Significance of chemical reaction on MHD near stagnation point flow towards a stretching sheet with radiation

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Received: 31 March 2020 / Accepted: 3 October 2020 / Published online: 15 October 2020
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Abstract

The influence of variable surface temperature and concentration on MHD stagnation point flow towards a stretching sheet plays an important role in wire coating, film blowing, fiber spinning and coating. In this work an attempt has been made to study the ramification of thermal radiation on MHD chemically reacting liquid past a stretching surface with nonlinear temperature and concentration. The nonlinear coupled governing equations are changed into a set of nonlinear ordinary differential equations by adopting similarity transformations. The set of nonlinear equations together with the boundary conditions are solved computationally by employing shooting technique. The influence of various flow field parameters (magnetic parameter, suction/injection parameter, velocity ratio parameter, heat absorption, radiation, chemical reaction parameter, Schmidt number) on momentum, heat measure, diffusion, skin friction coefficient, rate of heat transfer and rate of mass transfer is depicted and discussed in detail. The outcomes disclosed that the fluid temperature accelerates on rising the thermal radiation and reverse trend with heat absorption parameter. Species concentration diminishes on enhancing the chemical reaction parameter. A comparison has been made with the published results as a particular case and found to be in fair agreement.

Keywords Power law form of surface temperature and concentration · MHD · Thermal radiation · Chemical reaction

List of symbols

B_0	Uniform magnetic field	$Pr = \frac{\nu}{\alpha}$	Prandtl number
a, b, c, n	Constants	q_r	Radiative heat flux (W m^{-1})
c_{fx}	Skin-friction coefficient	q_w	Surface heat flux
c_p	Specific heat at constant pressure ($\text{J kg}^{-1} \text{K}$)	Re_x	Local Reynolds number
$\tilde{C}_w(x) = \tilde{C}_\infty + cx^n$	Concentration of the sheet	Sh_x	Sherwood number
f'	Dimensionless velocity	$\tilde{T}$	Fluid temperature (K)
k	Thermal conductivity of fluid ($\text{W m}^{-1} \text{K}^{-1}$)	$\tilde{T}_\infty$	Temperature far away from the wall (K)
$Kr = \frac{Kr_1 \delta^2}{\nu}$	Chemical reaction parameter	$\tilde{T}_w(x) = \tilde{T}_\infty + cx^n$	Temperature of the sheet
K_s	Rosseland absorption coefficient	$\tilde{u}, \tilde{v}$	Velocity components in x-, y-directions, respectively (m s^{-1})
$R = \frac{4\sigma^* \tilde{T}_\infty^3}{K_s k}$	Radiation parameter	$\tilde{U}_w(x) = ax$	Stretching velocity
Nu_x	Nusselt number	$\tilde{U}_\infty(x) = bx$	Free stream velocity
$M = \frac{\sigma B_0^2}{ap}$	Magnetic parameter	$\tilde{V}_w(x) = -(av)^{0.5} S$	Mass flux velocity
		S	$S > 0$ suction and $S < 0$ injection

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SN Applied Sciences (2020) 2:1822 | <https://doi.org/10.1007/s42452-020-03621-1>

Greek symbols

α	The thermal diffusivity of the fluid
$\gamma = \frac{Q}{\rho c_p}$	Dimensionless heat generation/absorption coefficient
η	Similarity variable
$\epsilon = \frac{b}{a}$	Velocity ratio parameter
$\Omega = \frac{v}{ak}$	Permeability parameter
μ	Dynamic viscosity
ν	Kinematic viscosity ($\text{m}^2 \text{s}^{-1}$)
ρ	Fluid density (kg m^{-3})
σ^*	Stefan–Boltzman constant ($\text{W m}^{-2} \text{K}^{-4}$)
θ	Non-dimensional temperature
ψ	Stream function

Subscripts

W	Sheet surface
∞	Infinity

Superscript

$'$	Differentiation with respect to η
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1 Introduction

Stagnation point flow induced by a variable heated stretching surface is frequently come across in many real-world technical applications such as: emergency core cooling systems, solar central receivers, blood flow problems, flow over tips of rockets, submarines and aircraft, glass production and crude oil purification. In view of these claims, Hayat et al. [1] explored the influence of radiation on MHD stagnation point flow past a vertical porous stretching plate. Pop et al. [2] investigated the influence of thermal radiation on the magneto-hydrodynamic stagnation point flow generated due to a sheet stretching. Bhattacharya et al. [3] presented the steady MHD stagnation point flow and heat transfer of a Casson fluid towards a stretching sheet. Bachok et al. [4] investigated the two-dimensional stagnation point flow over a stretching surface in the presence of nanofluid. Mukhopadhyay et al. [5] studied the combined effects of radiation and variable viscosity on the boundary layer stagnation point flow caused due to sheet stretching. Mabood et al. [6] discussed the simulation of the Cattaneo–Christov model near the stagnation point flow over a stretching surface. A few useful studies on MHD/stagnation point flow over different geometrical aspects are discussed under refs. [7–13].

