Upshots of cataclysmic chemical reaction and thermophoresis on hydromagnetic flow past an inclined plate

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Abstract. A probe is made into free convection flow of electrically conducting incompressible viscous fluid passing over a plate inclined at some angle to the vertical direction. The fluid is considered to be flown through a porous medium with invariable permeability with non-uniform temperature and concentration. The very essence of this study is to scrutinize the possible effect of thermophoresis and angle of inclination on the event of fluid flow in presence of cataclysmic chemical reaction and external heat absorption. Governing equations after being transformed into suitable non-dimensional forms have been solved numerically using Matlab solver bvp4c. The effects of pertinent flow parameters are assessed. This particular analysis delineates that externally applied magnetic field, chemical reaction, thermophoresis and angle of inclination contribute in reversal of fluid velocity but permeability of porous medium prevents retardation of the same. Presence of heat sink brings down the warmth of the fluid flow. It is reported that cataclysmic chemical reaction and thermophoresis dilute the fluid concentration. Influence of different flow parameters on skin friction and Nusselt number are also examined. Graphical depictions of all these results are put forth for visual substantiation.
Keywords: porous medium, hydromagnetic, chemical reaction, heat absorption, thermophoresis.

1. Introduction

Hydromagnetic flow of a viscous fluid past an inclined plate with heat absorption and chemical reaction under free convection has allured attentions form diverse directions considering the fact that it has fundamental applications in

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various problems of engineering field, for instance in chemical and metallurgical industries, in nuclear reactors for cooling purpose, etc.

Pop et al. [1] have discussed free convection boundary layer over a flat plate with a uniform surface with heat flux which is inclined at a small angle to the horizontal. Keller box numerical method has been employed to obtain the solution. An extensive formulation natural convection over an inclined heated plate is put forwarded by Umemura and Law [2]. Unsteady natural convection hydromagnetic flow past a plate with inclination with heat and mass fluctuation has been inspected by Ganesan and Palani [3]. They have employed finite difference method for analysis of the problem. Chen [4] has carried out the study of heat and mass transfer in magnetohydrodynamic flow past a permeable inclined plate taking Ohmic heating and viscous dissipation into consideration. Kandasamy and Devi [5] have ascertained the aftermath of chemical reaction, heat and mass transfer on non-linear hydrodynamic flow over a wedge with suction and injection. The problem of radiative heat and mass transfer over an inclined plate in presence of chemical reaction has been discussed by Kumar [6].

Free convection MHD heat and mass transfer flow past an inclined plate with heat generation has been studied by Alam et al. [7]. For solving the problem a particular shooting iteration procedure have been applied by them. Uddin and Kumar [8] have examined unsteady fluid flow with viscous dissipative heat past an inclined plate imbedded in a perforated medium. Fluid flow past a plate inclined to horizontal with fluctuating surface temperature under convection effects has been scrutinized by Palani [9]. Their studies bring forth the observation that angle of inclination of the plate retards the tempo of fluid flow and coefficient of heat transfer. Singh and Makinde [10] have inspected computational dynamic of free convection electrically conducting fluid flow along an inclined plate in presence of Newtonian heating and volumetric heat source. Pattnaik et al. [11] have elucidated radiation and mass transfer aftermath on free convection electrically conducting fluid through porous medium. Influence of heat radiation on unsteady flow past an inclined plate with cataclysmic chemical reaction has been assessed by Barik et al. [12].

Navier slip and Newtonian heating condition on MHD flow using computational modelling has been evaluuated by Makinde [13]. Mishra et al. [14] have examined the influence of spatial and thermal transfer on a viscoelastic fluid with suction and heat generation. Conjugated impact of variable thermal and concentration shift on free convective electromagnetic flow past an impulsively started plate has been realised by Ali et al. [15]. Similarity transformation of heat as well as mass transfer consequence on MHD dissipative fluid passing over an inclined porous surface with chemical reaction has been investigated by Reddy et al. [17]. They utilised numerical technique to obtain the solution. Raju et al. [18] have inspected heat transfer effects on a dissipative viscous fluid past a vertical plate in presence of induced magnetic field. They have assumed the plate to be electrically non-conducting.

