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MASS TRANSFER AND MHD FREE CONVECTION FLOW ACROSS A STRETCHING SHEET WITH A HEAT SOURCE AND CHEMICAL REACTION

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This work examines mass transfer and MHD free convective flow across a stretching sheet in the presence of a heat source and a chemical reaction. The sheet's stretching action propels the flow, while a magnetic field applied perpendicular to the flow direction influences it. The effects of gradients in temperature and concentration on buoyant forces are also taken into account. The continuity, momentum, energy, and concentration equations are among the coupled nonlinear partial differential equations that regulate the system. Similarity transformations are used to convert these equations into a system of ordinary differential equations, which are then numerically solved using bvp4c techniques. In this investigation, magnetic, buoyancy, chemical reaction rate, and heat source factors are the main parameters of interest. The outcomes show the influence of these parameters on the boundary layer's temperature, concentration, and velocity profiles. To quantify the mass transfer rate, heat transfer rate, and shear stress at the sheet surface, the skin friction coefficient, Nusselt number, and Sherwood number are calculated. By manipulating the magnetic field, chemical reactions, and heat generation, the work offers important new insights into how to best utilise MHD flows in industrial processes, such as polymer manufacturing, chemical reactors, and cooling systems.
Keywords: *MHD; Stretching Surface; Heat source; Chemical reaction; bvp4c*
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INTRODUCTION

An intricate and crucial subject in fluid mechanics, especially for industrial and engineering applications, is the study of magnetohydrodynamic (MHD) free convective flow and mass transfer over a stretching sheet with a chemical reaction and heat source. Heat transfer, chemical processes, magnetic fields, fluid dynamics, and heat transfer are all intricately entwined in the study of MHD free convective flow and mass transfer across a stretching sheet and with a heat source [20-21]. These studies' main goal is to comprehend how these variables affect flow and transfer characteristics, which can help create industrial processes that are more productive and efficient. Improved heat and mass transfer rates, flow separation control, and overall engineering system performance are all aided by this research.

Stretching sheets are surfaces that extend in a specific direction and are frequently modelled as moving with either a linear or nonlinear velocity. Owing to its applications in industrial operations including metal processing, polymer extrusion, and electronic device cooling, the study of fluid flow over a stretching sheet is a significant problem in fluid mechanics [4-5]. When comparing the analysis of fluid flow across a stretching sheet with slip conditions to the traditional no-slip boundary condition, more intricacy is added. Where the premise of no-slide may not hold true, slip conditions are crucial to understanding different types of micro- and nanoscale fluxes [14-16]. Double stratification's impact on heat transmission and magnetohydrodynamic (MHD) Williamson fluid boundary layer flow over a stretching or contracting sheet submerged in a porous medium is a complicated topic with important implications in a range of industrial and technical operations [17-18]. It is a crucial procedure to investigate how radiation affects flow and heat transfer across an unstable, stretched sheet. The interplay of radiative heat transfer, fluid flow, and heat transfer in the boundary layer that forms over a stretching sheet whose velocity varies with time is the subject of the problem [23].

A fluid's density, viscosity, and electrical conductivity can all change as a result of a chemical reaction occurring within it. The heat source and chemical kinetics may be coupled if the reaction rate is temperature-dependent. It is examined how a chemical reaction magnetohydrodynamics (MHD) viscous fluid flows steadily over a two-dimensional boundary layer with suction and injection over a diminishing sheet by Y. Khan [2]. Mahabaleshwar et al [12] studied the influence of a magnetic field on mixed convection heat transfer through Casson fluid flow across a porous material when thermo-diffusion mechanisms involving carbon nanotubes are present. Examining the interaction between molecules and the dissipation of viscosity in MHD convection flow across an infinite vertical plate embedded in a porous material using the Soret effect by Goud et al [19]. The temperature distribution inside the fluid is impacted by the presence of a heat source. This in turn may affect the fluid's electrical conductivity, density (by thermal expansion), and pace of chemical reaction [3]. K. Raghunath et al [7] examine the effects of radiation absorption and thermos diffusion on an unsteady magnetohydrodynamic flow past a moving plate that is infinitely vertical and permeable while thermal radiation, heat absorption, and a homogenous chemical reaction are present and the suction is varied. The steady free convection of an electrically conducting viscous and incompressible fluid in the coexistence of magnetic and suction/injection parameters

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is studied in a vertically oriented porous channel with a line/point heat source/sink (point/line heat generation/absorption) at various channel positions by Jha et al [8]. Ramudu [9] investigates how a constant convective magnetohydrodynamic shear-thickening liquid stream across a vertically extended sheet is affected by viscous dissipation stimuli.

