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Stagnation Point Flow of Magnetohydrodynamic Liquid across a Linear Stretching Sheet: A Numerical Study

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Abstract: ***This paper investigates the numerical result of stagnation point flow of Magnetohydrodynamic liquid (MHD) across a stretchable sheet in presence of chemical reaction and viscous dissipation. By applying the suitable similarity transformations, the essential governing physical phenomenon partial differential equations (PDE) are altered into non-linear ordinary differential equations (ODE). Later, were resolved numerically using the Lobatto III-A way technique in MATLAB (bvp4c). The results of the effect of the non-dimensional parameters like Velocity ratio parameter (λ), Porosity (k), Magnetic parameter (M), Radiation parameter (R), etc. on velocity, concentration, and the temperature profiles for their various values were analysed and presented graphically. For the diverse values of relevant stream parameters, the numerical evaluation of the physical quantities was given in a tabular form.***

Keywords: Chemical Reaction, Lobatto-III A technique, Stagnation point, Viscous Dissipation

1. Introduction

"Stagnation points arise in the flow field at the surface of objects, where the fluid is brought to a halt by the object. The study of stagnation point flow of Nanofluid over a linearly stretching surface has several applications in manufacturing industries such as saving power using Nano-fluid in closed-loop cooling cycles, in analytical chemistry and biological research, and in the extraction of Geothermal power". Many flows and heat transfer problems encountered in engineering applications, such as microelectronics cooling design, heat transfer in atmospheric re-entry, heat exchanger, friction reduction, and prediction of skin friction problems, were related to stagnation point flow problems [1]. Nanofluids are being used to cool the pipes exposed to high temperature, etc. "Choi (1995) coined the word nanofluid in his seminal paper presented at the American Society of Mechanical Engineers' winter annual meeting in 1995 [2]. A liquid containing a dispersion of submicronic solid particles (nanoparticles) with a standard duration of 1–50 nm is referred to as a nanoparticle suspension" [3].

"Hydromagnetic fluid (MHD) boundary layer flow of heat and mass transmit over a stretching sheet has extensive applications. Some of its applications are, polymer extraction, and paper production, drawing of plastic films, hot rolling, and metal spinning. In the process of manufacturing, the following activities like simultaneous heating or cooling and kinematics of stretching have a decisive influence on the quantity of the final products" [4]. Many scholars have looked into the stretching sheet difficulties since Crane [5] published the similarity solution for laminal boundary layer flow and heat transfer over a stretching / shrinking plane. Carragher and Crane [6], Dutta [7], Ch. Vittal. et al., [8], Hasmawani Hashim, et al., [9], are among the few researchers who explored it.

"Schlichting discussed the laminar flow in a planar stagnation-point flow (also known as Hiemenz flow) (1960). Chari and Rajagopalan investigated particle deposition in this type of system" as cited by M. Ibrahim et. al [10]. In their study M. Ibrahim et. al [10] investigated the influence of a magnetic field on stagnation point flow and heat transfer characteristics related to nanofluid towards a stretching sheet, taking into account Brownian motion and thermophoresis effects. "Microfluidic stagnation combines micro fluids and hydrodynamic stagnation to build and monitor a zero-velocity (stagnation) region within the fluid interface" as mentioned by M. Tanyeri et. al [11]. Despite the fact that both disciplines are quickly growing due to evident advantages in analytical chemistry and biological research, combining them gives a more compelling opportunity for growth [12]. Seth et. al investigated the diffusion of heat and mass of MHD stagnation point flow of electromagnetic nanofluid with Joule heating and viscous dissipation in the presence of convective and thermal radiation [13]. "The effect of chemical reactions on MHD convective flow through a porous medium past an exponentially stretching sheet in the presence of a heat source/sink and viscous dissipation" was studied by Nalivela Nagi Reddy, et al, [14]. The flow of a Nanofluid near a stagnation-point towards a stretching surface and the consequences of Brownian motion and also thermophoresis using analytic solutions was developed using the homotopy analysis method (HAM) by M. Mustafa, T. Hayat [15]. B. J. Gireeshaa et, al [16] investigated the stagnation-point stream and Melting heat transfer of micropolar nanofluid over a linear stretching Sheet. Sohaib Abdal et al [17] investigated the heat and mass transport of an unsteady tangent hyperbolic fluid flow through an expandable Riga wedge beneath the influences of stagnation point, supply of heat, and activation energy. Mohana Ramana. R [18] in their study have investigated the existence of a chemical reaction of order along with the heat source through several slip boundary conditions, considering the Joule warming and viscous dissipation for the of Casson fluid flow above a stretching sheet. The mix effects of velocity slip, thermal radiation along a nonlinear convective stretching surface of an MHD Casson nanofluid with slipped effects and the porous medium to decrease the drag at the surface near the stagnation point was analysed by Besthapu, P et al [19].

