UNSTEADY HOMOGENEOUS-HETEROGENEOUS REACTIONS IN MHD NANOFUID MIXED CONVECTION FLOW PAST A STAGNATION POINT OF AN IMPULSIVELY ROTATING SPHERE

by

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This paper establishes a mathematical analysis for describing the homogeneous and heterogeneous chemical reactions in the nearness of stagnation region of a sphere immersed in a single-phase nanofluid due to a Newtonian heating. The flow is resulted by an impulsively rotating sphere, and the nanofluid involves nanoparticles of copper and ferro. The available unsteady-states of the considered system are given in the case when the diffusion coefficients of both reactant and auto catalyst have the same size. The resulting non-linear dimensionless coupled PDE in which governing the mixed convection flow have been tackled numerically via an implicit finite difference technique in combination with the quasi-linearization scheme. The similarities and differences in the behavior of physical pertinent fluid parameters have been elaborated and discussed graphically. It has been clarified that the nanofluid velocity and temperature profiles grow gradually by adding nanoparticles in the base fluid. Again it is noticed from present contribution that concentration of the nanofluid is decreases function by rising the strength of homogeneous and heterogeneous chemical reactions. Finally, numerical computations of the skin friction and heat transfer factors are presented.

Key words: single-phase nanofluid, unsteady mixed, convective condition, homogeneous-heterogeneous reactions, sphere, heat generation

Introduction

Varied systems of chemically reacting arise through both heterogeneous and homogeneous reactions with instances arising in catalysis, combustion and biochemical systems. The relationship between heterogeneous reactions arising on some catalytic surfaces and homogenous reactions in the bulk of fluid is often particularly convoluted, including the production and consumption of reactant species at non-similar rates both on the catalytic surface and inside the fluid. Besides the feedback on these reaction rates through fluid temperature variations inside the reacting fluid, which leads to change the fluid motion. Therefore there exists a three-way coupling between fluid, fluid-surface temperatures, and reactant species concentrations. A number of catalyst-driven reactions, which are of significance in the chemical
process, there can be a cognizable reaction within the bulk (homogeneous reactions) and on the catalyst surface. Song et al. [1-3] and Williams et al. [4, 5] presented some examples of such homogeneous and heterogeneous reactions. Additionally, Chaudhary and Merkin [6, 7] have been presented a simple model for homogeneous and heterogeneous reactions in boundary-layer flow in which the heterogeneous (surface) reaction is considered to be raised by first order kinetics while homogeneous (bulk) reaction by isothermal cubic autocatalator kinetics. They have investigated the possible steady-states of their model in the particularly case when the diffusion coefficients of both reactant and autocatalyst are of the same size. Moreover, Merkin [8] has exhibited the boundary-layer flow of a uniform stream along a flat surface (Blasius solution) employing the same model of homogeneous and heterogeneous reaction. Hayat et al. [9] scrutinized simulation and modeling for chemically reacting Maxwell liquid according to modified Fourier approach. Khan and Pop [10] modeled the homogeneous and heterogeneous situation of reactions in viscoelastic fluid flow by stretching plate. Khan et al. [11] and Hayat et al. [12] disclosed homogeneous and heterogeneous reactions for viscous nanofluid and Maxwell fluid flow through slender surface.

Due to the low thermal conductivity of some fluids like water, oil, and ethylene glycol mixtures, the convectional heat transfer of these fluids are poor. The fluid thermal conductivity may be enhanced by hanging nano-sized particle materials in the liquid to arise a nanofluid. Nanofluid is a developed kind of material involving suspension of solid particles so-called nanoparticles. Nanofluid flow and heat transfer along a stretchable cylinder with applying magnetic field has been exhibited by Ashorynejad et al. [13]. They elaborated that choosing copper (for small of magnetic parameter) and alumina (for large values of magnetic parameter) results in the highest cooling performance. Abu-Nada et al. [14] reported free convection heat transfer improvement in horizontal concentric annuli field by nanofluid. Tiwari and Das [15] modified a model to describe the behavior of nanofluids considering the solid volume fraction. A number of extensive contributions of nanofluids and therein can be found in [16-32].