Studying the movement of a species (solute) inside a fluid is known as mass transfer in the context of MHD free convective flow over a stretching sheet with a chemical reaction and heat source. Reaction kinetics, convection, and diffusion all work together to control this process. Applications in industrial and technical processes, such as material processing, chemical reactors, and cooling systems, require a thorough understanding of these interactions. The behaviour of the concentration, temperature, and flow fields under different circumstances can be predicted by numerically solving these equations [1]. Aspects of mass and heat transport in MHD flow across an exponentially stretched sheet involving chemical reactions was studied by Paul and Das [13]. In the presence of a steady transverse magnetic field, the impact of a chemical reaction on the free convective flow and mass transfer of a viscous, incompressible, and electrically conducting fluid over a stretching surface is examined by Afify [22].

The novelty of this study is that it looks into 2D, steady flow, heat and mass transfer over a stretched sheet that has a heat source and a chemical process going on. According to the author's best knowledge, no researcher has earlier studied the combined effects of heat source and chemical reaction with the boundary conditions used in this article. Additionally, the hall effect is not taken into account since only a weak magnetic field is being addressed. To do the analysis, we usually have to solve a set of linked partial differential equations that control the flow, concentration, and temperature of the fluid while taking magnetic fields, gravity, chemical processes, and heat generation into account. Additionally, the new findings are thought to be pretty good when compared to earlier research.

MATHEMATICAL FORMULATION

We examine the mass transfer and steady free convective flow of an electrically conducting, viscous, and incompressible fluid across a stretching sheet. The sheet is being stretched at a rate proportionate to the distance from the fixed origin, x=0, by applying two equal and opposing forces along the x-axis. Figure 1 illustrates the imposition of the uniform transverse magnetic field Bo along the they-axis. There is very little magnetic field created by the electrically conductive fluid moving. For tiny magnetic Reynolds numbers, this assumption is correct. Additionally, it is believed that there is no external electric field and that the electric field created by charge polarisation is very small. Neglect is given to the pressure gradient and viscous dissipations. Viscous dissipations and the pressure gradient are disregarded. It is believed that the species concentration and temperature will disappear far away from the sheet and are kept at specified constant values, T_w and C_w.

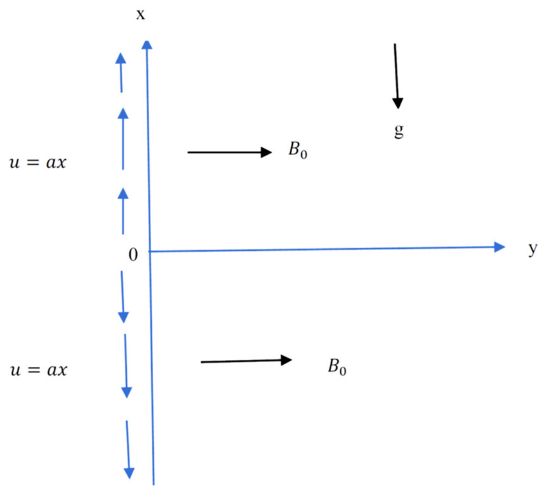

Figure 1. Coordinate system and Physical model of the problem

With the Boussinesq approximation and these presumptions in place, the governing equations for the laminar boundary layer flow's continuity, motion, energy, and species diffusion are as follows:

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = v\frac{\partial^2 u}{\partial y^2} + g\beta T + g\beta^* C - \frac{\sigma B_0^2}{\rho}u, \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho C_P}\frac{\partial^2 T}{\partial y^2} + \frac{Q}{\rho C_P}T, \tag{3}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} - k_0 C^n. \tag{4}$$