The impact of chemical reaction on the boundary layer flow has tremendous applications such as: in air and water emissions, fibrous insulation, air flows and

many other chemical engineering problems. Devi et al. [14] inspected the influence of chemical reaction past a semi-infinite horizontal plate. Chamkha et al. [15] examined the chemical reaction and convection flow of the MHD micropolar fluid over a heated vertical plate. Satya Narayana et al. [16] discussed numerically the chemical reaction effect of non-Newtonian fluid over a stretching surface. Magyari and Chamka [17] examined the ramification of chemical reaction and heat absorption/generation on the micropolar liquid flow via a permeable stretching sheet. Ibrahim et al. [18] described the influence of induced magnetic field and chemical reaction on mass and heat transfer mixed convection flow past a vertical sheet. Hussain et al. [19] explored the significance of chemical reaction with ramped surface concentration over a moving plate. Sarojamma et al. [20] explored magnetohydrodynamic non-Newtonian Casson liquid flow past a stretching surface with chemical reaction under various conditions. Azhar et al. [21] deliberated the stagnation point flow of a Jeffrey fluid over a stretching surface with viscous dissipation. Recently, Yusuf et al. [22] demonstrated the effect of non-linear convection flow and chemical reaction in a channel with convective boundary conditions. Khan et al. [23] concentrated stagnation point flow of Buongiorno's nanofluid over radially stretching rotational disk. Numerous researchers [24–29] furnished the effect of chemical reaction/thermal radiation on different physical situations.

The literature reveals that the non-linear surface temperature and concentration play a pivotal role in many engineering and industrial applications such as polymer extrusion process. The research available in this direction is scanty. Hence this mathematical model aims to investigate the influence of chemical reaction and thermal radiation over stretching sheet by considering the power-law form of surface temperature and concentration. The constituted fluid flow equations are changed to ordinary coupled differential equations by utilizing suitable similarity transformations and are resolved by using a shooting technique in conjunction with Runge–Kutta scheme. The impact of prominent parameters on momentum, heat transfer, concentration, rate of heat and mass transfer are explored graphically and the outcomes of the numerical study are tabulated and briefly reported. Arrangement of the paper is as follows. The modeling of the problem with its constituted equations and boundary conditions are defined in Sect. 2. The numerical approach is conferred in Sect. 3. The findings and discussion are represented in Sect. 4 and 5 respectively. Finally, conclusions are presented in Sect. 6.

2 Mathematical formulation of the problem

A steady two dimensional incompressible, electrically conducting and chemically reacting MHD stagnation point flow generated due to a stretching sheet is considered. Let a homogeneous magnetic field is applied in the direction of x-axis which is normal to y (> 0)-direction. The coordinate system and physical model of the problem are depicted in Fig. 1.

Based on aforesaid physical assumptions, the governing flow equations and corresponding conditions are represented by [30].

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

$$\tilde{u} \frac{\partial \tilde{u}}{\partial x} = -\tilde{v} \frac{\partial \tilde{u}}{\partial y} + \tilde{U}_\infty \frac{\partial \tilde{U}_\infty}{\partial x} + \tilde{v} \frac{\partial^2 \tilde{u}}{\partial y^2} - \frac{1}{\rho} B_0^2 \sigma (\tilde{u} - \tilde{u}_\infty) - \frac{\nu}{K} \tilde{u} \quad (2)$$

$$\tilde{u} \frac{\partial \tilde{T}}{\partial x} + \tilde{v} \frac{\partial \tilde{T}}{\partial y} = \alpha \frac{\partial^2 \tilde{T}}{\partial y^2} + \frac{1}{\rho} \frac{Q}{c_p} (\tilde{T} - \tilde{T}_\infty) - \frac{1}{\rho c_p} \frac{\partial q_r}{\partial y} \quad (3)$$

$$\tilde{u} \frac{\partial \tilde{C}}{\partial x} + \tilde{v} \frac{\partial \tilde{C}}{\partial y} = D \frac{\partial^2 \tilde{C}}{\partial y^2} - Kr_1 (\tilde{C}_\infty - \tilde{C}) \quad (4)$$