Reddy et al. [19] have scrutinized the influence of chemical reaction, radiation and rotation on electrically conducting nanofluid flow past a permeable plate in porous medium. Analytical solution for heat and mass transfer flow past a semi-infinite vertical porous plate with huge suction has been discussed by Khan et al. [20]. Selvarani and Govindarajan [21] have examined radiative fluid flow over an inclined plate. The duo have considered a nanofluid flow and the plate to be in nonuniform surface temperature. Free convection viscous dissipative flow past an inclined plate with heat transfer effects has been studied by Palani and Arutchelvi [22].

Thermophoresis is the movement of minuscule particles suspended in a nonisothermal fluid. The suspended particles due to presence of thermal gradient acquire a velocity relative to the fluid in the direction of retarding temperature. Such type of phenomenon has useful applicability in inventory drug mechanism, aerosol reactors, heat exchange fouling etc. Selim et al. [23] have discussed the effect of surface mass transfer on mixed convection flow past a heated vertical flat permeable plate with thermophoresis. Postelnicu [24] has examined the consequences of thermophoresis particle deposition in free convection boundary layer from a horizontal flat plate embedded in a porous medium. Effects of thermophoresis and radiation on laminar flow along a semi-infinite vertical plate has been analysed by Bakier and Gorla [25].

Noor et al. [26] have explored influence of heat and mass transfer of thermophoretic MHD flow over an inclined isothermal permeable surface in the presence of radiation and heat source/sink. Kundu et al. [27] have investigated combined effects of thermophoresis and chemical reaction on magnetohydrodynamic convection flow. Thermophoretic hydromagnetic dissipative heat and mass transfer with lateral mass flux, heat source, Ohmic heating and thermal conductivity effects have been explored by Zeuco et al. [28].

The essence of this probe is to scrutinize the possible effect of thermophoresis and angle of inclination on the event of fluid flow in presence of cataclysmic chemical reaction and external heat absorption in view of some physical situations,in particular drainage mechanism where the geometry of flow gets situated in situations other than two extreme positions viz.vertical and horizontal plate.

2. Formulation of the problem

A free convective flow of a viscous fluid past a semi-infinite plate is considered. The fluid is taken to be viscous and incompressible. The plate is inclined at an angle ψ to the vertical and is considered to be at constant concentration gradient. The flow is along the plate. $\overline{X}$ axis is considered along the plate and $\overline{Y}$ axis perpendicular to it. A uniform magnetic field of strength B_0 is applied parallel to $\overline{Y}$ axis. Induced magnetic field is neglected under the criteria that the magnetic Reynolds number is very small. Under Boussinesq's approximation, the boundary layer equations of mass, momentum, energy and concentration past an inclined plate are given by

$$\frac{\partial V}{\partial \overline{Y}} = 0 \Rightarrow V = \text{constant} = -V_W, V_W > 0, \tag{1}$$

$$V\frac{\partial U}{\partial \overline{Y}} = \nu \frac{\partial^2 U}{\partial \overline{Y}^2} - \frac{\sigma B_0^2}{\rho} U - \frac{\nu}{K_P} U \\ + g\beta (T - T_\infty) \cos\psi + g\bar{\beta} (C - C_\infty) \cos\psi, \tag{2}$$

$$V\frac{\partial T}{\partial \overline{Y}} = \frac{\kappa}{\rho C_P} \frac{\partial^2 T}{\partial \overline{Y}^2} + \frac{\nu}{C_P} \left(\frac{\partial U}{\partial \overline{Y}}\right)^2 - \frac{Q}{\rho C_P} (T - T_\infty), \tag{3}$$