 Besides, due to their applications in industry and engineering, the investigation of steady and unsteady uniform fluid flows on rotating sphere in which its axis of rotation parallel to the ambient velocity has been recognized by many researchers applying several analytical and numerical methods [33-36]. Motivated by such facts, this paper inspects the combined impacts of a homogeneous and heterogeneous reactions subject to internal heat generation in MHD mixed convection nanofluid flow around an impulsively rotating sphere. This investigation allowed to use the model developed by Merkin [8] for homogeneous and heterogeneous reactions in boundary-layer flow with cubic autocatalysis. The non-dimensional transformed boundary-layer equations of motion and concentration have been tackled numerically. To our best knowledge, this specific problem hasn’t been addressed before. Special cases of the current results are compared with those of Takhar et al. [34].

Flow configuration

Let us inspect an unsteady, 2-D, incompressible, boundary-layer nanofluid flow of MHD mixed convection in stagnation of an impulsively rotating sphere with existence of heat generation or absorption impact. A single-phase model is applied to simulate the nanofluid flow. The sphere rotates with a constant angular velocity, $\Omega$, around a diameter parallel to the ambient free stream velocity $\tilde{U}(x) = \tilde{u}_x$, as depicted in fig. 1. Besides, an external constant uniform magnetic field with strength, $B_0$, is given in $z$-direction. Before time $t = 0$, the sphere is at rest in an ambient fluid and surface temperature equals $T_\infty$. The fluid has constant physical properties with excluding the density which reults the buoyancy force. The impacts of viscous
dissipation and Joule heating is considered to be absent. Furthermore, a simple homogeneous-heterogeneous reaction model is assumed as given by Chaudhary and Merkin [25] and Merkin [8] as:

\[ A + 2B \rightarrow 3B, \quad \text{rate} = k_c a b^2 \quad (1) \]

but on the catalyst surface single, isothermal, first order chemical reaction i.e. heterogeneous, is given:

\[ A \rightarrow B, \quad \text{rate} = k_s a \quad (2) \]

in which \( a \) and \( b \) point out concentrations of the chemical species \( A \) and \( B \), \( k_c \), and \( k_s \) symbolize the rate constants. It is supposed that both reaction processes are isothermal. Follow these assumptions, the boundary-layer equations that depicting nanofluid flow can be stated in dimensional form as [25, 28]:

\[
\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} + \frac{\partial (\rho uv)}{\partial y} + \frac{\partial (\rho wv)}{\partial z} = \frac{\partial P}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} 
\]

\[
\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho u v)}{\partial x} + \frac{\partial (\rho v^2)}{\partial y} + \frac{\partial (\rho vw)}{\partial z} = \frac{\partial P}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} 
\]

\[
\frac{\partial (\rho w)}{\partial t} + \frac{\partial (\rho u w)}{\partial x} + \frac{\partial (\rho v w)}{\partial y} + \frac{\partial (\rho w^2)}{\partial z} = \frac{\partial P}{\partial z} + \frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} 
\]

\[
\frac{\partial T}{\partial t} + \frac{\partial (u T)}{\partial x} + \frac{\partial (v T)}{\partial y} + \frac{\partial (w T)}{\partial z} = \frac{k}{\rho c_p} \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + Q_h(T - T_w) 
\]

\[
\frac{\partial a}{\partial t} + u \frac{\partial a}{\partial x} + w \frac{\partial a}{\partial z} = D_a \frac{\partial^2 a}{\partial z^2} - k_c ab^2 
\]

\[
\frac{\partial b}{\partial t} + u \frac{\partial b}{\partial x} + w \frac{\partial b}{\partial z} = D_b \frac{\partial^2 b}{\partial z^2} + k_c ab^2 
\]

The recognized boundary conditions for flow governing eqs. (3)-(8) are taken as:

At: \( z = 0 \), \( u(t, x) = w(t, x) = 0 \), \( v(t, x) = \Omega x \), \( k_l \frac{\partial T}{\partial z} = h_l(T - T_l) \)

\[
D_a \frac{\partial a}{\partial z} = k_s a, \quad D_b \frac{\partial b}{\partial z} = -k_s a 
\]

As: \( z \rightarrow \infty \), \( u \rightarrow U \), \( v \rightarrow 0 \), \( T \rightarrow T_w \), \( a \rightarrow a_0 \), \( b \rightarrow 0 \) 

Notations \( u \), \( v \), and \( w \) explain the nanofluid velocity components in the \( x \)-, \( y \)-, and \( z \)-directions, respectively, \( \mu_{nf} \) gives the dynamic viscosity of the nanofluid, density of the
nanofluid is given by $\rho_{nf}, \sigma_{nf}$ represents electrical conductivity of the nanofluid, $T$ means the temperature of the nanofluid, $Q_0$ refers to the internal heat generation or absorption coefficient, $D_A$ and $D_B$ indicate the respective diffusion coefficients, $T_\infty$ is the nanofluid temperature of free stream, and $h_l$ indicates the convective heat transfer.