The boundary conditions are

$$u(x,0) = ax,\ v(x,0) = 0,\ T(x,0) = constant = T_w,\ C(x,0) = constant = C_w \tag{5}$$

$$u(x,\infty) = 0,\ \ T(x,\infty) = 0,\quad C(x,\infty) = 0. \tag{6}$$

Steam function is:

$$u = \frac{\partial \psi}{\partial y},\ v = -\frac{\partial \psi}{\partial x}. \tag{7}$$

Similarity transformations are:

$$\psi(x,y) = (av)^{\frac{1}{2}} x f(\eta),\quad \eta = \left(\frac{a}{v}\right)^{\frac{1}{2}} y,\quad \theta = \frac{T}{T_w},\quad \phi = \frac{C}{C_w}. \tag{8}$$

The non-dimensional equations are:

$$f''' + ff'' - f'^2 + Gr\theta + Gc\phi - M^2 f' = 0, \tag{9}$$

$$\theta'' + Prf\theta' - PrS\theta = 0, \tag{10}$$

$$\phi'' + Sc(f\phi' - \gamma\phi^n) = 0. \tag{11}$$

Boundary conditions are:

$$f(0) = 0,\quad f'(0) = 1,\quad \theta(0) = 1,\quad \phi(0) = 1 \quad \text{at } \eta = 0, \tag{12}$$

$$f'(\infty) = 0,\quad \theta(\infty) = 0,\quad \phi(\infty) = 0 \quad \text{at } \eta \to \infty. \tag{13}$$

Solution Method

The dimensionless quantities are used to convert the equations (1) to (4) with boundary conditions (5) to (6) into non-dimensional equations (9) to (11) with boundary conditions (12) to (13) that may then be solved in MATLAB using the BVP4C method. Numerical values for the fluid's temperature, velocity, and species concentration can also be found using this method. Analysis is also done on the different skin friction, Nusselt, and Sherwood numbers.

RESULTS AND DISCUSSION

The paper provides a thorough examination of how different parameters affect mass transfer and MHD free convective flow across a stretching sheet that has a heat source and a chemical reaction. By improving our knowledge of the intricate relationships between mass transfer across a stretching sheet and MHD free convective flow, this research will help build more effective and regulated industrial and chemical processing methods. Below is a discussion of the various impacts of these distinct parameters.

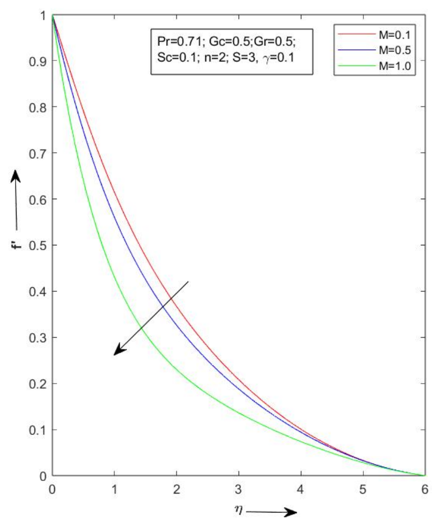

Figure 2. Velocity variation for M

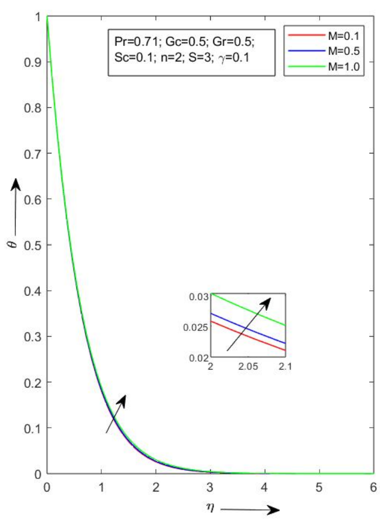

Figure 3. Temperature variation for M

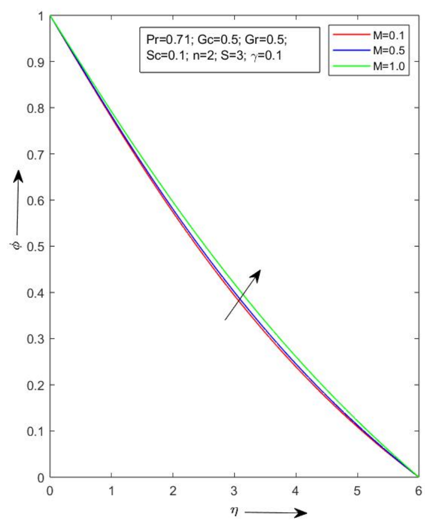

Figure 4. Concentration variation for M

Figures 2-4 illustrate how various fluid distributions vary in relation to the magnetic parameter. With increasing M, the temperature and fluid concentration will rise while the velocity will fall. Increases in M also result in increases in the Lorentz force opposing the flow, which accelerates the flow's deceleration. The fluctuation of various fluid distributions for the Prandtl number is shown in Figures 5-7.

