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Numerical Study of Chemical Reaction and Magnetic Field Effects on MHD Boundary Layer Flow over a Flat Plate

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ABSTRACT

This investigation explores the combined effects of magnetic fields and chemical reactions on the movement of a boundary layer toward a flat plate. The study considers the influence of viscous dissipation on the energy distribution. By utilizing partial differential equations (PDEs), the flow phenomenon is modeled. Through the application of suitable similarity transformations, the system of PDEs is transformed into a system of total differential equations. These modified equations are then solved using the spectral homotopy analysis method (SHAM), which incorporates the combination of the CSCM and HAM procedures. The analysis reveals that magnetohydrodynamic (MHD) fluxes generate a Lorentz force, and a higher magnetic parameter intensifies this effect, resulting in a flattened velocity profile. Furthermore, the velocity profile improves with an increase in the chemical interaction variable. The study also shows that as the Eckert number increases, the ambient temperature of the dense dissipative fluid rises. The findings have potential applications in various engineering fields, such as petroleum pipeline flow improvement. The spectral homotopy method used in this study offers a numerical solution for analyzing the problem. The results contribute to the understanding of heat and mass transfer phenomena and can guide future research in this area.

1. Introduction

The phenomenon of boundary layer flow plays a pivotal role in numerous fluid dynamics scenarios, ranging from industrial processes to environmental systems. Understanding and manipulating boundary layer behavior is of paramount importance in optimizing heat and mass transfer processes and enhancing fluid flow efficiency in various engineering applications. In recent years, investigations into the effects of external factors, such as magnetic fields and chemical reactions, on boundary layer flow have garnered significant interest among researchers and engineers alike. Chemical reactions occur at a predictable rate at a given temperature and chemical

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concentration. Many chemical processes are combined to produce the desired product during chemical synthesis. A series of chemical processes in biochemistry generate metabolic pathway routes. A first order reaction's rate is proportional to the concentration of a single component. In this study, the first order response is taken into account. The possible uses in disciplines as diverse as nuclear power, combustion modeling, heat exchangers, cooling system design, and a variety of aircraft propulsion technologies, chemical engineering, electronics, and electronics make the transfer of heat and mass analysis a fascinating area of study. In high-temperature environments, heat transfer characteristics are significantly influenced by thermal radiation heat transmission. Heating and quantity of chemicals can be used to compute the rates of chemical reactions. In chemical synthesis, numerous distinct chemical interactions are combined to create the final product. In biochemistry, metabolic pathways are constructed by connecting chemical responses. This analysis focuses on the first-order solution. Coupled heat and mass transfer problems in the presence of chemical reactions are crucial to the processes of drying, heat and moisture distribution over agricultural fields and orchards, crop damage from the freezing point, evaporated at the surface of a water body, energy transfer in a wet cooling processes tower, and move in a desert cooler. Heat and mass transfer in fluids undergoing chemical reactions has been studied by several authors [1-10]. Hayat *et al.,* [11] describe chemically reactive flow in a double-stratified Powel-Eying liquid. On the basis of their findings, they concluded that flux results from Fourier's expression in the absence of a thermal relaxation factor. Mondal *et al.,* [12] investigated the effects of chemical reactions on MHD mixed convection mass transfer. Using numerical computation, they solved their flow equations and determined that an increase in the rate of chemical reaction leads to a decrease in fluid concentration. Falodun *et al.,* [13] studied the effects of chemical reactions on non-Newtonian Casson fluid using a spectrum relaxation technique. Pop and Na [14] developed a mathematical representation in convection-free flow to examine the heat transfer and flow characteristics of each inclined flat plate submerged in a porous material. Falodun *et al.,* [15] investigated the effects of chemical reactions on non-Newtonian Casson fluid using a spectrum relaxation technique. Idowu and Falodun [16] investigated ongoing convection-free flow with a chemical response using spectral homotopy assessment. Hossain and Takhar [17] studied the natural convection boundary layer flow of a viscous incompressible fluid over an isothermal horizontal plate. Bataller [18] examined flows with thermal radiation effects, whereas Ishak [19] looked at the porous flat surface. While Ishak [19] investigated the porous planar surface, Bataller [18] examined the thermal radiation's effect on fluid flows. *Yao et al.,* [20] examined the heat transfer flow of a generalised stretching/shrinking wall with a convective boundary condition. The impact of viscous thermal dissipation on fluid flow and heat transmission was subject of numerous studies. These studies demonstrated that fluid fluxes with a high Eckert number generate heat through viscous thermal dissipation, dominate the fluid temperature when examining convective heat transfer and that the Eckert number cannot be zero. Oyelami and Dada [21] investigated the effect of thick dissipation on heat transmission by natural convection in a porous channel. Tyagi [22] researched the induced convection of a dissipative fluid in a channel with laminar flow. Oyelami and Dada [23] examined the effects of viscous dissipation and chemical interactions on heat and mass transport using the Eyring-Powell fluid model. Under laminar conditions, Tyagi [22] studied the forced convection of a dissipative fluid in a channel. Alao *et al.,* [5] investigated heat and mass transfer in fluids undergoing chemical reactions using a spectrum relaxation technique. As the chemical reaction parameter is increased, fluid velocity and fluid concentration decrease. This study is comparable to the one conducted by Desale and Pradhan [24] When analysing the boundary layer equations across a flat plate, viscoelastic dissipation and convective heat transport were taken into consideration. Heat transmission was mentioned in their work, but not mass transfer, chemical reaction, or magnetic fields. Although Oyelami and Falodun

[25] extended the work of Desale and Pradhan [24] by incorporating the transfer of heat and mass via magnetohydrodynamic flow across boundary layers and the effects of chemical reactions, Oyelami and Falodun [25] did not account for heat or mass transmission in the latter instance.