Brinkman [37] presented the dynamic viscosity of the nanofluid:

$$\mu_{nf} = \mu_f (1 - \varphi)^{-5/2} \tag{10}$$

in which the solid volume fraction of nanoparticles is indicated by $\varphi$. The effective density of the nanofluid, $\rho_{nf}$, and the nanofluid thermal expansion coefficient, $\beta_{nf}$, are approximated [15]:

$$\rho_{nf} = (1 - \varphi)\rho_f + \varphi\rho_p \tag{11}$$

$$\beta_{nf} = (1 - \varphi)\beta_f + \varphi\beta_p \tag{12}$$

where $(\rho c_p)_{nf}$ indicates the heat capacitance of the nanofluid and is defined [15]:

$$(\rho c_p)_{nf} = (1 - \varphi)(\rho c_p)_f + \varphi(\rho c_p)_p \tag{13}$$

Furthermore, $k_{nf}$ points out thermal conductivity of the nanofluid, due to Maxwell-Garnets (MG) model [38] it is approximated:

$$k_{nf} = k_f + 2k_f + 2\varphi(k_p - k_f) \tag{14}$$

Finally, the nanofluid effective electrical conductivity is approximated [38]:

$$\sigma_{nf} = \sigma_f \left[ 1 + \frac{3(\sigma - 1)\varphi}{(\sigma + 2) - (\sigma - 1)\varphi} \right] \left( \frac{\sigma}{\sigma_f} \right) \tag{15}$$

Notice the subscripts, $nf$, explains the nanofluid thermophysical properties, $f$, refers to base fluid, but, $p$, is known as nano-solid particles. Table 1 stands for the thermophysical values of the nanofluids given in this investigation.

### Table 1. Thermophysical properties of water and nanoparticles Jawad et al. [39]

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Water base fluid</th>
<th>Cu</th>
<th>Fe$_3$O$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ [kgm$^{-3}$]</td>
<td>997.1</td>
<td>8933</td>
<td>5200</td>
</tr>
<tr>
<td>$c_p$ [Jkg$^{-1}$K$^{-1}$]</td>
<td>4179</td>
<td>385</td>
<td>670</td>
</tr>
<tr>
<td>$k$ [Wm$^{-1}$K$^{-1}$]</td>
<td>0.613</td>
<td>401</td>
<td>6</td>
</tr>
<tr>
<td>$B\cdot10^5$ [K$^{-1}$]</td>
<td>21</td>
<td>1.67</td>
<td>1.3</td>
</tr>
<tr>
<td>$\sigma\cdot10^{-6}$ [cm$^{-1}$]</td>
<td>5.5$\cdot10^{-12}$</td>
<td>59.6</td>
<td>0.025</td>
</tr>
</tbody>
</table>

Non-dimensionalizing utilizing the following non-similarity transformation:

$$\eta = \sqrt{\frac{2\alpha}{V_f}} z, \quad \xi = 1 - e^{-\alpha t}, \quad u(x,z,t) = \bar{\alpha}x F(\xi,\eta), \quad v(x,z,t) = \Omega x V(\xi,\eta)$$

$$w(x,z,t) = -\sqrt{2\alpha v_f} z F(\xi,\eta), \quad \theta = \frac{T - T_\infty}{T_w - T_\infty}, \quad \phi_1 = \frac{a}{a_0}, \quad \phi_2 = \frac{b}{a_0} \tag{16}$$
Substituting eq. (16) into eqs. (3)-(8), consequently continuity eq. (3) is automatically satisfied and the following non-dimensional flow governing equations are resulted:

\[ \frac{2\nu^{*}}{\nu} \frac{\partial \phi}{\partial \xi} + \frac{2\rho^{*}}{\rho} \frac{\partial \phi}{\partial \eta} = \frac{\partial}{\partial \eta} \left( \frac{\partial \phi}{\partial \eta} \right) \]

\[ \frac{2\nu^{*}}{\nu} \frac{\partial \phi}{\partial \xi} + \frac{2\rho^{*}}{\rho} \eta \frac{\partial \phi}{\partial \eta} = \frac{\partial}{\partial \eta} \left( \frac{\partial \phi}{\partial \eta} \right) \]

\[ \frac{2k^{*}}{k} \frac{\partial^{2} \phi}{\partial \eta^{2}} + \frac{\partial}{\partial \eta} \left( \frac{\partial \phi}{\partial \eta} \right) \]

Associated with relevant boundary conditions:

\[ F(\xi, \eta) = F^{*}(\xi, \eta) = 0, \quad V(\xi, \eta) = 1, \quad \theta'(\xi, \eta) = Bi[\theta(\xi, 0) - 1] \]

\[ \phi(\xi, 0) = K_{\phi} \phi(\xi, 0), \quad \delta^{*} \phi(\xi, 0) = -K_{\phi} \phi(\xi, 0) \]

\[ F'(\xi, \infty) \to 1, \quad V(\xi, \infty) \to 0, \quad \theta(\xi, \infty) \to 0, \quad \phi(\xi, \infty) \to 1, \quad \phi_{2}(\xi, \infty) \to 0 \]

(22)

Follow the particular case, assume that the diffusion coefficients \( D_{A}, D_{B} \) of reactants \( A \) and \( B \) are of same size \( (i.e., \delta^{*}) \) according to Merkin [8]. Hence due to this assumption the following expression has been gained:

\[ \phi_{1}(\xi, \eta) + \phi_{2}(\xi, \eta) = 1 \]

Consequently, eqs. (20) and (21) are simplified to be one equation:

\[ \frac{1}{Sc} \phi^{*} + \frac{1}{4} \eta(1 - \xi) \phi^{*} - \frac{1}{2} \xi K_{c} S(1 - \phi^{*})^{2} = \frac{1}{2} \xi(1 - \xi) \frac{\partial \phi}{\partial \eta} \]

(24)

and conditions in eq. (22) becomes:

\[ \phi_{1}(\xi, \eta) = K_{\phi} \phi_{2}(\xi, 0), \quad \phi_{2}(\xi, \infty) \to 1 \]

(25)

The following important parameters are obtained, \( M_{k} = \frac{\sigma_{1} B_{0}^{2}}{\nu} \) gives magnetic field parameter, \( \lambda = \frac{\nu}{\nu^{*}} \) symbolizes the rotation parameter, \( \gamma = \frac{Gr}{Re^{2}} \) means mixed convection parameter, \( Gr = \frac{g \rho}{\mu^{*}} \) refers to Grashof number, \( Re = \frac{U \nu}{\nu^{*}} \) represents Reynolds number, \( K_{c} = \frac{C_{c}}{\nu^{*}} \) referring homogeneous and heterogeneous reaction strength, respectively, \( \delta = \frac{Q_{b}}{\nu^{*} \nu^{*}} \) point out heat generation or absorption parameter, \( \delta^{*} = \frac{D_{A}}{D_{B}} \) gives the ratio of diffusion coefficients; \( Pr = \frac{C_{p}}{C_{c} \rho \nu^{*}} \frac{\nu^{*}}{\nu^{*}} \) and \( Sc = \nu^{*} / \nu^{*} \) stand for Prandtl and Schmidt numbers, remember that the prime sign "'" refers to differentiation with respect to the non-similarity variable, \( \eta \).
The $x$- and $y$-direction shear stresses, respectively, are given by:

$$
\text{Re}^{1/2} \xi^{1/2} C_{f_x} = \frac{2 \mu_{nf}}{\rho_f U^2} \left( \frac{\partial u}{\partial \xi} \right)_{\xi=0} = 2 \sqrt{\text{Re}} \frac{H_{\mu_f}}{\mu_f} F'(\xi,0) \tag{26}
$$

$$
\text{Re}^{1/2} \xi^{1/2} C_{f_y} = -\frac{2 \mu_{nf}}{\rho_f U^2} \left( \frac{\partial v}{\partial \xi} \right)_{\xi=0} = -2 \sqrt{\text{Re}} \lambda^{1/2} V'(\xi,0) \tag{27}
$$