With an increase in Pr, the fluid's concentration will rise, but its velocity and temperature will fall. In comparison to thermal diffusivity, momentum diffusivity becomes increasingly prominent as the Prandtl number rises. The velocity profile close to the shrinking sheet decreases as a result of the thinner velocity barrier layer. A rise in the Prandtl number signifies a comparatively low thermal diffusivity. As a result, there is a thinner thermal barrier layer and a lower temperature profile due to less effective heat conduction. As the thermal boundary layer gets thinner in concentration profiles, an increase in the Prandtl number may cause the concentration boundary layer to get bigger. This may lead to a rise in the chemical species concentration in the vicinity of the surface.

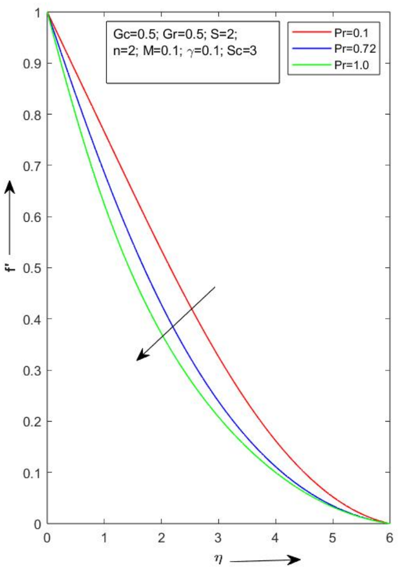

Figure 5. Velocity variation for Pr

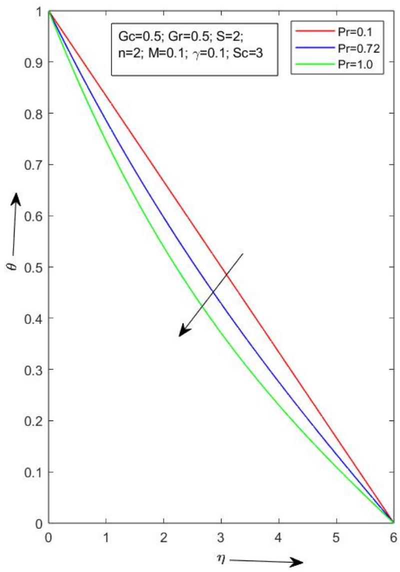

Figure 6. Temperature variation for Pr

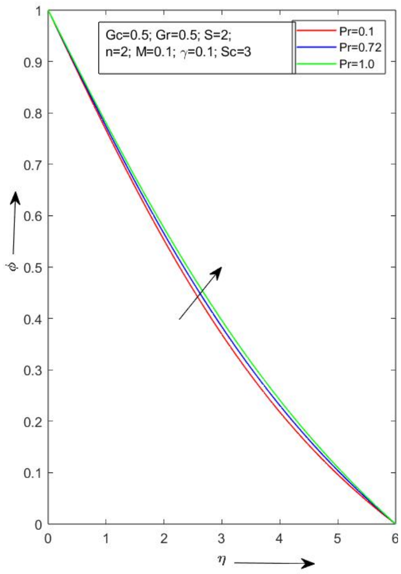

Figure 7. Concentration variation for Pr

Variations for the different fluid distributions for the heat source parameter are described in Figures 8-10. When a heat source is present, the fluid's temperature tends to rise. This can lower the fluid's density and, consequently, the buoyant forces that propel the flow. Convective heat transfer, which extracts heat from the boundary layer more effectively, may be the cause of the temperature profile's drop. The changed diffusion processes are responsible for the increase in the concentration profile. By altering the local temperature gradients, the heat source can have an impact on the diffusion of chemical species, which in turn affects the concentration boundary layer. The concentration of the chemical species close to the surface may rise as a result of this impact. When considering the effect of the chemical reaction parameter (γ), it describes the rate of chemical reaction within the fluid are shown in Figs. 11-13. The velocity profile often decreases as the chemical reaction parameter increases because of the increased reactant consumption, which might lessen the flow's overall driving forces. More heat is produced when the chemical reaction parameter is increased, which raises the temperature profile inside the boundary layer. Reactant consumption rate increases are indicated by increases in the chemical reaction parameter. Because the chemical species are being transformed into products more quickly, the concentration of those species within the boundary layer decreases as a result.