In all previously cited publications, heat and mass transfer of magnetohydrodynamic boundary layer flow along a flat plate was ignored. We generalized the heat and mass transport issue of Desale and Pradhan [24] as well as Oyelami and Falodun [25] to account for the effects of a magnetic field and a chemical reaction based on this premise. As far as we can tell, there is no prior research in the literature that specifically addresses this issue. This article analyses the effects of all flow parameters on velocity, temperature, and concentration profiles, focusing on the local skin friction coefficient, local Nusselt number, and local Sherwood number. The anticipated results of this research promise to offer valuable insights into the effects of magnetohydrodynamic (MHD) fluxes and chemical interactions on the generation of a Lorentz force, subsequently impacting the velocity profiles of the boundary layer flow. Additionally, the investigation is expected to reveal the influence of the magnetic parameter on the magnitude of the Lorentz force, ultimately leading to a flattened velocity profile. The role of the chemical interaction variable in enhancing the velocity profile further complements the findings. Furthermore, this research endeavors to explore the impact of the Eckert number, a crucial parameter accounting for the effect of viscous dissipation, on the ambient temperature of the dense dissipative fluid. These insights have the potential to revolutionize various engineering applications, with petroleum pipeline flow improvement being just one of the many potential beneficiaries.

The significance of this study extends beyond its immediate applications, as the findings will contribute to the broader understanding of heat and mass transfer phenomena. Furthermore, they hold the promise of guiding future research endeavors in this intriguing area of fluid dynamics and related scientific disciplines. By addressing the research gap in the combined effects of magnetic fields, chemical reactions, and viscous dissipation on boundary layer flow, this investigation aspires to make valuable contributions to scientific knowledge and pave the way for innovative engineering solutions.

2. Governing Equation

A steady stream of a velocipede-like fluid moving across a flat plate, with the entire surface maintained at a constant temperature T_w and concentration C_w is considered. At the open channels, the fluid temperature and concentration are $T_\infty$and C_∞ respectively. The assumption is made that the chemical interaction within the diffusing elements and the liquid is a homogeneous first-order reaction with a constant rate k_c. The properties of the fluid are believed to be unchanging. Assuming a low magnetic Reynolds number allows us to ignore the induced magnetic field. The magnetic field is consistently applied at full strength B_o. It is assumed that viscous dissipation has a significant impact. It's speculated that the flat plate's surface temperature shifts. Boussinesq approximation governing equations are as follows, assuming the validity of the boundary layer approximation.

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}-\frac{\sigma B_o^2}{\rho}u \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{\mu}{\rho C_p}\left(\frac{\partial u}{\partial y}\right)^2 \tag{3}$$

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

The constraints are stated as follows:

$$u=0,\ T=T_w(x),\ C=C_w(x)\ \ at\ y=0$$

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

Where σ represent the conductivity of the fluid, B_0 is the electromagnetic induction, u and v are velocities in x and y direction, ν implies the viscosity of fluid, α represents the thermal conductivity of the fluid, T stands for the temperature of the fluid, C signifies the concentration of the fluid, μ represents the coefficient of viscosity, C_p is the specific heat at constant pressure, ρ implies the density of the fluid, D stands for the mass diffusivity, k_c indicates the coefficient of chemical interactions, T_∞ indicates the heat at the free stream, C_∞ indicates for the concentration at the ambient, T_w indicates the heat at the wall and C_w indicates the concentration at the wall.

Supposing the temperature at the plate fluctuates in the following way.

$$T_w(x)-T_\infty=Ax^n \tag{6}$$

Implementing a similarity term η and a stream term ψ, temperature $\theta(\eta)$ and concentration $\phi(\eta)$ as

$$\eta=y\sqrt{\frac{U}{\nu x}}, \psi=\sqrt{U\nu x}f(\eta), \theta(\eta)=\frac{T-T_\infty}{T_w(x)-T_\infty}, \phi(\eta)=\frac{C-C_\infty}{C_w(x)-C_\infty} \tag{7}$$

$$u=\frac{\partial\psi}{\partial y}=Uf'\ and\ v=-\frac{\partial\psi}{\partial x}=\frac{1}{2}\sqrt{\frac{U\nu}{x}}(\eta f'-f) \tag{8}$$

It's important to note that prime refers to differentiation with respect to η.

