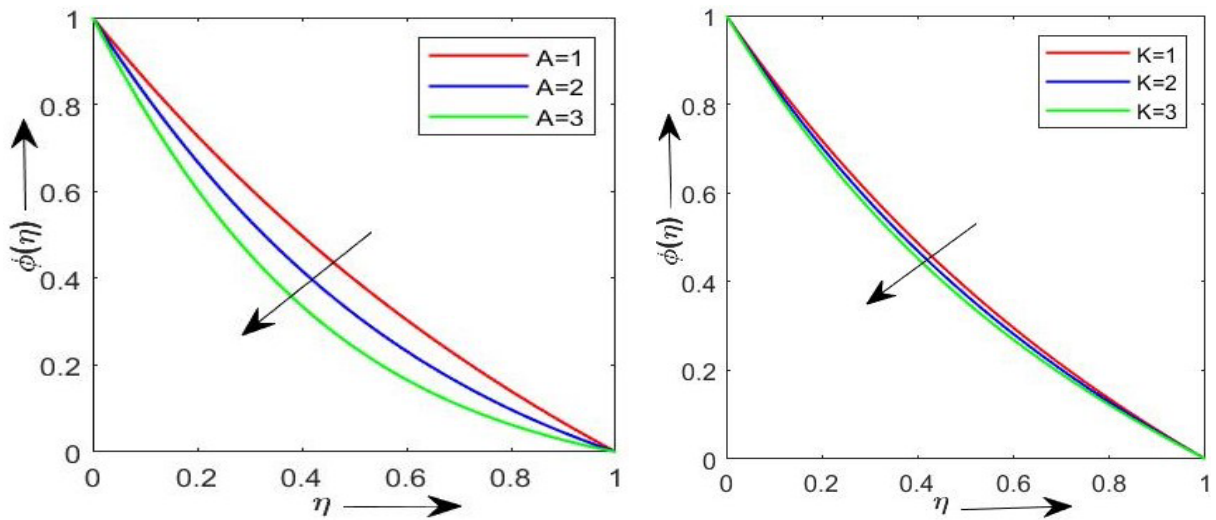


Fig. 9. Concentration profile with the variation of Sr .

Sr 's effect on concentration profiles is demonstrated in Figure 9. The fluid concentration escalates as Sr escalates. When the Soret number goes up, thermophoresis takes over more, moving solute particles from areas with high temperatures to areas with low temperatures. As a result, more solutes gather near the stretching sheet, which raises the concentration profile.



(a) Concentration profile with the variation of A .

(b) Concentration profile with the variation of K .

Fig. 10.

Figure 10 (a) and (b) depicts the sequel of A and K on concentration profiles. It is shown that as A and K levels rise, respectively, the fluid's concentration drops. The concentration of the fluid declines because a rise in K , quickly absorbs the chemical compounds contained in the fluid.

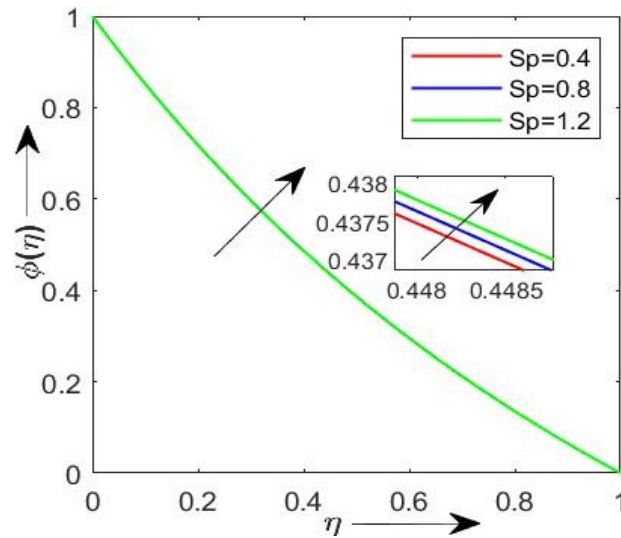


Fig. 11. Concentration profile with the variation of Sp .

Figure 11 demonstrates the fluctuation of the concentration profile with regard to varying values of Sp . The concentration profile is seen to escalate gradually as Sp increases. This results from the notion that increased viscosity will slow down fluid flow, causing a progressive acceleration of concentration.