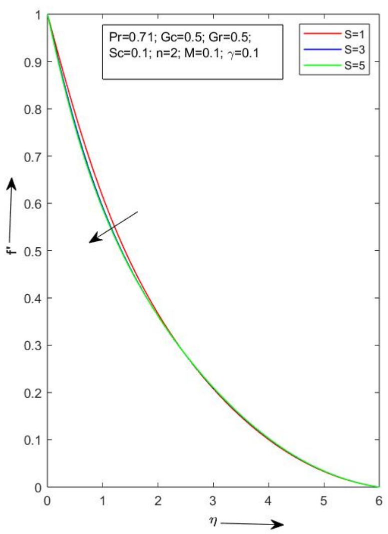

Figure 8. Velocity variation for S

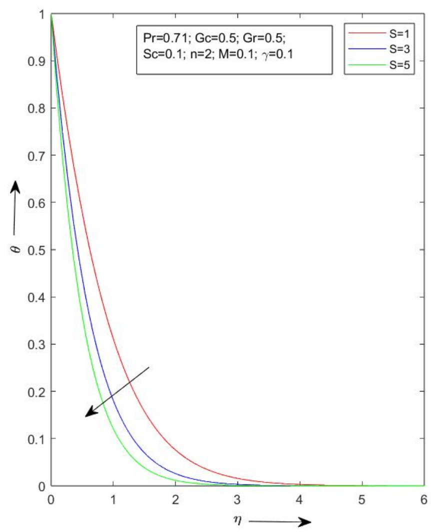

Figure 9. Temperature variation for S

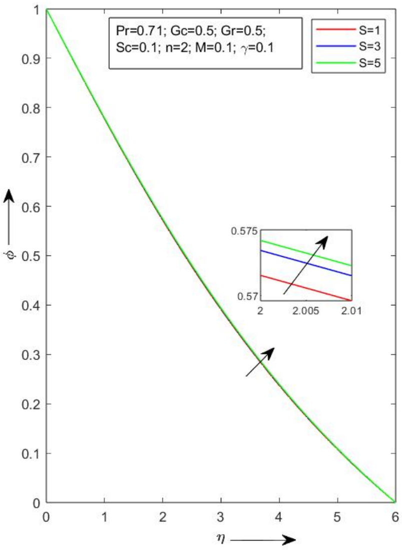

Figure 10. Concentration variation for S

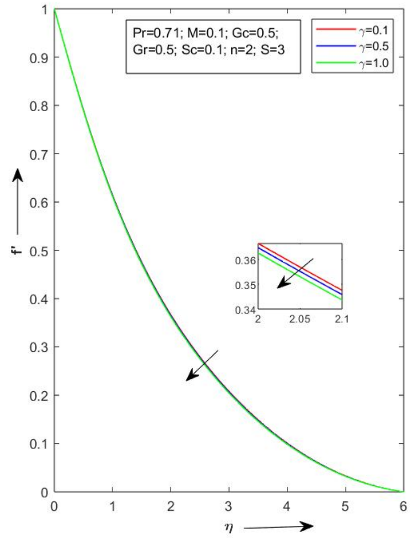

Figure 11. Velocity variation for γ

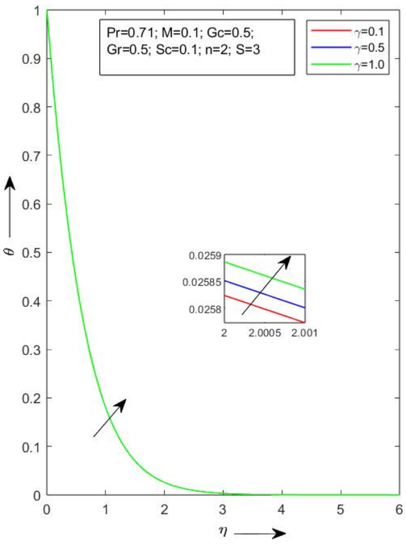

Figure 12. Temperature variation for γ

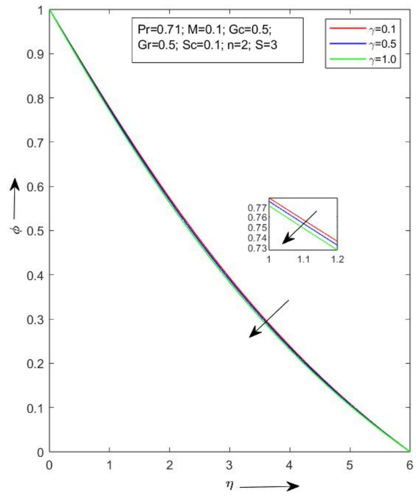

Figure 12. Concentration variation for γ

Table 1 explains the validity of our work. Given that the Nusselt number values are identical to those of previously published studies, our study is validated, taking all factors into account.

Table 1. Comparison of $-\theta'(0)$ value with previously published papers

M	γ	Afify [22]	Present study
0.1		0.2940	0.2941
0.5		0.2261	0.2263
1.0		0.1081	0.1082
	0.1	0.4826	0.4826
	0.5	0.4518	0.4518
	1.0	0.4231	0.4231

Table 2. Variations of $f''(0), -\theta'(0)\ and - \phi'(0)$ for different parameters

S	n	Pr	γ	M	Sc	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
1	2	0.71	0.1	0.1	0.1	0.3963	1.0181	0.2197
2						0.4344	1.5672	0.2186
5						0.4543	1.9692	0.2181
	1					0.4344	1.5672	0.2186
	2					0.4366	1.5671	0.2252
	3					0.4368	1.5671	0.2239
		0.1				0.3279	0.5836	0.2236
		0.72				0.4351	1.5783	0.2185

S	n	Pr	γ	M	Sc	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
		1.0				0.4514	1.8623	0.2181
			0.1			0.4344	1.5672	0.2186
			0.5			0.4271	1.5675	0.1971
			1.0			0.4182	1.5679	0.1721
				0.1		0.4344	1.5672	0.2186
				0.5		0.5707	1.5638	0.2147