After applying Eq. (6) to Eq. (8), Eq. (1) to Eq. (5) are reduced to the following

$$f'''+\frac{1}{2}ff''-M^2f'=0 \tag{9}$$

$$\theta''+\frac{1}{2}f\theta'+EcPr(f'')^2-nPrf'\theta=0 \tag{10}$$

$$\phi''+\frac{1}{2}f\phi'+Sc\lambda f'\phi-Sc\lambda\phi=0 \tag{11}$$

The following boundary conditions apply:

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

$$f'(\infty)=1, \theta'(\infty)=0, \phi'(\infty)=0 \tag{12}$$

Where $M=\frac{\nu\sigma B_o^2}{\rho\nu_o^2}$ stands for the magnetic term, $Pr=\frac{\nu}{\alpha}$ signifies the Prandtl, $Ec=\frac{U^2}{C_p(T_w(x)-T_\infty)}$ represents the Eckert, $Sc=\frac{\nu}{D}$ indicates the Schmidt, n is the surface temperature parameter and $\lambda=\frac{l^2\gamma}{\nu}$ is the chemical reaction parameter.

3. Numerical Solution

In this study, the spectral homotopy method of evaluation (SHAM) is utilised. SHAM is derived by combining the Chebyshev pseudospectral method and the homotopy analysis method (HAM). With the help of the domain truncation technique Sibanda *et al.,* [26] the physical region is first changed from $[0,\infty)$ to $[-1,1]$. In this way, the problem outcomes is gotten in the interval $[0,\eta_\infty]$ and not $[0,\infty)$ with this equation:

$$\zeta=\frac{2\eta}{L}-1,\ \xi\in[-1,1] \tag{13}$$

The algebraic term stated below is applied to the changed equations to write the boundary conditions in homogeneous form.

$$f(\eta)=f(\xi)+f_0(\eta),\theta(\eta)=\theta(\xi)+\theta_0(\eta),\phi(\eta)=\phi(\xi)+\phi_0(\eta) \tag{14}$$

Putting the above Eq. (14) into Eq. (9) - Eq. (11) to give:

$$\frac{d^3f}{d\xi^3}+\frac{1}{2}f\frac{d^2f}{d\xi^2}+a_1f+a_2\frac{d^2f}{d\xi^2}-M^2\frac{df}{d\xi}=H_1(\eta) \tag{15}$$

$$\frac{d^2\theta}{d\eta^2}+\frac{1}{2}f\frac{d\theta}{d\eta}+b_1f+b_2\frac{d\theta}{d\eta}+EcPr\frac{d^2f}{d\eta^2}\frac{d^2f}{d\eta^2}+b_3\frac{d^2f}{d\eta^2}+b_4\frac{df}{d\eta}+b_5\theta=H_2(\eta) \tag{16}$$

$$\frac{d^2\phi}{d\eta^2}+\frac{1}{2}f\frac{d\phi}{d\eta}+c_1f+c_2\frac{d\phi}{d\eta}+Sc\lambda\phi\frac{df}{d\eta}+c_3\frac{df}{d\eta}+c_4\phi-Sc\lambda\phi=H_3(\eta) \tag{17}$$

Where

$$a_1=\frac{1}{2}\frac{d^2f_0}{d\eta^2},a_2=\frac{1}{2}f_0,H_1(\eta)=-\frac{d^3f_0}{d\eta^3}-\frac{1}{2}f_0\frac{d^2f_0}{d\eta^2}+M^2\frac{df_o}{d\eta}$$

$$b_1=\frac{d\theta_0}{d\eta},b_2=\frac{1}{2}f_0,b_3=2EcPr\frac{d^2f_0}{d\eta^2},b_4=-nPr\theta_0,b_5=-nPr\frac{df_0}{d\eta}$$

$$H_2=-\frac{d^2\theta_0}{d\eta^2}-\frac{1}{2}f_0\frac{d\theta_0}{d\eta}-EcPr\frac{d^2f_0}{d\eta^2}\frac{d^2f_0}{d\eta^2}+nPr\theta_0\frac{df_0}{d\eta}$$

$$c_1 = \frac{1}{2}\frac{d\phi}{d\eta}, c_2 = \frac{1}{2} f_0, c_3 = Sc\lambda\phi_0, c_4 = Sc\lambda\frac{df_0}{d\eta}$$

$$H_3 = -\frac{d^2\phi_0}{d\eta^2} - \frac{1}{2} f_0\phi_0 - Sc\lambda\phi\frac{df_0}{d\eta} + Sc\lambda\phi_0$$

The Eq. (15)–(17) are nonlinear. SHAM is used to split nonlinear terms into linear and nonlinear. It worth noteing that the differential of f, θ and ϕ are defined with respect to ξ by:

$$\frac{d}{d\xi} = \frac{2}{L}\frac{d}{d\eta} \tag{18}$$

The functions defined are uutilized to make a first guess due to boundary conditions Eq. (12).

$$f_0(\eta) = e^{-\eta} - 1, \theta_0(\eta) = \phi_(\eta) = e^{-\eta} \tag{19}$$

The linear non-homogeneous part of Eq. (15) - Eq. (17) are splinted away from nonlinear as:

$$\frac{d^3 f}{d\xi^3} + a_1 f + a_2\frac{d^2 f}{d\xi^2} - M^2\frac{df}{d\xi} = H_1(\eta) \tag{20}$$

$$\frac{d^2\theta}{d\eta^2} + b_1 f + b_2\frac{d\theta}{d\eta} + b_3\frac{d^2 f}{d\eta^2} + b_4\frac{df}{d\eta} + b_5\theta = H_2(\eta) \tag{21}$$

$$\frac{d^2\phi}{d\eta^2} + c_1 f + c_2\frac{d\phi}{d\eta} + c_3\frac{df}{d\eta} + c_4\phi - Sc\lambda\phi = H_3(\eta) \tag{22}$$

