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Chemically Reactive Nanofluid Flowing across Horizontal Cylinder

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Abstract

The objectives of this work are to build a mathematical model for the nanofluid flow problem in the presence first order chemical reaction. The flow over an isothermal horizontal circular cylinder is selected due to many engineering applications for this geometry. A set of nonlinear partial differential equation, coupled, that describes the physical behavior of the problem under study was derived. Numerical ways, finite element techniques, were used to treat the mathematical model. The most important quantities that have a good effect on the physical matter that appeared in the mathematical definition are the dimensionless chemical reaction parameter, the Brownian motion parameter and the thermophoresis parameter.

The influence of these dimensionless quantities on the velocity, temperature and concentration profiles is drawn graphically. Moreover, the influence on the engineering measures that have physical implementation, such as the local skin-friction coefficient, Nusselt Number, and Sherwood number are also discussed. It is observed that increasing chemical reaction parameter Λ tends to decrease velocity and concentration values but slightly enhances temperatures in the flow field; a rise in Λ also enhances values of the local Sherwood number but strongly reduces the local Nusselt number at the cylinder surface as so as the local surface shear stress function.

Keywords: Nanofluid, Cylinder, Chemical reaction, Free convection.

1. Introduction

One real-world application that considers a nanofluid with a linear chemical reaction is the use of such fluids in catalytic reactors. In these reactors, a catalytic material is suspended in a fluid and used to facilitate chemical reactions, such as the conversion of feedstocks into useful products. The use of nanofluids in catalytic reactors can enhance the reaction rate and efficiency, due to the improved heat and mass transfer properties of the fluid and the increased surface area of the catalytic particles. Other potential applications of nanofluids with linear chemical reactions include the use in fuel cells and in chemical processing industries [1,2].

Convective heat transfer of nanofluids has been studied extensively. The nanofluid was proposed by Choi [3] to indicate colloids due to the presence of nanoparticles that are detached in a base fluid. Nanofluid is a conventional liquid like water, oil or ethylene glycol that contains a suspension of solid nanoparticles of size up to 100 nm diameter.

Nanofluids is a heat transfer fluid with better thermal properties. The improved property of nanofluids is the thermal conductivity as reported by Masuda et al. [4]. Such improvement referred to the size, shape, concentration, and thermal properties of the solid nanoparticles. The larger relative surface area of nanoparticles significantly improves the heat transfer potential and also increases the stability of the suspension. The existence of nanoparticles in fluid can also improve abrasion resistance properties over the conventional solid-fluid mixtures. The use of nanofluids will hold up the design of smaller and lighter heat transfer systems, Keblinski et al. [5]. Many researchers studied the mechanisms behind the enhancement of heat transfer characteristics using nanofluids. Das et al. [6] and Khanafer et al [7] collect a lot of papers on this matter. The study of transfer phenomena of nanofluids flow is of enormous meaning in many divisions of applied science applications such as cooling and heating, medical field and safe surgery, and different applications manufacturing of electronic devices. Buongiorno [8] made a complete review of convective flow of nanofluids.

He considered seven slip conditions that can create a relative velocity between the nanoparticles and the base fluid. The only important mechanisms were found to be the Brownian diffusion and thermophoresis. Many studies also discussed the enhancement in the thermal properties, conductivity, of nanofluids, see Bachok et al. (9), Khanafer et al. [7] and Makinde and Aziz [10]. Yu et al. [11] show experimentally that the characteristic improvements in thermal conductivity are noticed over the ordinary fluid and the improvements in the heat transfer coefficient will

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be up to 40 %. The thermal conductivity increases two times when little quantity of nanoparticles is added to the ordinary fluids, Choi et al. [12].

The convection flow over a horizontal circular cylinder were described by Sparrow and Lee [13], Ingham [14], Sadeghipour and Hannani [15]. Additional investigations of flow over a cylindrical geometry have been reported by Kaminski et al [16]. The convective mass transfer problem has been presented by Hyung et al [17]. Cesini et al [18] and Karniadakis [19] studied the force convection case. Rebhi A. Damseh [20] also studied the flow of a viscous incompressible fluid across an isothermal horizontal cylinder with the appearance and inclusion of some dust particles.

Studying the problem of heat and mass transfer in a moving chemically reactive fluid undergoing exothermic and endothermic chemical reaction is of great importance in many physical applications. A chemical reaction, in any chemical engineering processes, occurs between a strange mass and the occupation fluid. The chemical reaction order depends on several means. The straightforward chemical reactions are the first order reaction where the rate of reaction is in direct proportion to the species attentiveness. Chamkha [21] and Damseh et Al. [22] addressed the heat and mass transfer problem of the steady and unsteady flowing fluid of an electrically conducting fluid and the visco-elastic fluid in the presence of a first-order chemical reaction. They found that the friction coefficient decreased as the values of the chemical reaction parameter decreased. Other articles dealing with chemical reactions and thermophoresis effect on heat and mass transfer problems can be found in [23–29].

References [30-33] explore the topic of chemically reactive nanofluids flowing across a horizontal cylinder, with a focus on the effects of chemical reactions on convective heat transfer and fluid flow. The studies use experimental and modeling approaches to investigate the influence of various nanofluid properties on heat transfer and flow behavior. Findings from these studies could have potential applications in fields such as chemical processing and energy generation.