The wide range of uses of Nanofluids in various technologies and industries compelled many researchers to focus their studies on the stagnation point flow of Nanofluids over a stretching surface. Motivated by the above literature and the applications this paper aims to consider the effects of radiation and stagnation point flow in an MHD flow against a linearly stretching surface with variable surface thickness along with heat and mass transfer characteristics were investigated. The problem was formulated based on the boundary-layer approximation. The impacts of various associated flow variables on temperature and concentration areas were presented and examined. Furthermore, the rates of skin friction, heat, and mass transfer were also all numerically observed.

2. Mathematical Formulation

Consider a two-dimensional laminar steady flow of an incompressible hydro magnetic viscous, electrically conducting flow over a stretching sheet. The system's starting point is the slit from which the sheet is drawn. In this coordinate the frame of the axis is taken along the path of the continuous stretching plane [10].

Considering the stretching sheet's velocity to be $U_w(x) = bx$, and the free stream flow's velocity to be $U_\infty(x) = ax$, where a, b are positive constants and x is the coordinate all along the stretching plane.

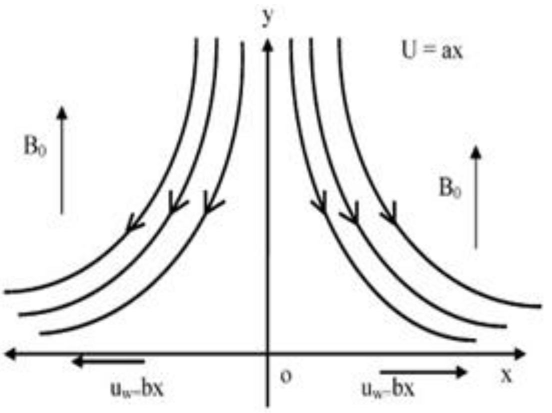

Figure 1: Physical sketch of the problem

The flow is carried out at $y \geq 0$, where y is the perpendicular to the stretching sheet coordinate. Let T_w, C_w be the temperature and concentration of the nanofluid at the stretching layer and let T_∞ and C_∞ be the ambient temperature and concentration.

$$\frac{\partial u_1}{\partial x} + \frac{\partial v_1}{\partial y} = 0 \tag{1}$$

$$u_1 \frac{\partial u_1}{\partial x} + v_1 \frac{\partial u_1}{\partial y} = \vartheta \frac{\partial^2 u_1}{\partial y^2} - \frac{\sigma B_0^2 u_1}{\rho} - \frac{\vartheta u_1}{k_p^{'}} + U_\infty \frac{\partial U_\infty}{\partial x} \tag{2}$$

$$u_1 \frac{\partial T_1}{\partial x} + v_1 \frac{\partial T_1}{\partial y} = \alpha \frac{\partial^2 T_1}{\partial y^2} - \frac{1}{\rho C_p} \frac{\partial q_r}{\partial y} + \frac{Q}{\rho C_p}(T_1 - T_\infty) + \frac{\vartheta}{C_p}\left(\frac{\partial u_1}{\partial y}\right)^2 \tag{3}$$

$$u_1 \frac{\partial C_1}{\partial x} + v_1 \frac{\partial C_1}{\partial y} = D_B \frac{\partial^2 C_1}{\partial y^2} - k_r (C_1 - C_\infty) \tag{4}$$

Where u_1 and v_1 are the elements of velocity along coordinate axes, T_1 is the temperature, C_1 is the concentration of species. The kinematic viscosity υ, α is the thermal diffusivity, D_B is the Brownian motion coefficient [2], [20]. Make use of the Roseland [20] approximation for radiation, the radiative heat flux q_r is given by

$$q_r = \frac{-4\sigma^*}{3k^*} \frac{\partial {T_1}^4}{\partial y} \tag{5}$$

Where k* is the average absorption coefficient, σ* is the Stefan-Boltzmann constant. We presume that the temperature change inside the flow sufficiently small. The expression ${T_1}^4$, enlarging in a Taylor series in powers of $(T_1 - T_\infty)$ and ignoring higher-order terms we get ${T_1}^4 \approx 4T_\infty^3 T_1 - 3T_\infty^4$, hence [20],

$$q_r = \frac{-4\sigma^* T_\infty^3}{3k^*} \frac{\partial T}{\partial y}$$

Then

$$\frac{\partial q_r}{\partial y} = \frac{-16\sigma^* T_\infty^3}{3\rho c_p k^*} \frac{\partial^2 T}{\partial y^2} \tag{6}$$