				1.0		0.9332	1.5552	0.2053
					0.1	0.4344	1.5672	0.2186
					5	0.6719	1.5583	1.3022
					10	0.7055	1.5574	1.7409

The fluctuation of physical parameters for various parameters is displayed in the Table 2. The skin friction parameter will go down with G but will increase with $S, n, Pr, M, and\ Sc$. as $S, Pr, and\ G$ The Nusselt number grows but falls as $n, M, and\ Sc$ increase. The Sherwood number goes down with $S, Pr, G, and\ M$ but goes up with $n\ and\ Sc$. Because of the increased Lorentz force, the skin friction coefficient usually increases as M increases. Depending on how much the magnetic field promotes or inhibits the formation of thermal boundary layers, the Nusselt number may go down or up. Since the Sherwood number is dependent on convective mass transfer, which is controlled by the magnetic field, it fluctuates similarly to the Nusselt number. Changes in the concentration profile can impact the Sherwood number when a chemical reaction is taking place. The kind of response can also affect the Nusselt number and, consequently, the thermal boundary layer. Friction on the skin Increased viscosity brought on by the heat source parameter's influence causes the coefficient to rise. Because of variations in the surface temperature gradient, the heat source parameter directly affects the Nusselt number. A stronger temperature gradient causes the Nusselt number to rise, although thermal saturation might cause it to fall. Sherwood numbers may rise if the boundary layer stabilises but may drop with less mass diffusion.