Subject to the boundaries

At $y = 0$:

$$\tilde{u} = \tilde{U}_w(x), \quad \tilde{v} = \tilde{V}_w(x), \quad \tilde{T} = \tilde{T}_w(x), \quad \tilde{C} = \tilde{C}_w(x) \quad (5)$$

As $y \rightarrow \infty$:

$$\tilde{u} \rightarrow \tilde{U}_\infty(x), \quad \tilde{T} \rightarrow \tilde{T}_\infty, \quad \tilde{C} \rightarrow \tilde{C}_\infty \quad (6)$$

Fig. 1 Physical configuration

The radiative heat flux q_r is defined as $q_r = -\frac{4}{3} \frac{\sigma^*}{K_s} \frac{\partial \tilde{T}^{*4}}{\partial y}$ by utilizing the Rosseland approximation [31]. Use $-\frac{\partial q_r}{\partial y} = \frac{16}{3} \frac{\sigma^* \tilde{T}_\infty^3}{K_s} \frac{\partial^2 \tilde{T}}{\partial y^2}$ such that eq. (3) becomes

$$\tilde{u} \frac{\partial \tilde{T}}{\partial x} + \tilde{v} \frac{\partial \tilde{T}}{\partial y} = \alpha \frac{\partial^2 \tilde{T}}{\partial y^2} + \frac{1}{\rho} \frac{Q}{c_p} (\tilde{T} - \tilde{T}_\infty) + \frac{16}{3\rho} \frac{\sigma^* \tilde{T}_\infty^3}{K_s} \frac{\partial^2 \tilde{T}}{\partial y^2} \quad (7)$$

$$\text{where } \tilde{T}^{*4} = 4\tilde{T} \tilde{T}_\infty^3 - 3\tilde{T}_\infty^4$$

Introducing subsequent similarity transformations [30]:

$$\eta = y \sqrt{a/\nu}, \quad \theta(\eta) = \frac{(\tilde{T}_\infty - \tilde{T})}{(\tilde{T}_\infty - \tilde{T}_w)}, \quad \psi = x \sqrt{avf(\eta)}, \quad \phi(\eta) = \frac{(\tilde{C}_\infty - \tilde{C})}{(\tilde{C}_\infty - \tilde{C}_w)} \quad (8)$$

In view of Eq. (8), the Eqs. (2)–(6) are transformed to:

$$f'''' = -ff'' + f'^2 + \epsilon^2 - M(\epsilon - f') + \Omega f' \quad (9)$$

$$\left(1 + \frac{4R}{3}\right) \theta'' = -Pr[(f)\theta' - nf'\theta + \gamma\theta] \quad (10)$$

$$\phi'' = -Sc(f\phi' - n\phi f' - Kr\phi) \quad (11)$$

$$f'(0) = s, f'(\infty) = \epsilon, f(0) = 0, \theta(0) = 1, \theta(\infty) = 0, \phi(0) = 1, \phi(\infty) = 0 \quad (12)$$

Physical quantities are skin-friction C_{fx} , Nusselt number Nu_x and Sherwood number Sh_x (these are useful in numerous branches of engineering) represented as follows

$$C_{fx} = \frac{\tau_w}{\rho u_e^2} = Re_x^{-0.5} f''(0) \quad (13)$$

$$Nu_x = \frac{1}{k} \frac{x \cdot q_w}{(T_w - T_\infty)} = -Re_x^{0.5} \left(1 + \frac{4}{3}R\right) \theta'(0) \quad (14)$$

$$Sh_x = \frac{x \cdot m_w}{D(C_w - C_\infty)} = -Re_x^{0.5} \phi'(0) \quad (15)$$

3 Numerical procedure

The nonlinear boundary values problem (BVP) described by Eqs. (9)–(11) subject to the boundaries given in Eq. (12) is solved by employing numerical technique i.e. shooting method with R-K fourth order method [32]. In this method, the system of equations are reduced into first order ODE's by employing: $\alpha_1 = f, \alpha_2 = f', \alpha_3 = f'', \alpha_4 = \theta, \alpha_5 = \theta', \alpha_6 = \phi, \alpha_7 = \phi'$ as follows

$$\begin{pmatrix} \alpha'_1 \\ \alpha'_2 \\ \alpha'_3 \\ \alpha'_4 \\ \alpha'_5 \\ \alpha'_6 \\ \alpha'_7 \end{pmatrix} = \begin{pmatrix} \alpha_2 \\ \alpha_3 \\ \alpha_2^2 + \Omega\alpha_2 - \alpha_1\alpha_3 - M(\epsilon - \alpha_2) - \epsilon^2 \\ \alpha_5 \\ \frac{-1}{1+\frac{4R}{3}} [Pr(\alpha_1\alpha_5 - n\alpha_2\alpha_4 + \gamma\alpha_4)] \\ \alpha_7 \\ Sc[n\alpha_6\alpha_2 - \alpha_1\alpha_7 + k_r\alpha_6] \end{pmatrix} \text{ with } \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \\ \alpha_7 \end{pmatrix} = \begin{pmatrix} S \\ 1 \\ x_1 \\ 0 \\ x_2 \\ 0 \\ x_3 \end{pmatrix}$$