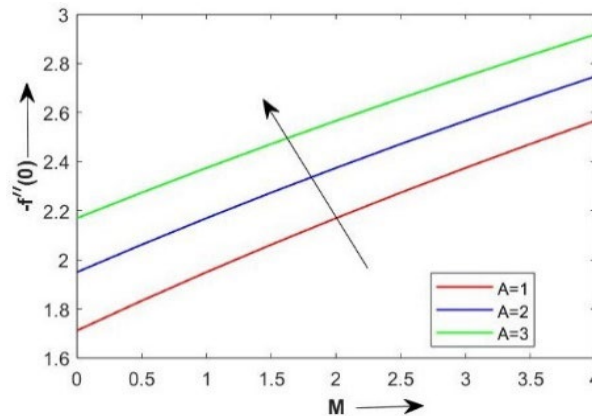
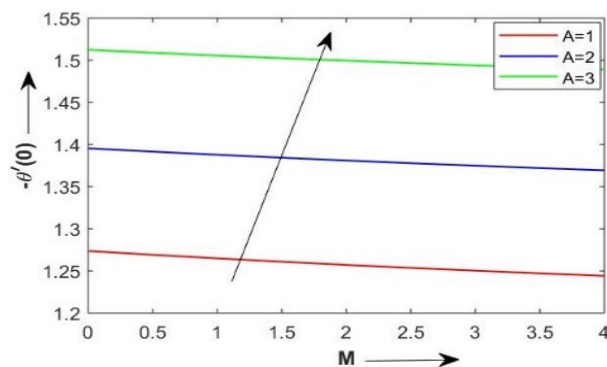
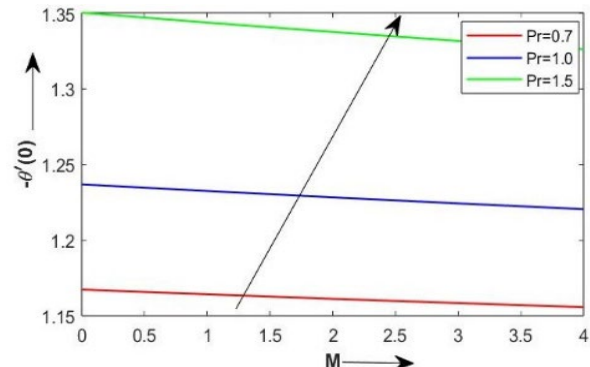


Fig. 12. Skin Friction (τ) with the alteration of M for different values of A .



(a) Nu with the alteration of M for distinct values of A .



(b) Nu with the alteration of M for distinct values of Pr .

Fig. 13.

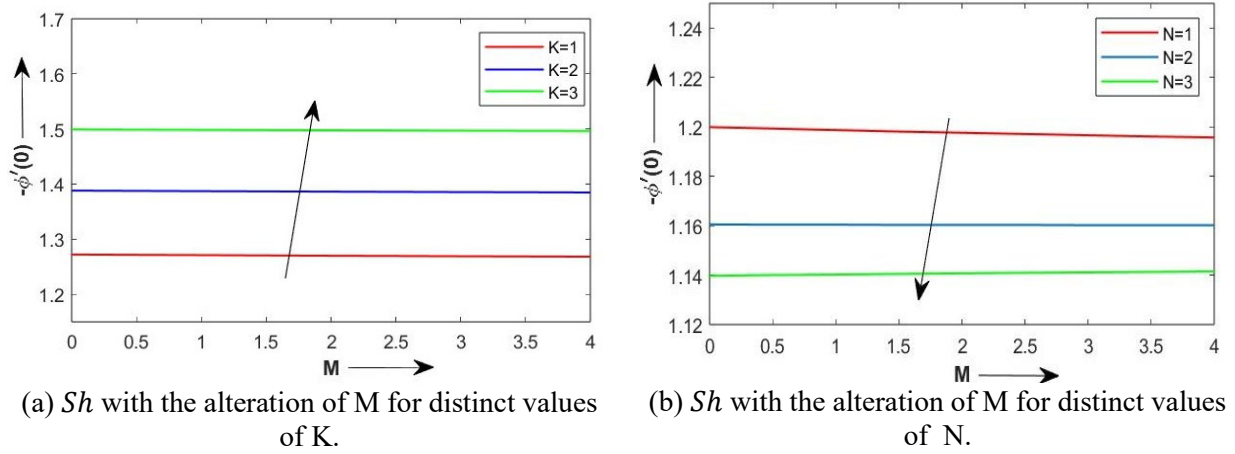


Fig. 14.