$$V\frac{\partial C}{\partial \overline{Y}} = D\frac{\partial^2 C}{\partial \overline{Y}^2} - K_C (C - C_\infty) - \frac{\partial}{\partial \overline{Y}} [V_T (C - C_\infty)], \tag{4}$$

where U and V are velocity components along $\overline{X}$ and $\overline{Y}$ respectively, ν is kinematic viscosity, β, $\bar{\beta}$ are coefficients of thermal and spatial expansion, respectively, T, C are fluid temperature and concentration, respectively, T_∞,C_∞ are respective fluid temperature and concentration far away from the plate, σ is electrical conductivity, ρ is density of the fluid, K_P is permeability coefficient, κ is thermal conductivity, Q is heat absorption coefficient, C_P is specific heat at constant pressure, D is mass diffusion coefficient, K_C is rate of chemical reaction and $V_T(= -\frac{\nu K_T}{T_r}\frac{\partial T}{\partial \overline{Y}})$ is thermophoretic velocity with K_T and T_r being thermophoretic coefficient and reference temperature respectively.

The boundary conditions are:

$$\overline{Y} = 0, U = U_W, T = T_W, -D\frac{\partial C}{\partial \overline{Y}} = C_W, \\ \overline{Y} \to \infty, U \to 0, T \to T_\infty, C \to C_\infty, \tag{5}$$

where U_W, T_W are velocity and temperature at the plate and C_W is concentration gradient at the plate.

For convenience, the following dimensionless variables and physical quantities are introduced:

$$\eta = \frac{\overline{Y}}{V_W}, f = \frac{U}{U_W}, \theta = \frac{T - T_\infty}{T_W - T_\infty}, \\ \phi = \frac{(C - C_\infty)V_W D}{C_W \nu}, G_r = \frac{g\beta(T_W - T_\infty)\nu}{U_W V_W^2}, G_m = \frac{g\bar{\beta} C_W \nu^2}{U_W V_W^3 D}, \\ M = \frac{B_0^2 \nu \sigma}{V_W^2 \rho}, P_r = \frac{\rho \nu C_P}{\kappa}, K = \frac{K_P V_W^2}{\nu^2}, \\ S_C = \frac{\nu}{D}, E = \frac{U_W^2}{(T_W - T_\infty)C_P}, S = \frac{Q\nu}{\rho C_P V_W^2}, \\ \gamma = \frac{\nu K_C}{V_W^2}, \delta = -\frac{K_T(T_W - T_\infty)}{T_r}, \tag{6}$$

where η is dimensionless ordinate, f is dimensionless velocity in the direction of the plate, θ and ϕ are non-dimensional temperature and species concentration,G_r and G_m are Grashof numbers for heat transfer and mass transfer respectively, M is magnetic parameter, P_r is Prandtl number,$K$is permeability parameter, S_C is Schmidt number, E is Eckert number, S is heat absorption parameter, γ is chemical reaction parameter and δ is thermophretic parameter.

Using introduced surrogates from (6) in the Equations (2) to (4), the following demensionless equations are obtained:

$$f'' = -f' + \left(M + \frac{1}{K}\right) f - G_r \theta \cos\psi - G_m \phi \cos\psi, \tag{7}$$

$$\theta'' = -P_r \theta' + P_r S \theta - P_r E \left(f'\right)^2, \tag{8}$$

$$\phi'' = -S_C \phi' + S_C \gamma \phi + S_C \delta \left(\phi \theta'' + \phi' \theta'\right). \tag{9}$$

Boundary conditions represented by (5) transmute into the following shape:

$$\begin{aligned} &\eta = 0, f = 1, \theta = 1, \phi' = -1 \\ &\eta \to \infty, f \to 0, \theta \to 0, \phi \to 0. \end{aligned} \tag{10}$$

3. Method of solution

The Equations (7) to (9) with the boundary conditions (10) have been solved numerically using Matlab's built in solver bvp4c. The dimensionless velocity, skin friction, temperature, Sherwood number and concentration are represented in pictorial form with the help of graphs obtained through the computing environment supported by Matlab.