Subject to:

$$f_l(-1) = f'_l(1) = f'_l(1) = 0, \theta_l(-1) = \theta_l(1) = 0, \phi_l(-1) = \phi_l(1) = 0 \tag{23}$$

In order to carry out the linear portion of the SHAM solution, the requirements for the boundaries Eq. (23) are set equal to zero in relation to the modified domain. Chebyshev's pseudospectral method is applied to Eq. (20) - Eq. (22). In the modified domain, the Gauss-Lobatto points of collocation Trefethen [27] define the Chebyshev nodes.

$$\xi_J = cos\left(\frac{\pi j}{N}\right) \tag{24}$$

Provided $j = 0,1,...N$ and $N+1$ is the number of collocation points. The unknown functions $f_l(\xi), \theta_l(\xi)$ and $\phi_l(\xi)$ are approximated by the use of Lagrange form of interpolating polynomial which interpolates the unknown functions $f_l(\xi), \theta_l(\xi)$ and $\phi_l(\xi)$ at the Gauss-Lobatto collocation points as defined in Eq. (24).

4. Discussion of Results

Using SHAM, we investigate a possible solution to the problem of heat and mass transmission in a magnetohydrodynamic boundary layer. The concept behind SHAM is to decompose nonlinear differential equations using a combination of Chebyshev pseudospectral and homotopy analysis techniques. Following are the parameters used in this task and their default values. Unless otherwise specified, these values therefore serve as the foundation for all graphs and tables.

Figures 1(a), 1(b), and 1(c) depict the influence of various reaction parameters on the rates, temperatures, and concentrations, respectively. According to the plots, when the chemical reaction parameter is enhanced, the momentum and mass boundary layer benefits from an increase in fluid velocity and concentration. The species concentration influences the reaction rate. When fluid particles come into contact with the atmosphere, heterogeneous reactions that occur between two distinct states of matter generate new compounds. The buoyancy effect due to concentration gradients is highlighted in Figures 1(a), 1(b), and 1(c), indicating that the chemical reaction is safe. As shown in Figure 1 (b), the distribution of temperatures does not change appreciably as the reaction parameter is increased.

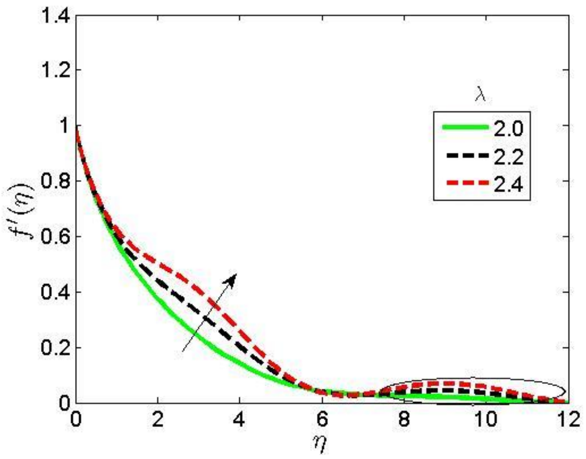
Figures 2(a), 2(b), and 2(a) depict the effects of the magnetic parameter M on the velocity, temperature, and concentration curves, respectively. The velocity boundary layer thins with increasing magnetic parameter at the plate, as shown in Figure 2 (a). The presence of a transverse magnetic field induces Lorentz force, which exerts a decelerating force on the velocity field. Consequently, the velocity profile rises as a result of an increase in Lorentz force caused by modifications to the magnetic parameters, resulting in an increase in electrical motions. Figures 2 (b) and (c) demonstrate that an increase in the magnetic field parameter has no effect on the temperature and concentration curves. This demonstrates that the transmission rate of heat and mass is independent of M. In addition, it was found that the concentration and thermal boundary layers maintained their original thicknesses. The effects of the Prandtl number Pr on the profiles of velocity, temperature, and concentration are depicted in Figures 3 (a), (b), and (c), respectively. As the Prandtl number rises, the boundary layer becomes thinner and the velocity, temperature, and concentration profiles all decrease marginally. Because a lower Prandtl number indicates that less heat can be transmitted through the fluid, this is the case. Nonetheless, as Pr rises, the heat transfer rate near the plate marginally improves. This is due to the increasing temperature difference between the plate and the ambient air.

Figures 4 (a), (b), and (c) represent, respectively, the impacts of Sc on velocity, temperature, and concentration profiles. The profiles of velocity, temperature, and concentration behave erratically as Sc increases. Momentum, temperature, and mass transfer all exhibit spontaneous behaviour. presence of heated air close to the ground may be to blame. When the surface temperature is zero, Sc heightens the velocity, temperature, and concentration profiles. Figures 5(a), (b), and (c) illustrate the effect of the viscous dissipation parameter Ec on the velocity, temperature, and concentration profiles, respectively. The Eckert number quantifies the force exerted against the tension of a viscous fluid to produce useful labour. As the viscous dissipation parameter Ec (a) increases, the velocity profile near the plate (illustrated in Figure 5) decreases and then increases. As one moves away from the plate, the temperature rises abruptly, only to drop in the zone's centre (b) (see Figure 5). This indicates that the thermal boundary layer thickens as the Eckert number increases. Figure 5's temperature distribution (c) is marginally affected by Ec.