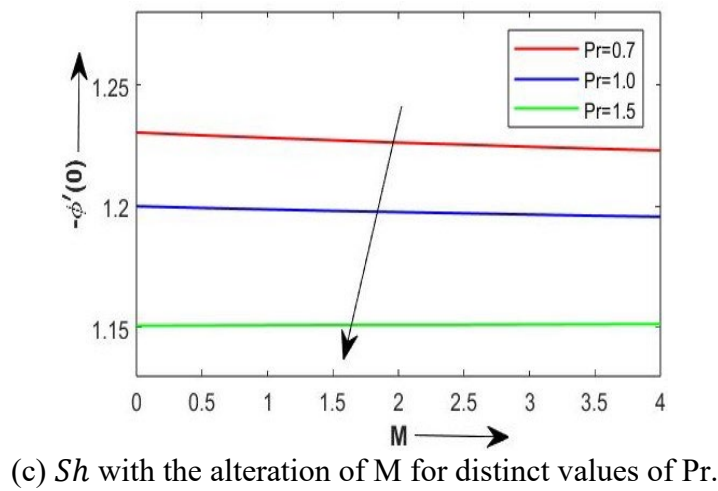
Fig. 15. Sh with the alteration of K for distinct values of A .

Figure 12 indicates that Skin friction (τ) escalates with the rise of M and A . Figure 13 (a) and (b) shows that Nu escalates with rise of A & Pr , but declines with the rise of M . As Pr rises, thermal diffusivity falls, slowing heat diffusion from heated surfaces and, as a result, raising the surface temperature gradient. Sequel of Sherwood number (Sh) against M for numerous values of K , N , Pr are demonstrated in Figure 14 (a), (b) & (c). Also, it is seen that with the rise of K , Sh increases as shown in Fig. 20 and with the rise in N and Pr , Sh decreases. While Sh decreases with the rise of M , and escalates with the rise in K as shown in Figure 15. Figure 15 also indicates that with the rise in A , Sh escalates.

Conclusion

In this study, a thorough examination of unsteady magnetohydrodynamic (MHD) boundary layer fluid flow of a chemically reacting fluid over a porous stretching sheet, taking into account the Soret effect. The main conclusions are as follows:

1. As the Hartmann number (M), unstable parameter (A), and porosity parameter (Sp) increase, the surface velocity profile decreases.
2. When M and Ec increase, the surface temperature rises. An increase in the Prandtl number (Pr) leads to a decrease in temperature.
3. The surface temperature falls as the radiation parameter (N) and unstable parameter (A) increase. With the rise in A , mass transfer coefficients K and Schmidt number (Sc) cause a decrease in the surface concentration of the fluid.
4. Conversely, as N , Sp , Sr , and Pr increase, the fluid's concentration also increases.
5. An increase in A result in higher values of skin friction (τ), Nusselt number (Nu), and Sherwood number (Sh).
6. When Pr rises, the magnitude of Nu increases while Sh decreases.
7. An increase in the Hartmann number (M) raises the skin friction coefficient (τ) but decreases both Nu and Sh .
8. The magnitude of Sherwood number increases with a rise in K .
9. As N and K increase, Sherwood number decreases and increases, respectively.

Future research should focus on how it relates to activation energy and entropy generation. Expanding this study to a three-dimensional flow problem and examining the various flow effects for non-Newtonian fluids, such as Maxwell, Carreau, and Williamson fluids, is another possibility. Furthermore, since just a mild magnetic field is being studied in this study, the hall effect is not taken into consideration. The consequences of hall effect can also be examined in the near future.

Nomenclature

a, b, e, d	Constant
B_0	Constant Magnetic field, (Nm/A)
A	Unsteady parameter, (e/a)
K^*	Rate of first order chemical reaction,
f	Dimensionless stream function,
Ec	Eckert number,
q_r	radiative heat flux, ($\frac{W}{m^2}$)
k_0	Permeability of porous medium, (m^2)
C_p	Specific heat at constant pressure, ($\frac{J}{kgK}$)
k_1	Absorption coefficient,
M	Magnetic parameter (Hartmann number),
Pr	Prandtl number,
Sp	Porosity parameter,
N	Radiation parameter,
D_M	Coefficient of molecular diffusivity,
D_T	Coefficient of thermal diffusivity,
Sc	Schmidt number,

Sr	Soret number,
Nu	Nusselt number,
K	Chemical reaction parameter
t	Dimensionless time, (K)
T	fluid's temperature, (K)
C	Species concentration, (kg/m ³)
u	fluid's velocity through x-axis, (m/s)
v	fluid's velocity through z-axis, (m/s)
(x,z)	Cartesian coordinates

Greek Symbols

ρ	fluid's density, (kg/m ³)
μ	fluid's viscosity, (Pa s)
σ_e	Electrical conductivity, ($\frac{1}{\Omega m}$)
η	Dimensionless similarity variable,
ν	Kinematic viscosity, (m ² /s)
κ	Thermal conductivity, ($\frac{W}{mK}$)
α	Thermal diffusivity, (m ² /s)
ψ	Stream function,
τ	Skin friction,
θ	Dimensionless temperature,
ϕ	Dimensionless concentration

Superscript

'	Derivative w.r.t η
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Subscript

w	Properties at the plate
∞	Free stream condition

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