The corresponding boundary conditions are

$$\begin{aligned} &u_1 = bx;\ v_1 = 0;\ T_1 = T_w;\ C_1 = C_w \quad at\ y = 0 \\ &u_1 = U_\infty = ax;\ T_1 = T_\infty;\ C_1 = C_\infty \quad as\ y \to \infty \end{aligned} \tag{7}$$

Introducing the similarity transformations, which satisfy the equation of continuity

$$u_1 = \frac{\partial \psi}{\partial y} \quad and \quad v_1 = -\frac{\partial \psi}{\partial x} \tag{8}$$

Such that

$$u_1 = bxf'(\eta),\ v_1 = -\sqrt{\upsilon b} f(\eta);\ \eta = \sqrt{\frac{b}{\upsilon}} y,$$

$$\theta = \frac{T - T_\infty}{T_w - T_\infty}, \phi = \frac{C - C_\infty}{C_w - C_\infty} \ (9)$$

Substituting Equations (6), (8), (9) in equations (2)-(4) we get the following coupled nonlinear differential equations.

$$f''' + ff'' - \left(M + \frac{1}{k}\right) f' + \lambda^2 - [f']^2 = 0 \tag{10}$$

$$\frac{1}{P_r}\left(1 + \frac{4R}{3}\right)\theta'' + Ec[f'']^2 + S\theta + f\theta' = 0 \tag{11}$$

$$\phi'' + Sc[f\phi' - \gamma\phi] = 0 \tag{12}$$

The parameters that are present in the above equations are, magnetic parameter M, Prandtl number Pr, Schmidt number Sc, Eckert number (Ec), chemical reaction rate parameter γ, and the Source parameter S, R is the radiation parameter, $\lambda$is the velocity ratio parameter and 1/k Porosity parameter given as follows

$$P_r = \frac{\vartheta}{\alpha}, M = \frac{\sigma B_0^2}{\rho b}, \frac{k_p' b}{\vartheta} = k, R = \frac{4\sigma^* T_\infty^3}{k^* k}, \lambda = \frac{a}{b},$$

$$Ec = \frac{b^2 x^2}{(T - T_\infty)\ C_p}, S = \frac{Q}{\rho c_p b}, Sc = \frac{\vartheta}{D_B}, \gamma = \frac{k_r}{b}.$$

The transformed boundary conditions are

$$f(\eta) = 0, f'(\eta) = 1, \theta(\eta) = 1, \phi(\eta) = 1 \; as \; \eta \to 0$$
$$f'(\eta) \to \lambda, \theta(\eta) \to 0, \phi(\eta) \to 0 \; as \; \eta \to \infty \quad (13)$$

Where η is the similarity variable, f (η), θ (η), ϕ (η) is the dimensionless stream velocity, temperature concentration, and prime denotes the differentiation with respect to η. Physical Quantities of concern are the Local skin friction coefficient C_f, the heat N_u and mass transfers Sh coefficients from the plate, respectively are given by

$$C_f = \frac{\tau_w}{\rho U_w^2} \Rightarrow C_f\sqrt{Re} = f''(0)$$

$$N_u = \left(\frac{xq_w}{(T-T_\infty)}\right)_{y=0} \Rightarrow \frac{N_u}{\sqrt{Re}} = -\theta'(0), Sh = \frac{-x\left(\frac{\partial c}{\partial y}\right)_{y=0}}{(C_w - C_\infty)} \Rightarrow \frac{Sh}{\sqrt{Re}} = -\phi'(0) \quad (14)$$

Where$Re = \sqrt{\frac{bx^2}{\vartheta}}$ is the local Reynold 's number.