The novel aspect of chemically reactive nanofluids flowing across a horizontal cylinder lies in their unique properties, which are caused by the presence of nanoscale particles suspended within the fluid. These particles can enhance the thermal conductivity and viscosity of the fluid, leading to improved heat transfer and flow characteristics. In addition, the chemical reactivity of the nanofluids can be exploited for a variety of applications, including in chemical processing and energy generation. The study of these fluids and their behavior as they flow across a cylinder is an active area of research.

2. Mathematical Model

Let us use the case of steady, laminar, two-dimensional, incompressible, natural driven convection heat and mass transfer problem. The fluid with existence of nano species past flows over an isothermal horizontal circular cylinder of radius, r, in the presence of first order chemical reaction as shows Figure 1. The coordination system for tangential x is measured along the circumference of the horizontal cylinder and the radial y axis is perpendicular to the cylinder surface.

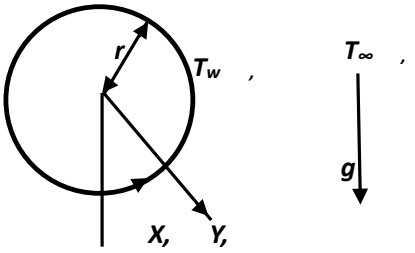

Figure 1. Physical model and coordinate system

Little concentration of reactive soluble particles is diffusing in the fluid so that thermal energy created through the chemical reaction may be discarded. Initially, the horizontal cylinder and the naofluid are maintained at the same temperature and concentration. Immediately, the temperature of the naofluid is raised to a temperature T_w which is greater than that of the ambient naofluid T_∞. The concentration of the reactive species is continued at a constant scale. The concentration at $y = 0$, cylinder surface equal C_w . The reaction of the species at bulk nanfluid is considered as a first order homogenous chemical reaction with concentration equal to C_∞. In the convective flow, the direction of gravity acts downward. When applying the Boussinesq approximation and constant thermophysical properties, the governing boundary layer equations, continuity, momentum, heat, and mass conservation can be drawn as below [34, 35]:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{1}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=\nu\frac{\partial^2 U}{\partial Y^2}+ g\beta_T\left(T-T_\infty\right)\sin(\frac{X}{r})+g\beta_C\left(C-C_\infty\right)\sin(\frac{X}{r}) \tag{2}$$

$$U\frac{\partial T}{\partial X}+V\frac{\partial T}{\partial Y}=\alpha_n\left(\frac{\partial^2 T}{\partial Y^2}\right)+ \tau\left[D_B\frac{\partial C}{\partial Y}\frac{\partial T}{\partial Y}+\left(\frac{D_T}{T_\infty}\right)\left(\frac{\partial T}{\partial y}\right)^2\right] \tag{3}$$

$$U\frac{\partial C}{\partial X}+V\frac{\partial C}{\partial Y}=D_B\left(\frac{\partial^2 C}{\partial Y^2}\right)+\left(\frac{D_T}{T_\infty}\right)\frac{\partial^2 T}{\partial Y^2}-\gamma C \tag{4}$$

U and V are the velocity components along the X and Y directions, g is the acceleration due to gravity, ρ is the fluid density, β_T is the coefficient of thermal expansion, β_C is the coefficient of concentration expansion, ν is the kinematic viscosity, T and C are the temperature and concentration, D_B is the Brownian diffusion coefficient, and D_T is the thermophoretic diffusion coefficient. The term $\alpha_n=k_n/\left(\rho c_p\right)_f$ is the thermal diffusivity of the nanofluid. The $\tau=\left(\rho c_p\right)_p/\left(\rho c_p\right)_f$ is the ratio between the heat capacity of the spherical nanoparticles and that of the base fluid.

The no-slip boundary conditions are given by:

$$Y=0: \quad U=0, \quad V=0, \quad T=T_w, \quad C=C_w$$
$$Y\to\infty: \quad U=0, \quad T=T_\infty, \quad C=C_\infty \tag{5}$$

The viscosity, density, heat capacitance and the effective thermal conductivity of the nanofluid are defined as given by H.C. Brikman [36] and R. I. Hamilton et all [37] respectively:

$$\mu_n=\frac{\mu_f}{(1-\varphi)^{2.5}} \tag{6}$$

$$\rho_n=(1-\varphi)\rho_f+\varphi\rho_s \tag{7}$$

$$(\rho c_p)_n=(1-\varphi)(\rho c_p)_f+\varphi(\rho c_p)_s \tag{8}$$

$$\frac{k_n}{k_f}=\frac{k_s+(n-1)k_f-(n-1)(k_f-k_s)\varphi}{k_s+(n-1)k_f+(k_f-k_s)\varphi} \tag{9}$$

Where; n is the nanoparticle shape factor and φ is the nanoparticle volume fraction.

To solve equations (1-5) the non-dimensional variables are set to be:

$$x=\frac{X}{r}, \quad y=\frac{Y}{r}Gr^{1/4}, \quad u=\frac{rU}{\nu Gr^{1/2}},$$
$$v=\frac{rV}{\nu Gr^{1/4}}, \quad \theta=\frac{T-T_\infty}{T_w-T_\infty}, \quad \varphi=\frac{C-C_\infty}{C_w-C_\infty},$$
$$Gr=\frac{g\beta_T(T_w-T_\infty)r^3}{\nu^2}, N=\frac{\beta_C(C_w-C_\infty)}{\beta_T(T_w-T_\infty)}, \tag{10}$$
$$\Pr=\frac{\nu}{\alpha_m}, \quad Sc=\frac{\nu}{D_B}, \quad \Lambda=\frac{\gamma r^2}{\nu Gr^{1/2}}$$
$$N_B=\frac{\tau D_B(C_w-C_\infty)}{\alpha_n}, N_T=\frac{\tau D_T(T_w-T_\infty)}{T_\infty\alpha_n}$$

x and *y* are dimensionless coordinates. *u* and *v* are dimensionless velocities. *Gr*, *Pr* and *Sc* are Grashof number, Prandtl number and Schmidt number respectively. θ and *C* are the dimensionless temperature and concentration. Λ is the dimensionless chemical reaction parameter, *N* is the buoyancy ratio parameter, N_B is the Brownian motion parameter, and N_T is the thermophoresis parameter.