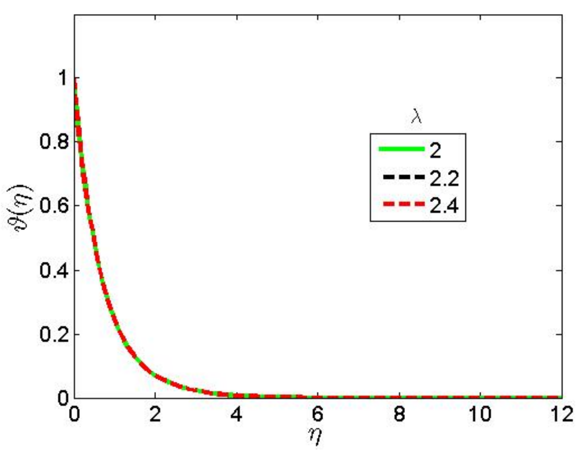
Table 1 lists the computed Skin Friction, local Nusselt number, and Sherwood number for various flow parameter values such as and. The rate of heat transfer increases as the number of objects increases. As the rate of heat transfer, mass transfer, and skin friction increases with increasing viscosity, fluid motion generates more heat. With an increase in M, both the coefficient of surface friction and the mass transfer rate increase, while the Nusselt number decreases. Sc is the ratio of momentum and mass diffusivities that characterises fluid fluxes with both momentum and mass convective processes. The number of Sherwood residents grows as the increase persists. As a result, the concentration boundary layer is narrower than the momentum boundary layer, and the Skin friction decreases as Sc increases. Increasing the value of the chemical reaction parameter increases the rates of mass transfer and heat transfer, while decreasing the rate of skin friction. The self-heating of a fluid owing to dissipation processes is known as its Ec. As Ec increases, however, the rate of heat and mass transport decreases. By moving heat away from the plate and into the fluid, an increase in the Eckert number reduces heat transfer at the wall.

Table 1
Computational values of Skin Friction, local Nusselt number and Sherwood number for different values Fluid parameters

Ec	Sc	Pr	M	λ	C_f	Nu_x	Sh_x
0.2					0.716373	0.847160	0.848305
0.6					0.693201	0.746368	0.803232
0.8					0.656790	0.647766	0.730969
	0.8				0.755036	0.818468	0.759490
	0.9				0.735265	0.832610	0.803271
	1.0				0.716181	0.846150	0.847938
		0.71			0.675573	0.664045	0.762979
		1.00			0.693201	0.746368	0.803232
		3.00			0.703033	0.785716	0.824739
			1.0		0.332460	0.865159	0.787642
			2.0		0.693201	0.746368	0.803232
			3.0		1.775424	0.389998	0.850003
				0.3	0.693201	0.746368	0.803232
				0.6	0.682253	0.782880	0.863908
				0.9	0.671291	0.818928	0.926724



(a)