3. Numerical Solution

The nonlinear ODE's (10)-(12) along with the boundary conditions (13) are solved using MATLAB, where the three-stage Lobatto IIIa formula is performed using the bvp4c finite difference algorithm. To accomplish this, the above-mentioned equations are converted into first-order ODEs as follows:

$$f(1) = f, f(2) = f', \quad f(3) = f''; \quad \theta(1) = \theta, \theta(2) = \theta'; \quad \phi(1) = \phi, \phi(2) = \phi'$$

$$f''' = -f(1)f(2) + \left(M + \frac{1}{k}\right)f(2) - \lambda^2 + \left[f(2)\right]^2$$

$$\theta'' = \frac{-\Pr}{\left(1 + \frac{4R}{3}\right)}\left[Ec\left(f(3)\right)^2 + S\,\theta(1) + f(1)\,\theta(2)\right]$$

$$\phi'' = Sc\left[\gamma\,\phi(1) - f(1)\phi(2)\right]$$

Along with the boundary conditions**,**

$$\boldsymbol{f(0) = 0, f(2) = 1, \theta(0) = 1, \phi(0) = 1}$$
$$\boldsymbol{f(2) \to \lambda, \theta(1) \to 0, \phi(1) \to 0}$$

4. Results and Discussion

The role of the various parameters involved in the coupled ordinary differential equations, such as the velocity ratio λ, source parameter S, the magnetic parameter M, the Schmidt number Sc, the Prandtl number Pr, Radiation parameter R, and the chemical reaction parameter γon the stagnation point flow of hydro magnetic fluid over a linear stretching surface have been explained with the support of their graphs and tabulated values. To confirm the exactness of the current findings, a comparison in conjunction with previously published data was conducted, as shown in Table 1 the similarity was impressive.

Table 1: Comparison of the values of $f''(0)$with those of Ishak et. al [21] and Mustafa et. al [13] for various values of λ= b/a.

λ	Ishak et. al	M. Musthafa et. al	Present result
0	-	-	-1.019
0.1	-0.96954	-0.96954	-0.98128
0.2	-0.91813	-0.91813	-0.92627
0.5	-0.66735	-0.66735	-0.67393
2	2.01767	2.01767	2.00852

In Table 2 as the values of the porosity parameter are inflated, the skin friction values decreased and the Nusselt number, the Sherwood number enhanced. Owing to the resistance force known as the Lorentz force, the velocity and boundary thickness decreased as the magnetic field parameter was increased. The Nusselt number increases as the radiation and the Eckert number rises so that the thermal boundary layer thickness declines as it is shown in the third and fourth part of Table 2. In the fifth part of Table 2, raising the chemical reaction parameter escalated the Sherwood number that shrinks the concentration boundary layer.

For λ <1 i. e., the stretching surface's velocity is higher than the free stream's velocity, the boundary layer thickness and the fluid velocity are enlarged with the upgrade of λ. When the free stream velocity is greater than the velocity of the stretching surface, however, the flow velocity increases and the boundary layer thickness decreases. (i. e., λ >1). In the third case where the two velocities are equal, near the surface there is no boundary layer thickness of the fluid as it is shown in Fig (2). The increase in the value of Magnetic parameter decreases the velocity profile, and the contrary was observed with temperature and concentration profile as shown in Fig (3)-(5), this is because the applied transverse magnetic field produces a retarding Lorentz force. Because of improvements in parameters such as the Radiation parameter (R), Eckert number (Ec), and Source parameter (S), the thermal boundary layer is increased as shown in the Fig (6)-(8). Figures (9) and (10) indicate that as the Schmidt parameter Sc is increased, the concentration profile decreases. The concentration boundary layer thickness drops as the chemical reaction parameter is intensified because higher values of the chemical reaction parameter result in a decrease in chemical molecular diffusivity.

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Table 2: Comparison of the values of $f''(0)$.

λ	k	M	Pr	S	R	Ec	γ	Sc	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
	2								-1.2538	-0.0091	1.11799
0.1	10	0.5	1	0.2	0.2	0.2	0.2	0.1	-1.0761	0.17105	1.12867
	100								-1.0301	0.20711	1.13175
		0.5							-1.2167	0.44111	1.12008
0.1	100	1	1	0.2	0.2	0.2	0.2	0.1	-1.4091	0.38259	1.10981
		1.5							-1.577	0.33535	1.10182
					0.3				-1.2167	0.00743	0.05709
0.1	100	0.01	1	0.2	0.4	0.2	0.2	0.1	-1.2167	-0.0134	1.5506
					0.5				-1.2167	-0.028	2.79238
						0.3			-1.2167	-0.0124	1.57958
0.1	0.01	0.01	1	0.01	0.01	0.4	0.1	5	-1.2167	-0.0602	1.63822
						0.5			-1.2167	-0.1081	1.6969
							0.3		-1.2167	0.0355	-0.0124
0.1	0.01	0.01	1	0.01	0.01	0.01	0.4	5	-1.2167	0.0355	-0.0602
							0.5		-1.2167	0.0355	-0.1081