4. Results and discussion

The graphical delineations of the fluid locomotion and its thermal and spatial transfer affairs bring out the impact of various parameters that dictate flow of the fluid. Amongst the visible influences of different pertinent flow parameters, thermophoresis along with chemical reaction have been kept around the nucleus of the observation. Moreover, the effect of inclined plate on the fluid mobility and other flow characteristics has been observed. It has been emphasised that the angle of inclination is acute with exclusion of both the extreme values ($\psi = 0$ and $\psi = \pi/2$). This study is carried out with numeric values of parameters as $G_r = 5, G_m = 6, P_r = 2.4, M = 2, K = 0.5, E = 0.01, S = 2, S_C = 0.4, \psi = \pi/4, \gamma = 0.5$ and $\delta = 0.7$ unless otherwise stated.

Figures 1-6 evince the velocity profile for some key flow parameters. The profiles depict the behaviour of velocity in the region of fluid flow. It is observed that velocity drops suddenly in the vicinity of the plate and then maintains slow and steady diminution to the boundary condition away from the plate.

Figure 1 displays the impact of permeability of porous medium on velocity. The locomotive strength of the fluid gets encouraged with the rise of permeability parameter (K). Influence of magnetic parameter (M) on velocity is shown in Figure 2. It disposes the fact that growth in the intensity of magnetic field inflicts a retarding effect on fluid velocity. Figure 3 presents the role of angle of inclination of the plate in mobility of fluid. While excluding the extreme values of angle of inclination, ψ $(0 < \psi < \pi/2)$, it is spotted that an increment in angle of inclination dwindles the velocity. Effect of chemical reaction parameter(γ), thermophoretic parameter(δ) and heat absorption parameter(S) have been represented by Figure 4, Figure 5 and Figure 6 respectively. In all the cases, an increment in the parameters results into a significant depletion in the velocity of the fluid.

Figures 7-11 illustrate the impact of permeability parameter, magnetic parameter, angle of inclination, chemical reaction parameter and thermophoretic parameter on skin friction (S_F). In view of maintaining uniformity, the impact of fore-said parameters are measured against different values of thermal Grashof number (G_r).

Figure 7 elucidates that with the hike in numerical values of permeability , the skin friction gets enhanced. Influence of magnetic parameter on skin friction has been exhibited in Figure 8. It proclaims the fact that with a hoist in magnetic parameter the skin friction gets elevated. Figure 9 assists in visualising the effect of angle of inclination the plate on skin friction. It helps in comprehending that angle of inclination induces a hindering effect on skin friction. However, the amount of hindrance inflicted for a specific position of inclination shows some fluctuation with reference to thermal buoyancy(G_r). Figure 10 and Figure 11 illustrate that chemical reaction and thermpophoresis prompt escalation in skin friction.

Figure 12 to Figure 14 elucidate the sleek variation of temperature all over the region of fluid flow. Figure 12 exhibits that with declination in thermal diffusion (i.e. rise in Prandtl number, P_r) prompts drop in fluid temperature while Figure 13 confirms that increment in kinetic energy relative to enthalpy (i.e. increase in Eckert number,E) induces rise in temperature of the fluid. Further, intensification of strength of heat absorption (S) cast significant reduction in temperature as demonstrated by Figure 14.

Figure 15 to Figure 17 demonstrate the impact of chemical reaction, thermophoresis and inclination of the plate on Nusselt number(Nu). Figure 15 and Figure 16 illustrate that inflation in chemical reaction parameter (γ) and thermophoresis parameter(δ) have impeding influence on the Nusselt number. This suggests that more there are cataclysmic chemical reaction and thermophoresis near the plate,less is the rate of heat transfer. However, increment in angle of inclination instigates an escalation in Nusselt number which is shown by Figure 17.