Now substituting equation (10) into equations (1–5), we come across the governing differential equations for the system as below:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{11}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial Y}y=\frac{\partial^2 u}{\partial y^2}+[\theta+N\varphi]\sin(x) \tag{12}$$

$$u\frac{\partial\theta}{\partial x}+v\frac{\partial\theta}{\partial y}=\frac{1}{\Pr}\left[\frac{\partial^2\theta}{\partial y^2}+N_B\frac{\partial\theta}{\partial y}\frac{\partial\varphi}{\partial y}+N_T\left(\frac{\partial\theta}{\partial y}\right)^2\right] \tag{13}$$

$$u\frac{\partial\varphi}{\partial x}+v\frac{\partial\varphi}{\partial y}=\frac{1}{Sc}\left[\left(\frac{\partial^2\varphi}{\partial y^2}\right)+\frac{N_T}{N_B}\frac{\partial^2\theta}{\partial y^2}\right]-\Lambda\varphi \tag{14}$$

The transformed boundary conditions for the equations (11–14) are

$$y=0: \quad u=0, \quad v=0, \quad \theta=1, \quad \varphi=1$$
$$y\to\infty: \quad u=0, \quad \theta=0, \quad \varphi=0 \tag{15}$$

In order to solve equations (11–14), subject to boundary conditions (15), we use the following variables:

$$\psi=xf(x,y), \quad u=\frac{\partial\psi}{\partial y}, \quad v=-\frac{\partial\psi}{\partial y} \tag{16}$$

Substituting equation (16) into equations (11–15), we can finally write the transformed equations as:

$$f'''+ff''-f'^2+(\theta+N\varphi)\frac{\sin x}{x}=x\left(f'\frac{\partial f'}{\partial x}-f''\frac{\partial f}{\partial x}\right) \tag{17}$$

$$\theta''+\left(N_B\theta'\varphi'+N_T(\theta')^2\right)+\Pr f\theta'=\Pr x\left(f'\frac{\partial\theta}{\partial x}-\theta'\frac{\partial f}{\partial x}\right) \tag{18}$$

$$\varphi''+\frac{N_T}{N_B}\theta''+Sc\,f\varphi'+-Sc\Lambda\varphi=Sc\,x\left(f'\frac{\partial\varphi}{\partial x}-\varphi'\frac{\partial f}{\partial x}\right) \tag{19}$$

Equations (17-18) are subjected to the following generated:

$$f'(x,0)=0, \quad f(x,0)=0, \quad \theta(x,0)=1, \quad \varphi(x,0)=1$$
$$f'(x,\infty)=0, \ \theta(x,\infty)=0, \quad \varphi(x,\infty)=0 \tag{20}$$

Here, Ψ is the stream function. The primes stand for differentiations with respect to *y*.

The engineering quantities of physical interest are the local Nusselt number, skin-friction coefficient, and Sherwood number, and they are defined as:

$$Nu_x=-\frac{\partial\theta(x,0)}{\partial y}=-(Gr)^{1/4}\theta'(x,0) \tag{21}$$

$$Sh_x = -\frac{\partial \varphi(x,0)}{\partial y} = -(Gr)^{1/4}\,\varphi'(x,0) \quad (22)$$

$$Cf_x = x\frac{\partial^2 f(x,0)}{\partial y^2} = 2(Gr)^{-1/4}\,x\,f''(x,0) \quad (23)$$

3. Numerical Solutions

Equations (17-20) are coupled, nonlinear partial differential equations and no analytical solution can be defined. The local similarity solutions for the set of governing equations can be achieved when assigning zero value to *x*, which is the lower stagnation point. Nazar et. al [38] use some simplifications to reduce the present model conservation equations to simpler ordinary equations. Here, at the upper stagnation point (x = π), the local Nusselt number, local Sherwood number and local skin friction coefficient at the cylinder surface are defined by equations (21-23)

In the present analysis, the derived equations (17-20) are nonlinear partial differential equations and may be solved using the implicit finite difference approach discussed by Cebeci and Bradshaw, Keller [39, 40]. This method is the most powerful one that is used extensively in many viscous fluid simulations.

The computations were carried out for uniform grid of $\Delta y = 0.05, \Delta x = 0.05$. The criterion of convergence is employed between any two successive iterations. At the edge of the boundary, the grid size, and the thickness of the boundary layer y_∞ has been examined. The results at hand are independent of the grid size and the thickness of boundary layer is considered up to the fourth decimal point.

4. Results and Discussion

Extensive computations are presented for water case (*Pr* = 7). A set of numerical results are carried out for different of values of the physical parameters that describe the flow behavior. The results are generated graphically in Figures 3-16. The graphical representation of the numerical results are present for the effects of Brownian motion parameter (N_B), thermophoresis number (N_T) and chemical reaction parameter (Λ) on temperatures profiles (θ) ,concentration profiles (φ) and velocity profiles (f') with *y* coordinate which is normal to the cylinder surface, at the stagnation point ($x = \pi$).