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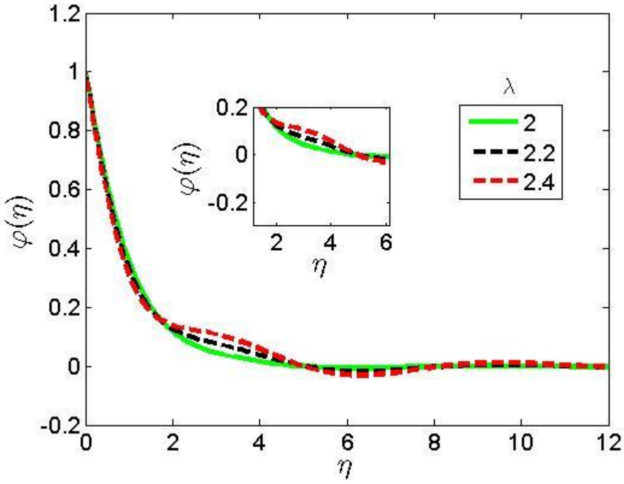
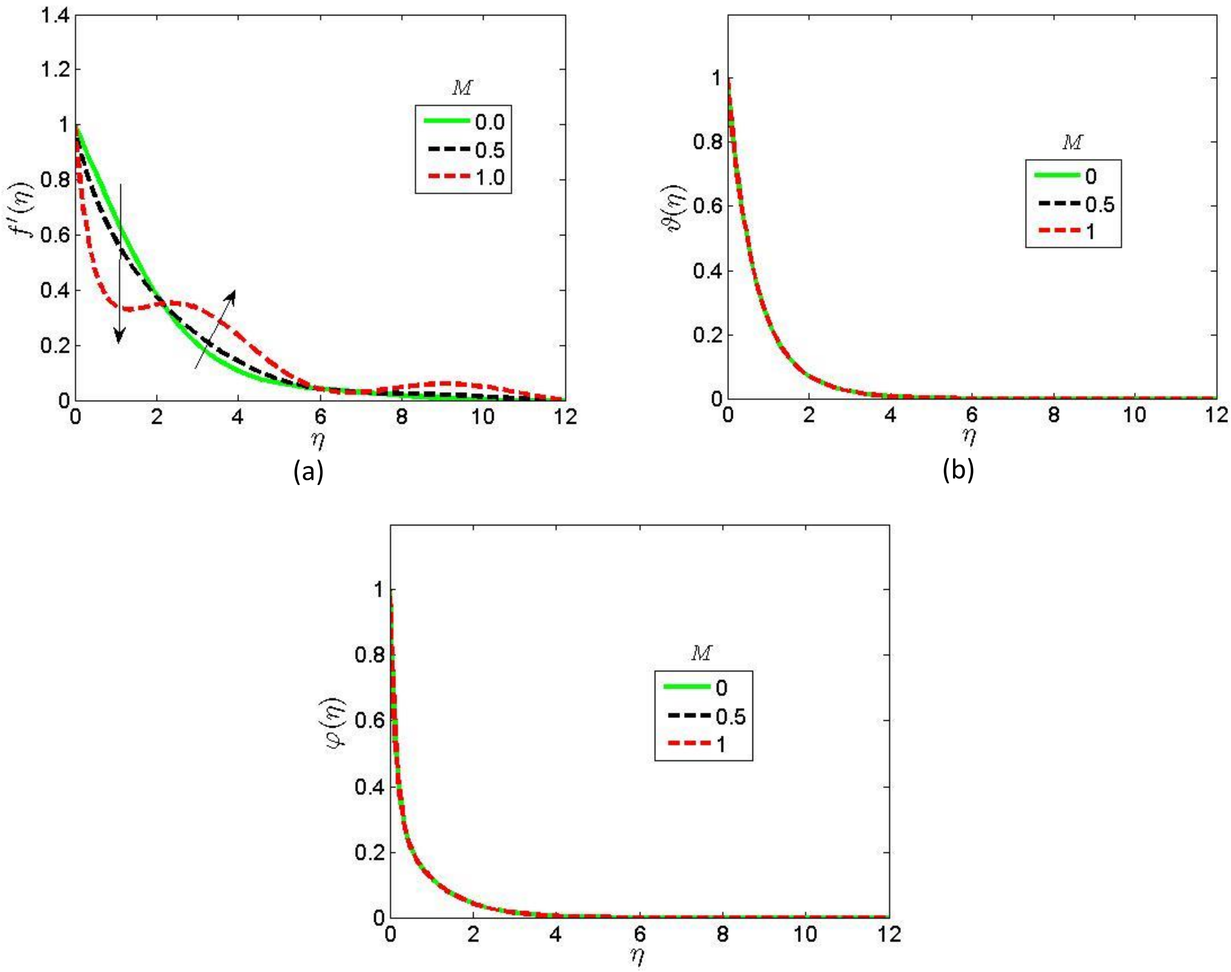


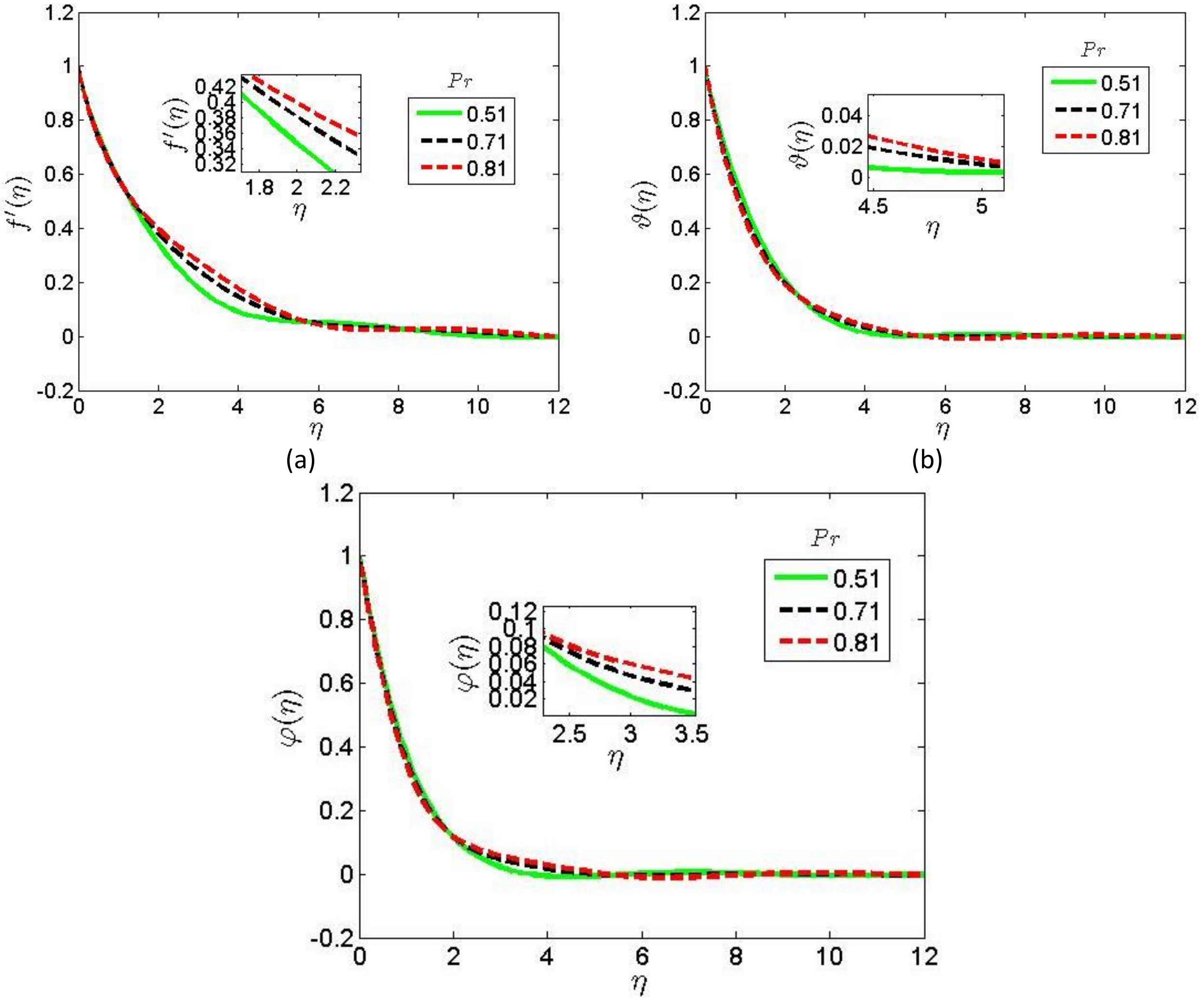
(c)