Figure 18 to Figure 20 represent the effect of relevant flow parameters on species concentration. Figure 18 depicts the effect of Schmidt number(S_C) on species concentration. It is noticed that a surge in Schmidt number reduces the concentration. Similar impact on species concentration is inflicted by chemical reaction parameter and thermophoresis parameter as indicated by Figure

19 and Figure 20, respectively. Thus, denser fluid species with low diffusion (larger S_C values) exposed to high rates of cataclysmic chemical reaction and thermophoresis results into diminution of the concentration throughout the flow region.

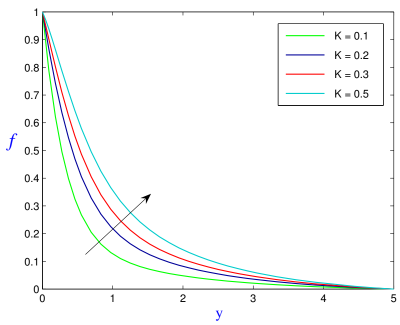

Figure 1: Velocity for K

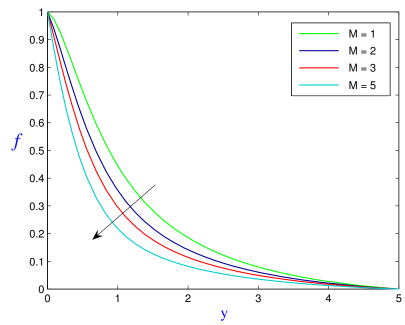

Figure 2: Velocity for M

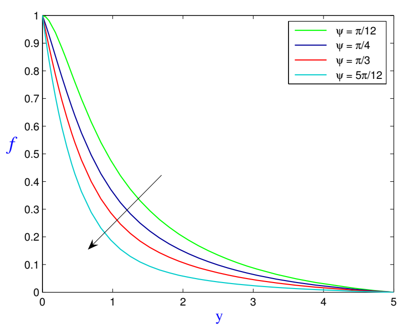

Figure 3: Velocity for ψ

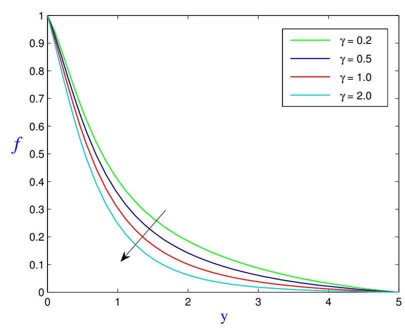

Figure 4: Velocity for γ

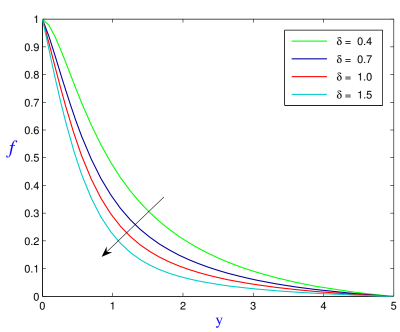

Figure 5: Velocity for δ

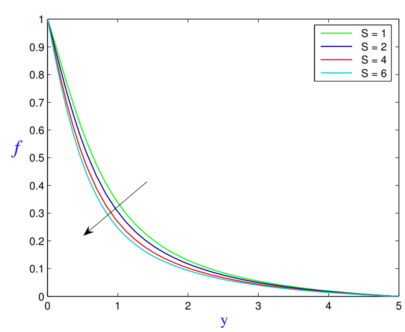

Figure 6: Velocity for S

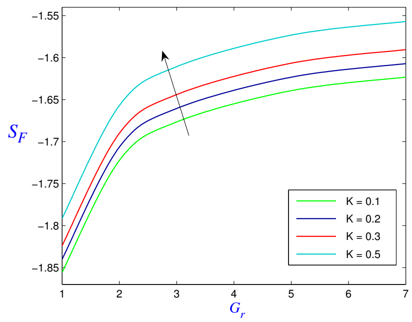

Figure 7: Skin friction for K

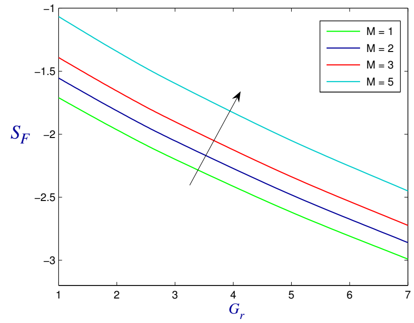

Figure 8: Skin friction for M

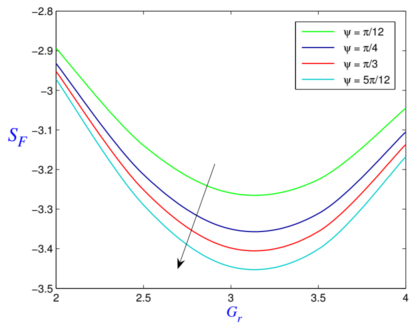