Furthermore, The local skin friction coefficient (Cf_x), Sherwood number (Sh_x) and Nusselt number (Nu_x) are also calculated with curvature parameter, *x*. In all results a constant value is assigned for the buoyancy ratio parameter (*N* = 0.5), the Prandtl number (*Pr* =7.0), and the Schmidt number (*Sc* = 0.7) since the effect of such parameters were addressed in the literature.

To check the accuracy of the current computations, the results have been verified and compared with the results reported by Merkin and Pop [41] and also Prasad, el all [42], for the non-reactive, purely fluid i.e., with $A = N_B = N_T = N = 0$ The results obtained by Merkin and Pop [41] and Prasad, el all [42], and also the present solutions are all shown in Table 1 below.

Figures 2–4 illustrate the upshot of Brownian motion parameter (N_B) on the velocity profiles (f'), temperatures profiles (θ) and concentration profiles (φ) with (*y*) coordinate at the stagnation point ($x = \pi$). The values of the other parameters are set as *Pr* = 7.0, *Sc* = 0.7, *N* = 0.5, N_T = 0.1, Λ = 1.0 and different N_B values.

Table 1. Calculations come to the local skin-friction coefficient Cf_x for *Pr* = 0.72, $A = N_B = N_T = N = 0$ for selected values of *x*

x	Merkin and Pop [37]	Prasad, el all [38]	Present
0	0.000	0.000	0.000
0.4	0.609	0.608	0.604
0.8	1.160	1.157	1.159
1.2	1.602	1.598	1.600
1.6	1.855	1.880	1.868
2	1.971	1.968	1.969
2.4	1.824	1.820	1.822
2.8	1.404	1.400	1.401
π	0.739	0.702	0.723

The physical reasons of the Brownian motion come due to the random motion of suspended nanoparticles in the base fluid. The power of this motion is a result of speedy moving atoms or molecules in the main fluid. The Brownian motion has a significant effect on temperature and concentration shape. The boundary layer velocity decreases with increasing Brownian motion number N_B. The temperature is somewhat increased, and concentration decreased. Moreover, the nanoparticle volume fraction tends to decrease with an increase in the Brownian motion number N_B, so this may also contribute to the enhancement in temperatures gradient. The Brownian motion number also works to elevate thermal conductivity. This may be caused directly by the nanoparticles that carry the thermal energy or by a roundabout contribution due to micro convection of the fluid surrounding the individual nano particles. The Brownian motion is physically powerful for small particles and the opposite will be relevant for large particles.

Figures 5–7 show the effect of thermophoresis number (N_T) on velocity profiles (f'), temperatures profiles (θ) and concentration profiles (φ) with distance normal *y* at the stagnation point ($x = \pi$). The values of the other parameters are set as *Pr* = 7.0, *Sc* = 0.7, *N* = 0.5, N_B = 0.2, Λ = 1.0 and different N_T values.

It is noticed from these figures that increasing of thermophoresis number (N_T) decreases velocities inside the boundary layer; this is explained by the small positive buoyancy forces that exist. The temperature increases inside the thermal boundary layers and the thicknesses of the boundary layer broadened. To make this, the particles next to the hot surface generate a thermophoretic force, and these forces bear the particle decomposition away from the fluid at the cylinder surface as well. This is the reason for the augmentation in the temperature boundary layer thickness.

The skin friction coefficient (Cfx) and Nusselt Number (Nux) at the cylinder surface are presented in figure 8 and figure 9. Both are increased very slightly with increasing the thermophoresis number (NT) due to extra thermophoretic forces.

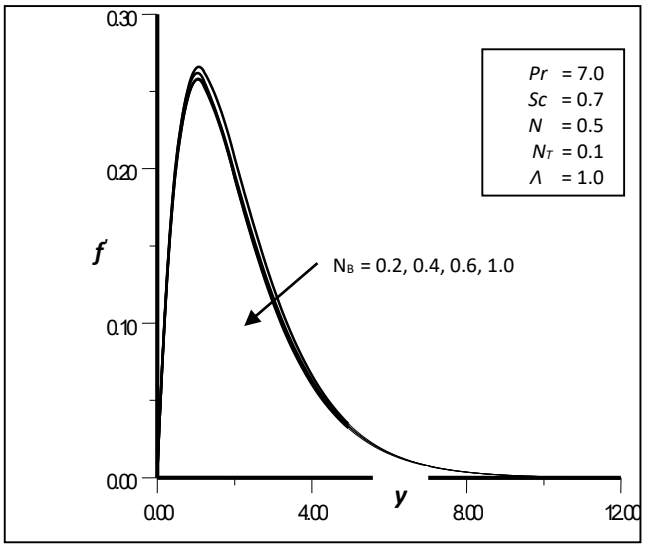

Figure 2. Influence of Brownian motion parameter on velocity profiles at upper stagnation point