The above system of equations are solved computationally with the help of shooting technique depending on the R-K fourth order method by choosing the suitable missing conditions α_3, α_5 and α_7 . However, the step size and convergence criteria are fixed at 0.001 and 10^{-6} respectively.

4 Results

Influence of chemical reaction and radiation on MHD stagnation point flow over a stretching surface with heat source is examined numerically. This section presents the influence of different physical parameters on velocity, heat measure, concentration, skin friction, rate of heat transfer, Sherwood number through Figs. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12.

The velocity profile is described respectively in Figs. 2 and 3 for different values of injection and suction parameters. It is noticed that the velocity of fluid increases with decreasing the injection parameter ($S < 0$), while opposite behavior is seen with increasing suction parameter ($S > 0$).

Fig. 2 Variation of Injection parameter $S (< 0)$ on $f'(\eta)$

Fig. 3 Variation of Suction parameter $S (\geq 0)$ on $f'(\eta)$

Figure 4 portrayed that the velocity profile for different values of M . From this figure, it can be seen that the velocity profile decays on enhancing the values of M . Owing to the reality that, the application of the transverse magnetic field appears to give rise to a resistive kind of force known as Lorentz force which impedes the velocity profile. Thus, the impact of M leads to diminish the velocity field.

Fig. 4 Variation of magnetic field M on $f'(\eta)$

Fig. 5 Variation of ratio parameter ϵ on $f'(\eta)$

Fig. 7 Variation of Radiation parameter R on $\theta(\eta)$

Fig. 6 Variation heat absorption parameter γ on $\theta(\eta)$

Fig. 8 Variation of Chemical reaction parameter Kr on $\phi(\eta)$

Figure 5 depicts the effect of velocity ratio parameter ϵ on $f'(\eta)$. It is seen that $f'(\eta)$ boosts on enhancing the ratio parameter ϵ .

Figures 6 and 7 illustrate the variation of temperature for the distinct values of heat absorption parameter γ and the radiation parameter R . From Fig. 6 it is observed that the non-dimensional temperature declined with an

increase in γ . Physically, the temperature falls when the intensity of heat is minimized. From Fig. 7 it is perceived that the fluid temperature augments on rising values of R . This is because the higher thermal radiation value means a greater heat flux that increases the fluid temperature.

The impact of the chemical reaction parameter Kr and the Schmidt number Sc on the species concentration is

Fig. 9 Variation of Schmidt number Sc on $\phi(\eta)$ Fig. 11 Variation of Pr on Nusselt number against R Fig. 10 a, b Variation of S on Skin friction coefficient against M

displayed respectively in Figs. 8 and 9. The concentration profile decelerates on rising Kr . It is true because the higher values of chemical reaction make fall in the chemical molecular diffusivity. The concentration profile retards on enhancing Sc as noticed in Fig. 9. This is due to the fact that the molecular diffusivity decreases with increase in

Fig. 12 Variation of Kr on Sherwood number against n

Schmidt number. Therefore, the species concentration is high for smaller values of Sc and low for superior values of Sc . Figure 10a, b represent the effect of skin-friction coefficient Cf_x against the magnetic parameter M . It is obvious that Cf_x decrease for decreasing values of S which is shown in Fig. 10a and the reverse trend is noticed for increasing values of S in Fig. 10b. Also noticed that Cf_x decreases with

the rise of magnetic parameter M for both suction and injection. The variation of $-\left(1 + \frac{4}{3}R\right)\theta'(0)$ for different values of Prandtl number Pr and radiation parameter R is shown in Fig. 11. It is observed that $-\left(1 + \frac{4}{3}R\right)\theta'(0)$ augments with an increase in Pr and the reverse trend has seen on augmenting the radiation parameter R . The effect of Kr and n on $-\phi'(0)$ is portrayed in Fig. 12. It is evident that $-\phi'(0)$ increases with an increase in the chemical reaction parameter Kr as well as n .