Fig. 1. (a) Reaction of chemical reaction on velocity counter, (b) Reaction of chemical reaction on temperature counter, (c) Reaction of chemical reaction on concentration counter



(c)

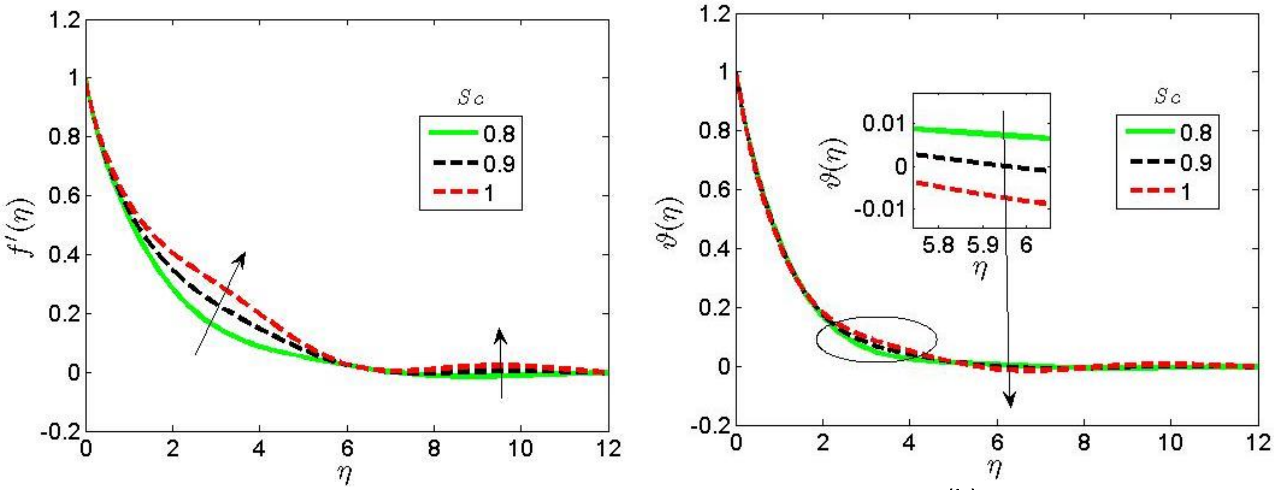
Fig. 2. (a) Reaction of magnetic field on velocity counter, (b) Reaction of magnetic field on temperature counter, (c) Reaction of magnetic field on concentration counter



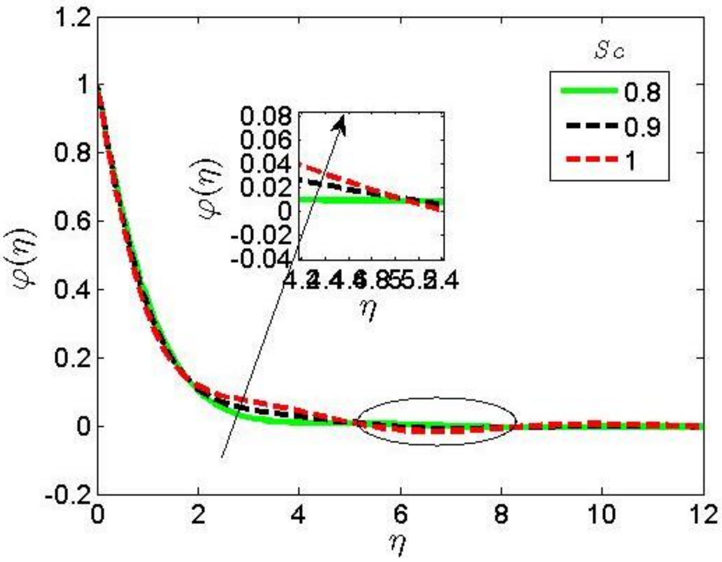
(a) (b)