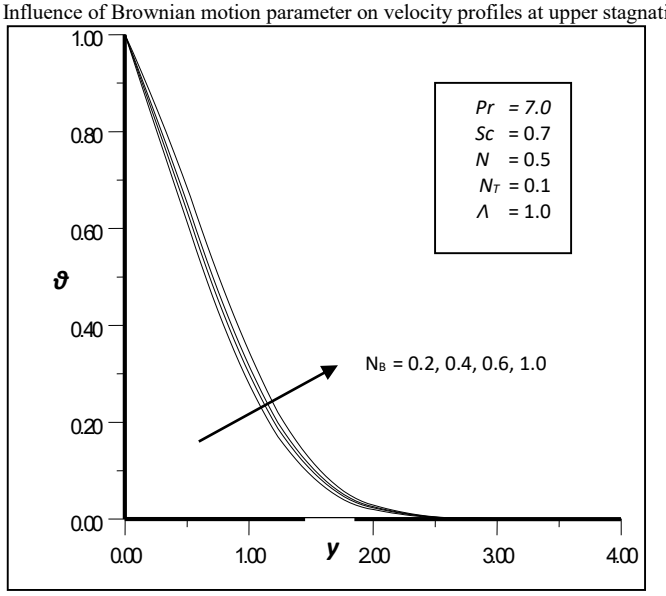

Figure 3. Influence of Brownian motion parameter on temperature profiles at upper stagnation point

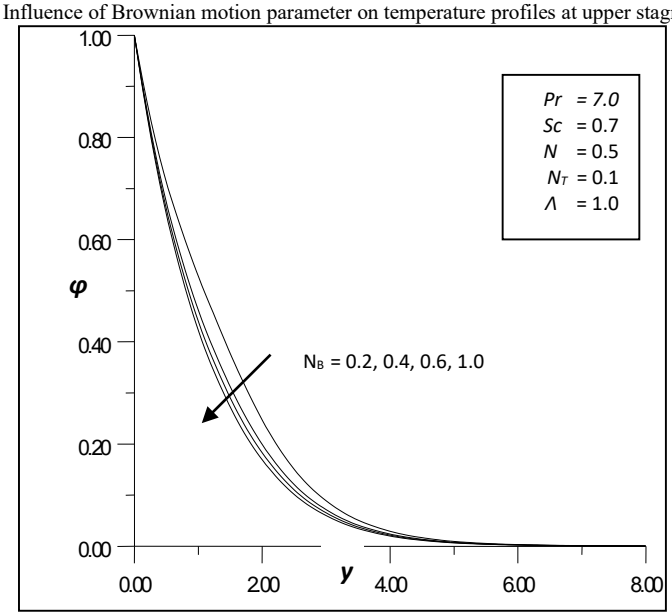

Figure 4. Influence of Brownian motion parameter on concentration profiles at upper stagnation point

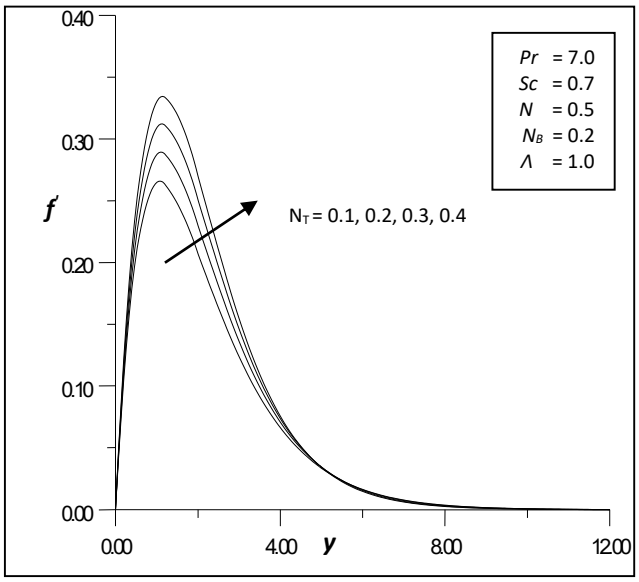

Figure 5. Influence of thermophoresis number on velocity profiles at upper stagnation point

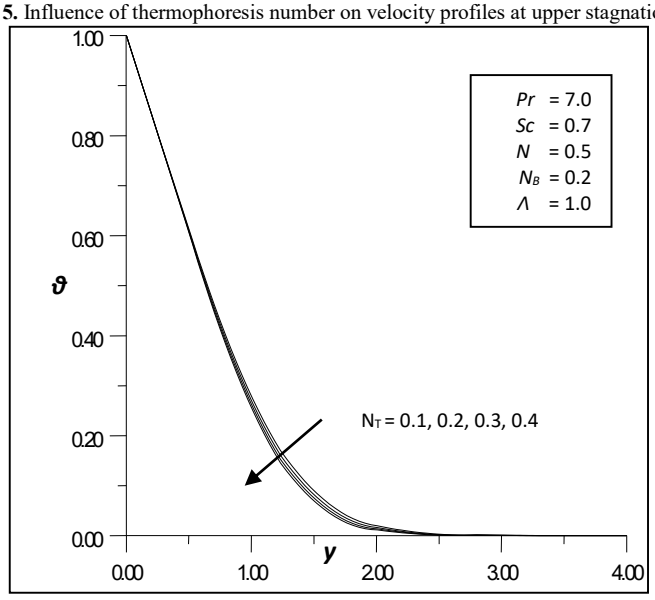

Figure 6. Influence of thermophoresis number on temperature profiles at upper stagnation point