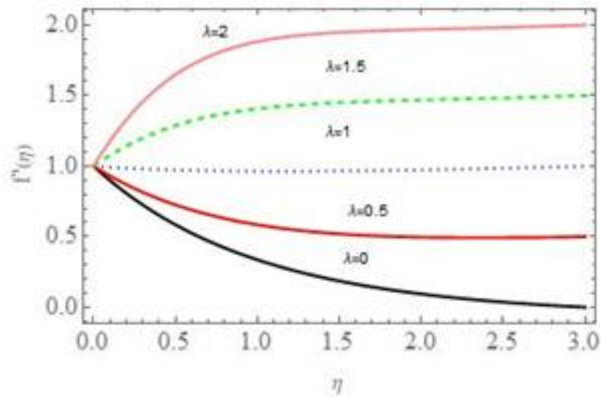

Figure 2: Impact of velocity ratio parameter on velocity

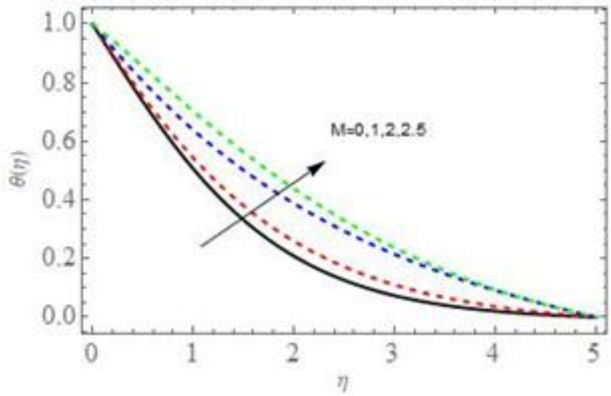

Figure 4: Impact of Magnetic parameter M on Temperature

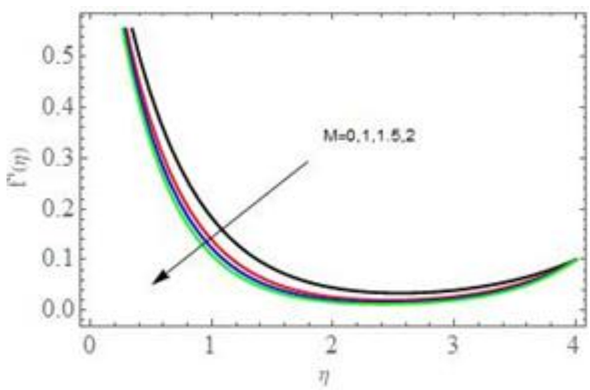

Figure 3: Impact of Magnetic parameter on velocity

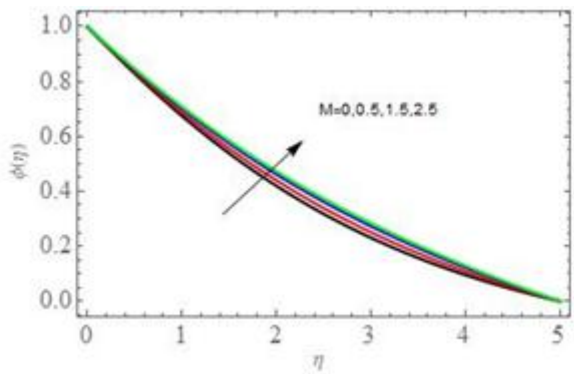

Figure 5: Impact of Magnetic parameter on concentration

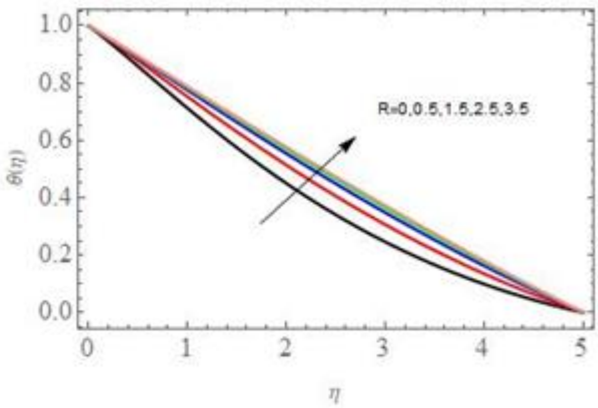

Figure 6: Impact of Radiation (R) on Temperature

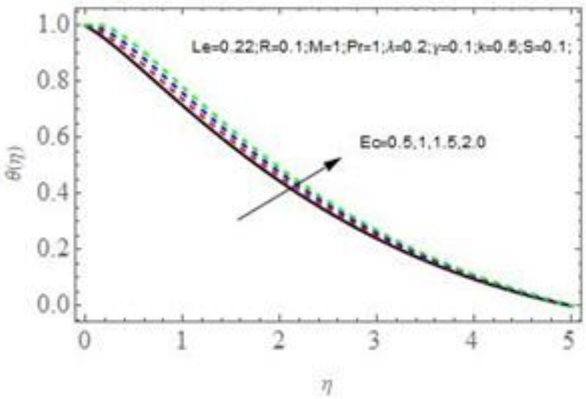

Figure 7: Impact of Eckert number on Temperature

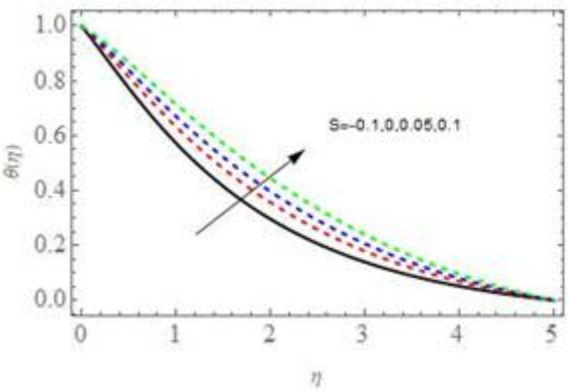

Figure 8: Impact of source parameter on temperature

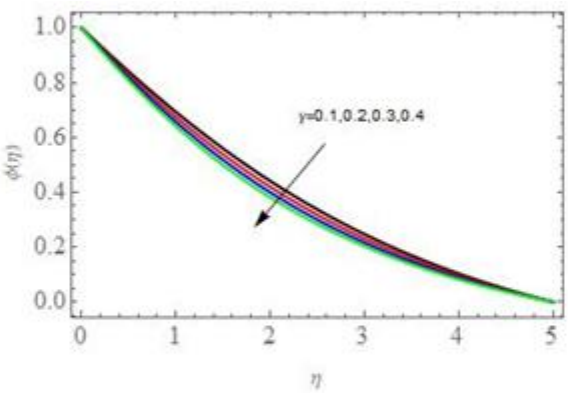

Figure 9: Impact of Chemical reaction parameter on concentration

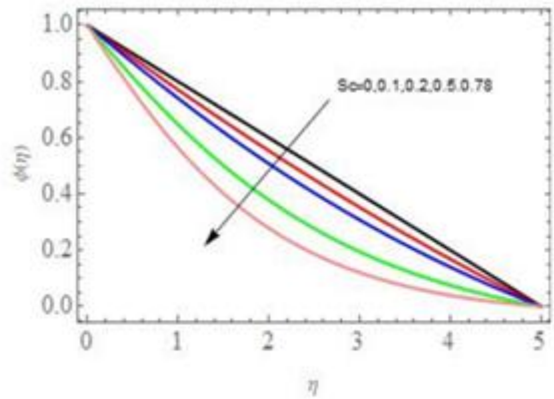

Figure 10: Impact of Schmidt number on concentration profile

5. Conclusion

On MHD stagnation point flow heat and mass transfer in a permeable media, the combined effects of chemical reaction, radiation, and viscous dissipation are numerically explored. Lobatto III A strategy was used to solve the governing problem numerically using MATLAB (bvp4c). From the results the following conclusions can be taken.

1) The velocity profile for λ<1 decreased, whereas the opposite was true for λ>1. Furthermore, in both situations, the temperature profile was reduced.
2) The dimensionless velocity decreases as the magnetic parameter values raise, while in the case of the concentration and temperature their boundary layer thickness increases this is because of the Lornetz force influence on the fluid flow.
3) The temperature profile is boosted by increasing the Eckert number values, due to the reason that the energy gets stored within the fluid region because of the dissipation due to viscosity and elastic deformation.
4) The Schmidt number (Sc) and the chemical reaction parameter (γ) with higher values reduce the concentration boundary layer.
5) The momentum and thermal boundary layer thickness increase as the Radiation parameter is increased.
6) The friction factor is reduced, and the mass transfer rate is improved as the chemical reaction parameter is increased.
7) The rate of heat and mass transport is reduced as the porosity parameter is improved.

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