CONCLUSIONS

A magnetic field has been used to study the effects of a heat source, chemical reaction, and mass transfer on free convective flow and the mass transfer of a viscous, incompressible, and electrically conducting fluid over a stretching surface. A similarity transformation has been used to translate the governing equations with the boundary conditions into a system of non-linear ordinary differential equations with the necessary boundary conditions. The bvp4c approach has also been utilised to obtain numerical solutions for the similarity equations. It can be inferred from the current study that

- The fluid's temperature and velocity are both lowered by the heat source parameter, but its concentration profile is also raised.
- The fluid's temperature profile rises when the chemical reaction parameter is increased, but the fluid's velocity and concentration drop.
- The fluid's temperature and concentration profile rise along with the fluid's decreased velocity when the magnetic parameter is raised.
- Skin-friction increases with increasing $S, n, Pr, M\ and\ Sc$; but it decreases with increasing γ.
- With increasing S, Pr $and\ \gamma$, the coefficients of Nusselt number increases; it decreases with $n\ and\ Sc$.
- Sherwood number drop with growing $S, Pr, \gamma\ and\ M$; but it increases with $n\ and\ Sc$.

The expansion of this field's theoretical, computational, and applied aspects may be the main focus of future research prospects. For other applications that are important to industry, expand the research to non-Newtonian fluid models like Casson or viscoelastic fluids. To investigate coupled effects, incorporate Hall currents and heat radiation into the MHD equations. Expand the research to include turbulent flow regimes and look at the system's stability analysis. Examine how adding nanoparticles such as metallic oxides or graphene to nanofluids might improve mass and heat transmission. Investigate three-dimensional stretching sheets to more accurately simulate intricate systems, including industrial sheets or biological membranes.

List of symbols

B_o: imposed magnetic field
a: stretching rate constant
C_p: specific heat
C : concentration
D: diffusion coefficient
S: Heat source parameter
Gc: local modified Grashof number
f : similarity function
n: order of reaction
k_o: reaction rate constant
g : acceleration due to gravity
Gr: local Grashof number

Subscripts

w: wall condition
o: constant condition
∞: free stream condition

Greek symbols

ϑ: kinematic viscosity
β: coefficient of thermal expansion
ψ: stream function
ρ: density
σ: electric conductivity
θ: dimensionless temperature
β^*: coefficient of expansion with concentration

k: thermal conductivity
Sc: Schmidt number
T: temperature
M: magnetic parameter
Pr: Prandtl number
(x, y): Cartesian coordinates
(u, v): velocity components along (x, y) −axes
ϕ: dimensionless concentration
η: similarity variable
γ: non-dimensional chemical reaction parameter

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МАСОПЕРЕНОС ТА ВІЛЬНИЙ МГД КОНВЕКЦІЙНИЙ ПОТІК ЧЕРЕЗ ЛИСТ ЩО РОЗТЯГУЄТЬСЯ З ДЖЕРЕЛОМ ТЕПЛА ТА ХІМІЧНОЮ РЕАКЦІЄЮ

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У цій роботі розглядається масообмін і МГД вільний конвективний потік через лист ЩО розтягується за наявності джерела тепла та хімічної реакції. Дія розтягування листа прискорює потік, тоді як магнітне поле, прикладене перпендикулярно напрямку потоку, впливає на нього. Також враховується вплив градієнтів температури та концентрації на виштовхувальні сили. Рівняння безперервності, імпульсу, енергії та концентрації належать до пов'язаних нелінійних диференціальних рівнянь у частинних похідних, які регулюють систему. Перетворення подібності використовуються для перетворення цих рівнянь у систему звичайних диференціальних рівнянь, які потім чисельно розв'язуються за допомогою методів bvp4c. У цьому дослідженні основними параметрами, що представляють інтерес, є магнітне поле, плавучість, швидкість хімічної реакції та джерело тепла. Результати показують вплив цих параметрів на температуру, концентрацію та профілі швидкості прикордонного шару. Для кількісного визначення швидкості масообміну, швидкості теплообміну та напруги зсуву на поверхні листа розраховують коефіцієнт шкірного тертя, число Нуссельта та число Шервуда. Маніпулюючи магнітним полем, хімічними реакціями та виділенням тепла, робота пропонує нове важливе уявлення про те, як найкраще використовувати потоки МГД у промислових процесах, таких як виробництво полімерів, хімічні реактори та системи охолодження.

Ключові слова: *МГД; поверхня, що розтягується; джерело тепла; хімічна реакція; bvp4c*