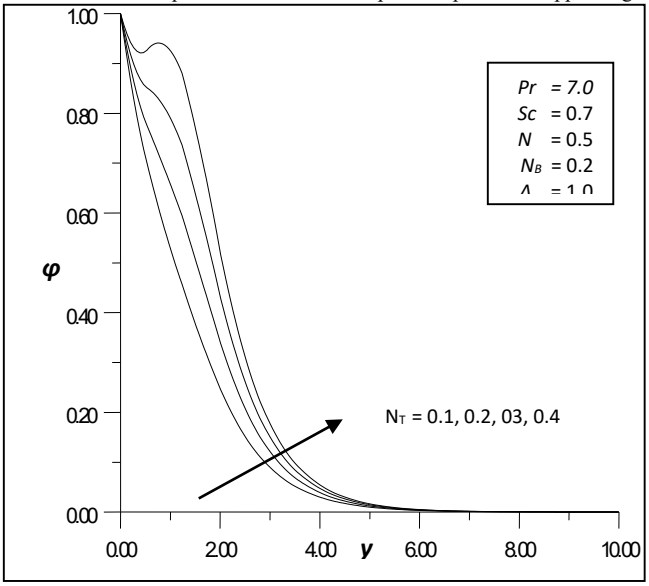

Figure 7. Influence of thermophoresis number on concentration profiles at upper stagnation point

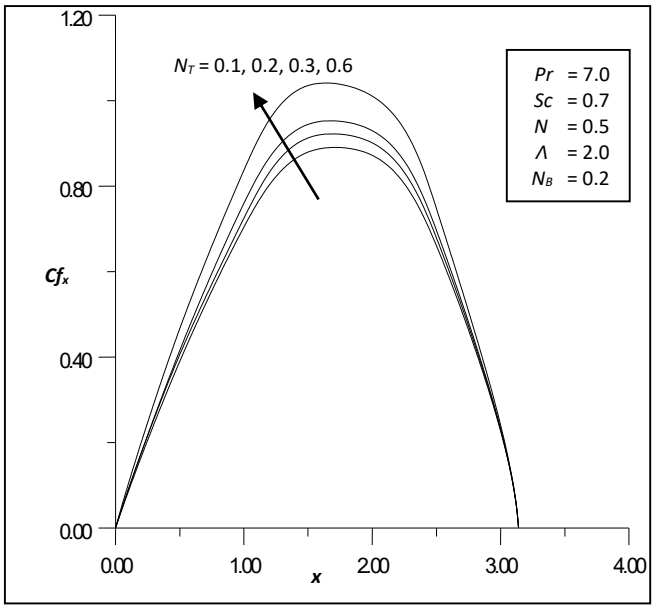

Figure 8. Local skin friction coefficient versus x for various values of thermophoresis parameter

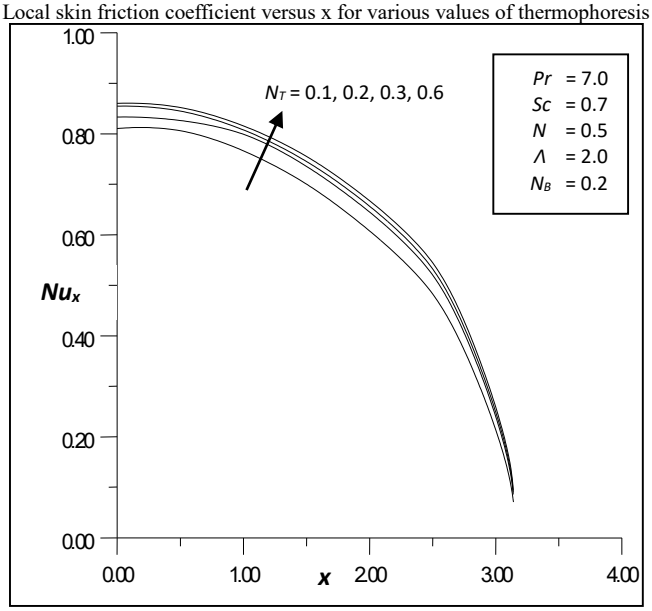

Figure 9. Local Nusselt number versus x for various values of thermophoresis parameter

Finally, increasing of thermophoresis number cause to decrease the concentration inside boundary layers and as a result decreasing mass flux. Thermophoresis account for the elevated concentration (nanoparticle) magnitudes. Fig. 10 shows that the mass transfer rate (Sh_x) decreases by increasing the thermophoresis number.

Variation of velocity (f'), temperatures (θ) and concentration (φ) distributions for different values of dimensionless chemical reaction parameter (Λ) is shown in Figs. 11–13. The values of the other parameters are set as $Pr = 7.0$, $Sc = 0.7$, $N = 0.5$, $N_B = 0.2$, $= N_T = 0.2$

One can observe that a significant increase in chemical reaction parameter Λ accounts for the decrease in the nanofluid velocity and the increase of the temperature distributions. We see also that the concentration profiles are highly influenced and are decelerated with the higher values of chemical reaction parameter. The consumption of chemical species causes a fall in the concentration field which in turn diminishes the buoyancy effects due to concentration gradients, hence the flow field is retarded. The nanoparticle volume fraction of the fluid decreases with increase of chemical reaction parameter. In particular, the nanoparticle volume fraction of the fluid gradually changes from higher value to the lower value only when the strength of the chemical reaction is higher than the thermophoresis particle deposition. For nanoparticle volume characteristics mechanism, interesting result is the large distortion of the nanoparticle volume field. It is observed from figures 14-16 that both skin-friction coefficient and Nusselt number diminish while the Sherwood number enhances with the improving values of chemical reaction parameter (Λ).