(c)

Fig. 3. (a) Reaction of Prandtl on velocity counter, (b) Reaction of Prandtl on temperature counter, (c) Reaction of Prandtl on concentration counter

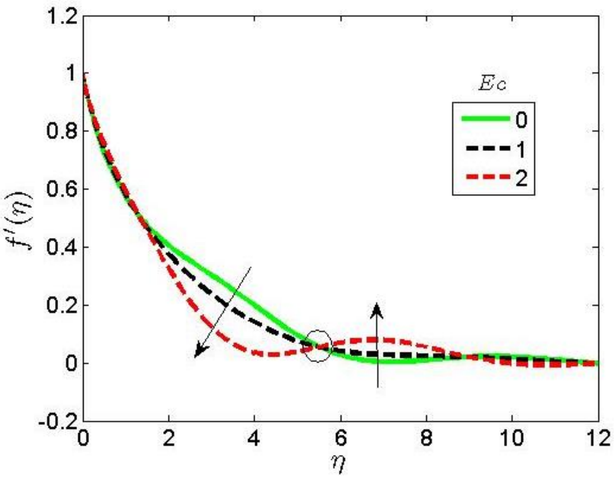


(a) (b)

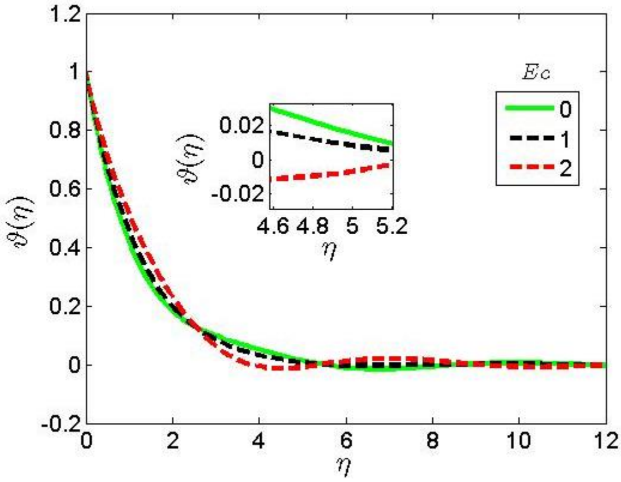


(c)

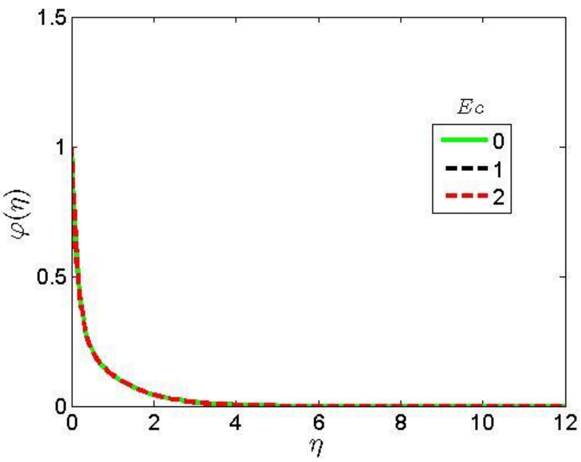
Fig. 4. (a) Reaction of Schmidt on velocity counter, (b) Reaction of Schmidt on temperature counter, (c) Reaction of Schmidt number on concentration counter



(a)



(b)



(c)

Fig. 5. (a) Reaction of Eckert number on velocity counter, (b) Reaction of Eckert number on temperature counter, (c) Reaction of Eckert number on concentration counter

5. Conclusions

This study addresses the issue of boundary layer flow along a flat plate and its effect on heat and mass transfer. Numerical solutions to the flow equations was carried out using spectral homotopy analysis method (SHAM), and our results correspond well with those found in the literature [24,25]. The SHAM is superior to other approaches in the reviewed literature because of its flexible application of linear operators, and also because of its sophistication and accuracy. Data is provided for velocities, temperatures, concentrations, skin friction coefficients, Nusselt numbers, and Sherwood numbers in the area. Various flow parameters are studied to determine their significance. These include the Prandtl number, Schmidt number, Eckert number, magnetic field, and chemical reaction parameter. Here are the results:

i. The profiles of velocity, temperature, and concentration all increase as Sc rises.
ii. As Pr, M, and Ec rise, the velocity profile exhibits irregular behavior.
iii. As the chemical reaction parameter rises, the concentration profile exhibits irregular behaviour.
iv. The velocity of a chemical reaction increases with an increase in the reaction constant.

The rate of mass transfer, heat transfer, and the reduction of skin friction are all increased with an increase in the chemical reaction parameter. At the same time that the Nusselt number decreases with increasing M, the skin friction coefficient and the rate of mass transfer also increase.

In conclusion, this research has not only addressed a crucial research gap in the understanding of boundary layer flow with magnetic fields, chemical reactions, and viscous dissipation but also has promising applications in various engineering and scientific disciplines. The outcomes contribute to the body of knowledge in heat and mass transfer, guiding future research and offering practical solutions to optimize fluid flow systems and industrial processes.

Conflict of Interest
The authors declare that there is no conflict of interest.

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