Figure 9: Skin friction for ψ

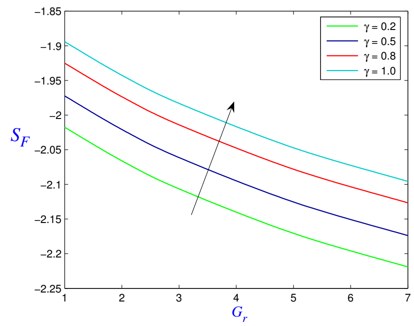

Figure 10: Skin friction for γ

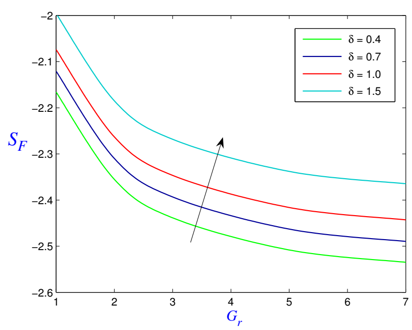

Figure 11: Skin friction for δ

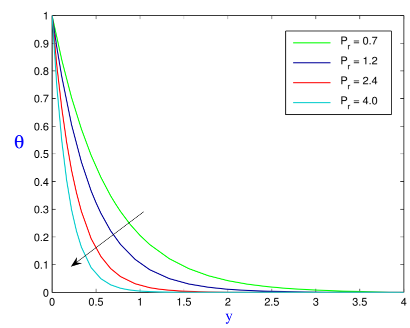

Figure 12: Temperature for P_r

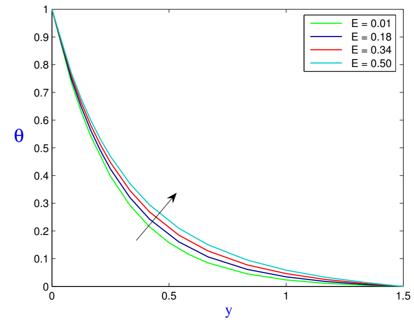

Figure 13: Temperature for E

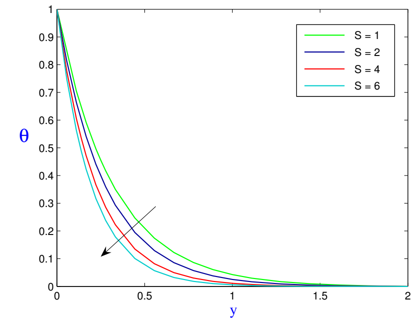

Figure 14: Temperature for S

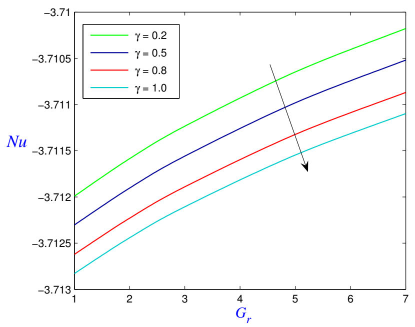

Figure 15: Nusselt number for γ

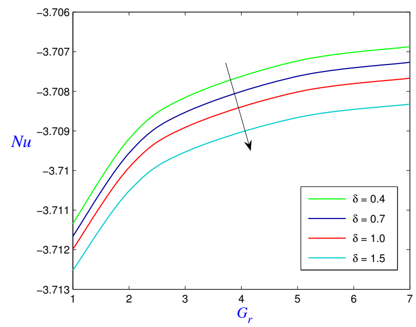

Figure 16: Nusselt number for δ

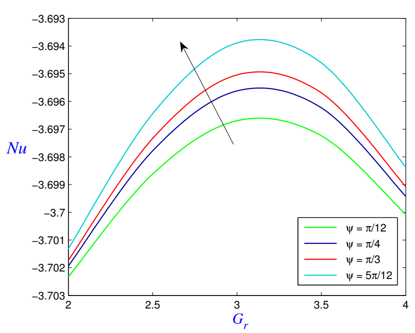

Figure 17: Nusselt number for ψ

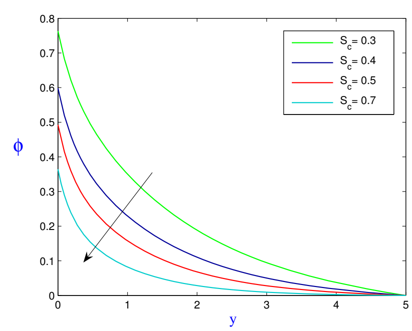

Figure 18: Concentration for S_C

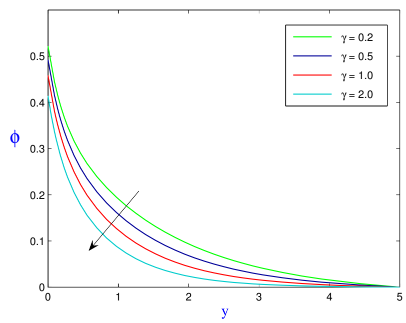

Figure 19: Concentration for γ

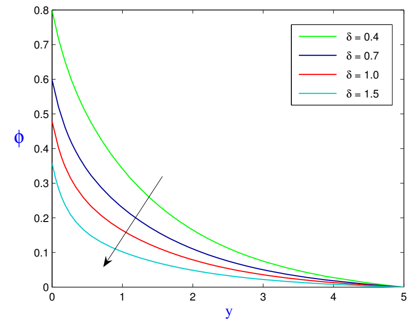

Figure 20: Concentration for δ

5. Conclusion

The present exploration regarding free convection flow of electrically conducting incompressible viscous fluid past a plate inclined at some angle under the effect of thermophoresis, cataclysmic chemical reaction and external heat absorption unveils some interesting inferences.

It is observed that intensification of magnetic parameter inflicts hindrance to fluid velocity while the same action on permeability of porous medium offers assistance to growth of velocity. Angle of inclination of the plate and thermophoresis impose impeding effect in forward locomotion of the fluid. Further, inflation in cataclysmic chemical reaction and heat absorbing source have dwindling effect on flow velocity.

An increment in the angle of inclination of the plate intrudes a reduction in skin friction while rise in magnetic parameter and permeability parameter encourages increase in skin friction. Thermophoresis and chemical reaction, when escalated, bring about growth in values of skin friction.

The temperature of the fluid flow gets lowered with the elevation in values of Prandtl number and heat absorption parameter while an opposite scenario is observed with the increment of Eckert number.

An increment in the angle of inclination encourages the growth of Nusselt number. However, increment in rate of chemical reaction and thermophoresis inflict suppressing effect on Nusselt number.

The concentration of the fluid flow erodes with the inflation in Schmidt number, chemical reaction parameter and thermophoreis parameter.

Acknowledgement

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