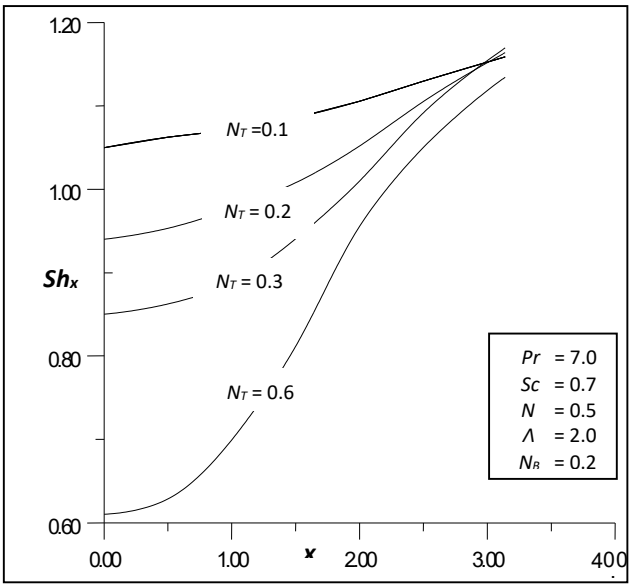

Figure 10. Local Sherwwod number versus x for various values of thermophoresis parameter parameter

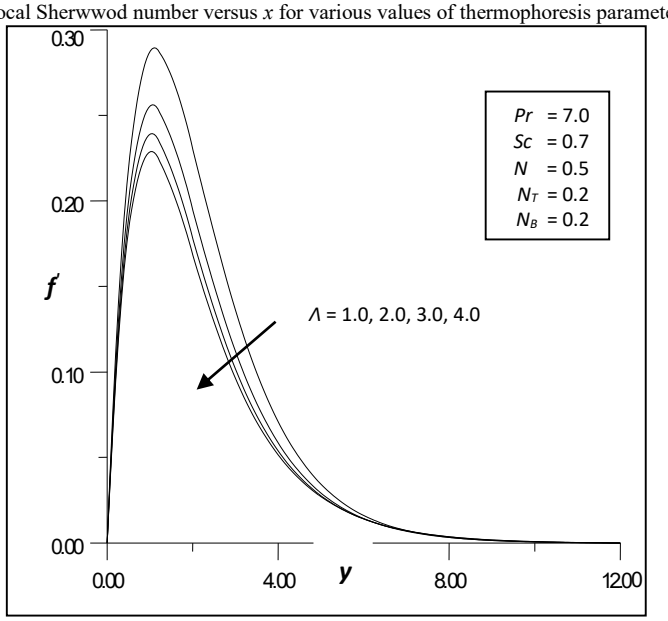

Figure 11. Influence of chemical reaction parameter on velocity profiles at upper stagnation point

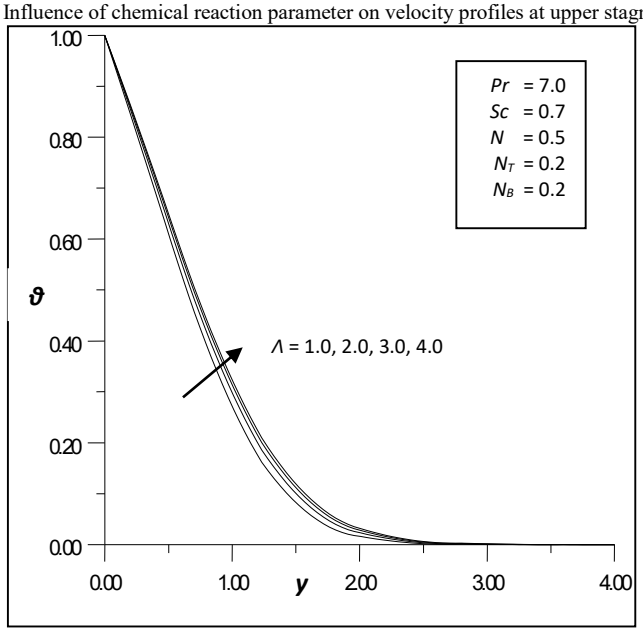

Figure 12. Influence of chemical reaction parameter on temperature profiles at upper stagnation point

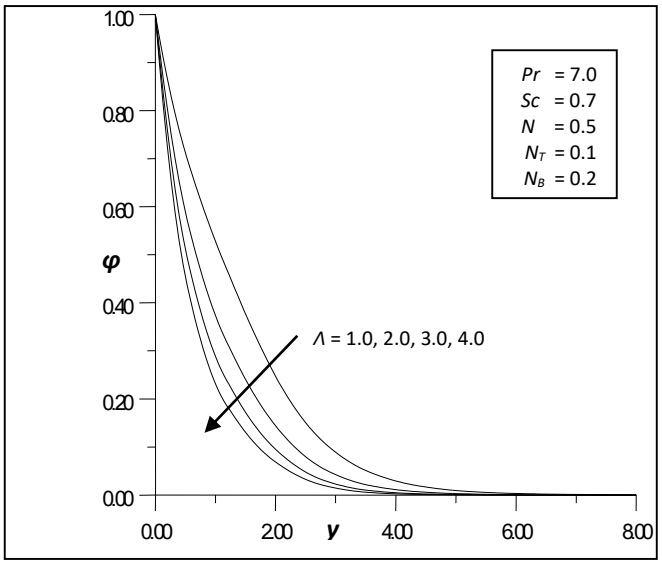

Figure 13. Influence of chemical reaction parameter on concentration profiles at upper stagnation point