5 Discussion

The influence of variable surface temperature $T_w(x) = T_\infty + Ax^r$ on laminar flow due to a sheet stretching was theoretically presented by Xu et al. [33]. Further heat and mass transfer of non-Newtonian nanofluid nearby stagnation point flow impinge an oblique wall under the constant condition as $T^* = T_w, C^* = C_w$ was studied by Nadeem et al. [34]. Also, Pal et al. [35] studied the impact of viscous scattering and radiation of the flow nearby stagnation point over the nanofluid stretching surface under the conditions $u_w = \pm cx, T_w - T_\infty = b\left(\frac{l}{x}\right)^{-2}$. More recently, Fenuga et al. [36] demonstrated the heat transfer rate on the non-linear vertical sheet near the stagnation point. In view of these, the present work is focused on the significance of chemical reaction and thermal radiation nearby stagnation point by considering the power-law form of surface temperature $\tilde{T}_w(x) = \tilde{T}_\infty + cx^n$ and surface concentration $\tilde{C}_w(x) = \tilde{C}_\infty + cx^n$. The governing equations are solved numerically by using RK method scheme along with shooting technique. Further, the characteristics of skin-friction coefficient, rate of heat transfer are discussed in Tables 1 and 2 for pertinent physical parameters.

In Table 1, a comparison has made for $f''(0)$ when $M = S = \Omega = R = Kr = Sc = 0$ with Ibrahim et al. [37], Hayat et al. [38] and Agbaje et al. [30] by giving different values to ϵ . It is found that $f''(0)$ increases with an increase in the velocity ratio parameter. Table 2 presents the

Table 2 A numerical analogy for $-\left(1 + \frac{4}{3}R\right)\theta'(0)$ contrary those of Ibrahim et al. [37] and Agbaje et al. [30] for diverse values of ϵ and Pr , when $M = S = \Omega = R = Kr = Sc = n = \gamma = 0$

ϵ	Pr	Ibrahim et al. [37]	Agbaje et al. [30]		Present
			SPM	SQLM	
0.1	1.0	0.6022	0.6022	0.6022	0.602213
0.2	1.0	0.6245	0.6245	0.6245	0.624656
0.5	1.0	0.6924	0.6924	0.6924	0.692455
0.1	1.5	0.7768	0.7768	0.7768	0.776815
0.2	1.5	0.7971	0.7971	0.7971	0.797129
0.5	1.5	0.8648	0.8648	0.8648	0.864800

comparison of $-\left(1 + \frac{4}{3}R\right)\theta'(0)$ for $M = S = \Omega = R = Kr = Sc = n = \gamma = 0$ with Ibrahim et al. [37] and Agbaje et al. [30] for different values of Pr and ϵ . It is observed that Nusselt number enhances on augmenting Pr and ϵ . From these tables, it is thus apparent that the current results are in very good agreement.

6 Conclusion

In this article, the significance of radiation and chemical reaction on MHD stagnation point flow due to sheet stretching is investigated. Power law form of surface temperature and concentrations are considered in this mathematical model. The flow governing equations are solved computationally. The key results in the current research are listed as follows:

1. Fluid momentum amplifies on raising the velocity ratio parameter and opposite trend with suction and magnetic parameters.
2. The dimensionless fluid temperature accelerates for augmenting the thermal radiation parameter and retards with heat absorption parameter.
3. Species concentration retards for rising values of chemical reaction parameter and Schmidt number.

Table 1 A numerical analogy for $f''(0)$ contrary those of Ibrahim et al. [37], Hayat et al. [38] and Agbaje et al. [30] for diverse values of ϵ , when $M = S = \Omega = R = Kr = Sc = 0$

ϵ	Ibrahim et al. [37]	Hayat et al. [38]	Agbaje et al. [30]		Present
			SPM	SQLM	
0.01	- 0.9980	- 0.99802	- 0.9980	- 0.9980	- 0.998043
0.02	-	- 0.99578	- 0.9958	- 0.9958	- 0.996083
0.05	-	- 0.98757	- 0.9876	- 0.9876	- 0.987729
0.10	- 0.9694	- 0.96938	- 0.9694	- 0.9694	- 0.969436
0.20	- 0.9181	- 0.91810	- 0.9181	- 0.9181	- 0.918112
0.50	- 0.6673	- 0.66732	- 0.6673	- 0.6673	- 0.667260
1.00	-	0.00000	-	0.0000	0.000000

4. Skin friction-coefficient rises with suction parameter.
5. Nusselt number increases with growing Prandtl number.

The results of this model are useful in the fields of oil recovery, mass transfer, drying processes and solar Collectors, where variable surface heat and mass transfers are involved.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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