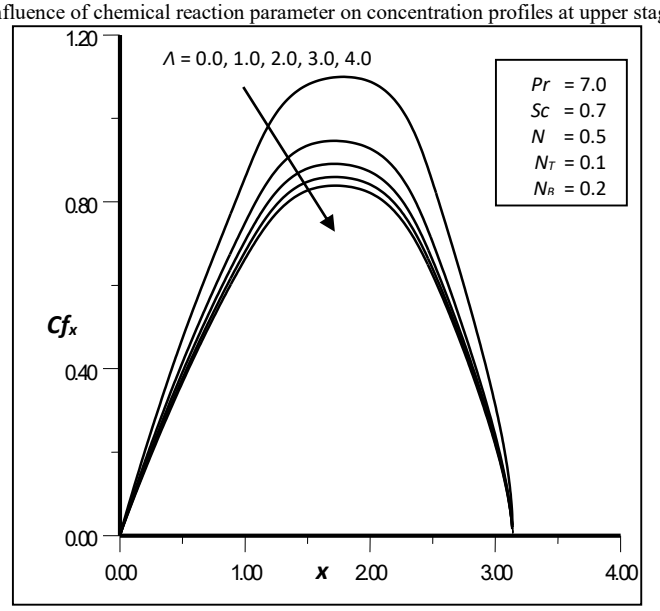

Figure 14. Local skin friction coefficient versus x for various values of chemical reaction parameter

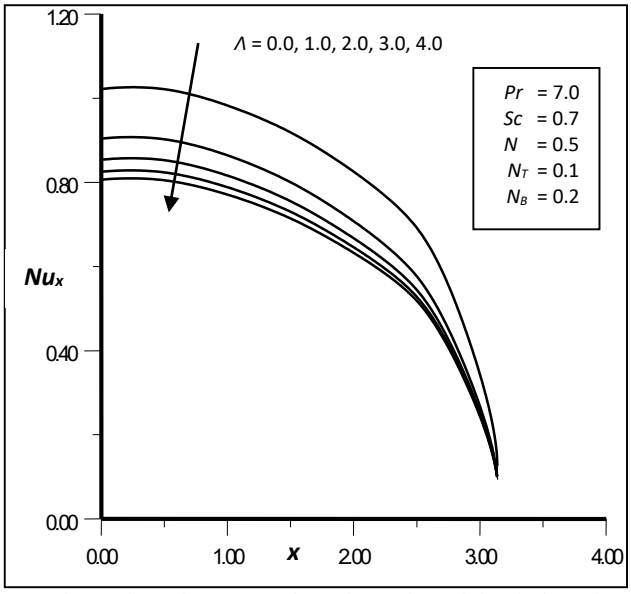

Figure 15. Local Nusselt number versus x for various values of chemical reaction parameter

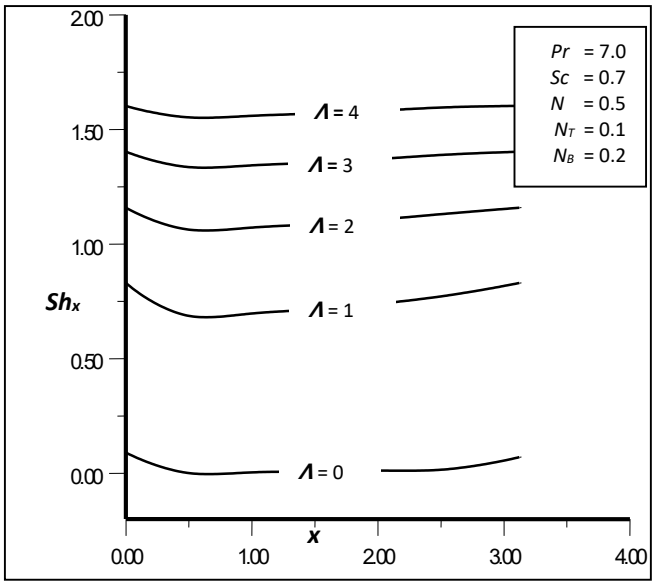

Figure 16. Local Sherwwod number versus x for various values of chemical reaction parameter

In the theory, the nano particle volume fraction decreases as the chemical reaction parameter increases. The nano particle volume fraction of the fluid changes regularly from higher value to the lower value when the potency of the chemical reaction is higher than the thermophoresis particle deposition.

5. Conclusions

The buoyancy-driven boundary layer problem is formulated mathematically using the continuity, momentum, and heat and mass transfer principles. The addressed geometry considers the flow of a nanofluid past an isothermal horizontal cylinder in the presence of chemical reaction effect. The produced partial differential equations are nonlinear, and the numerical methods used to find an approximate solution. The effects of the various parameters appearing in the problem are discussed and analyzed. The results are generated and represented by graphs.

Following the results and discussion section, we draw the following conclusions:

Due to Brownian motion number, thermophoresis number and chemical reaction parameter, the temperature profiles accelerate whereas the concentration decelerates in the boundary layer.

1. An increase in the Brownian motion parameter (N_B) decreases the velocity, and the heat transfer rate is decelerated.
2. An increase in thermophoresis number (N_T) will accelerate the flow and concentration and tends to decelerate the mass transfer rate.
3. Fluid motions as well as concentration of the nanofluid are retarded due to existence of chemical reaction. Increasing the chemical reaction parameter (Λ) increases the dimensionless rates of mass transfer and decrease the heat transfer rate due to the decrease in flow resistance.

CONFLICT OF INTEREST DISCLOSURE:

The author declares no competing financial interest.

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