The rate of surface heat transfer in terms of Nusselt number is described by:

$$
\text{Re}^{-1/2} \xi^{1/2} \text{Nu} = \frac{k_{nf} x}{k_f (T_w - T_{\infty})} \left( \frac{\partial T}{\partial \xi} \right)_{\xi=0} = -\sqrt{\text{Re}} \frac{k_{nf}}{k_f} \theta'(\xi,0) \tag{28}
$$

Thus, we have to tackle numerically eqs. (17)-(19), and (24) along with the boundary conditions (22) and (25) for some values of the resulting parameters.

**Results and discussion**

The combined aspects of homogeneous and heterogeneous reactions, unsteady mixed convection, convective boundary condition, internal heat generation or absorption and magnetic field on the flow of a viscous, incompressible, and electrically conducting nanofluid in a stagnation point of an impulsively rotating sphere is addressed. The nanofluid is water based fluid with a suspended nanoparticles of ferro, Fe$_3$O$_4$, and copper, Cu. The resulting non-linear partial differential equations along with the boundary conditions are tackled numerically via MATLAB routine bvp4c. Once again for establishing the validity of present results, these are compared with the computations in the literature. Figure 2 stands for a comparison of the values of $V'(\xi,0)$ against $(a)$ magnetic field, $M$, and mixed convection parameter, $\gamma$. An excellent agreement is shown with our presented results.

![Figure 2](image.png)

*Figure 2. Comparison of the present results with those given by Takhar et al. [34] for $V'(\xi,0)$ against (a) magnetic field, (b) mixed convection parameters*

Once again, for highlighting the impacts of various significant parameters on $x$ velocity, $F'(\xi,0)$, temperature, $\theta(\xi,0)$, and concentration, $\phi(\xi,0)$, distributions for different suspended solid nanoparticle, here the graphical results are disclosed. The difference in species
concentration outline, \( \phi(\xi, 0) \), for the measure of homogeneous \( K_c = 0.1, 0.5, 1, 2, \) and 10, and heterogeneous \( K_s = 0.1, 0.3, 0.5, 0.7, 1, 2, \) and 5, reactions strengths are presented in fig. 3. Aspects of \( K_c \) on the concentration distribution are displayed in fig. 3. It is noticed that with ascending the measure of homogeneous reaction strength the species concentration field decreases. Figure 3 as well demonstrates the influences of \( K_s \) on concentration curves \( \phi(\xi, \eta) \). A reduction in concentration field is given when the measure of the strength of heterogeneous reaction \( K_s \) becomes higher. Figure 4 portrays that the species concentration at the sphere surface decays asymptotically when \( K_c \) and \( K_s \) approaches to infinity. Unlike, the characteristic of Schmidt number, \( Sc = 0.2, 0.44, 0.9, 1.3, \) and 2, leads to improve the species concentration distribution.

The influence of rotation parameter, \( \lambda = 1, 5, 10, 15, 20, \) and 25 on the \( x \) and \( y \) velocities, nanofluid temperature distributions, the rate of heat transfer and \( x \) and \( y \) shear stresses with \( Cu \) and \( Fe_3O_4 \) nanoparticles \( \phi = 0.04 \) is stated in figs. 5-7. An enhance in the rotation parameter, \( \lambda \), posses strong positive impacts on the rate of heat transfer and shear stresses. All of \( Nu(\xi, 0) \), \( F''(\xi, 0) \), and \( V'(\xi, 0) \) boost with rising values of rotation parameter, \( \lambda \). Besides, the
y velocity and nanofluid temperature fields reduce, slightly, with ascending the rotation parameter. Because of the reduction of momentum and thermal boundary-layers which leads to augment the velocity and temperature gradients at the wall. Again the nanofluid velocity, \( F' \), becomes larger with higher values of \( \lambda \). Figures 8 and 9 are provided to analyze the aspects of Biot number, \( \text{Bi} = 0.1, 0.5, 1, 5, 10, \) and \( \infty \), and solid volume fraction of nanoparticles \( \phi = 0.0, 0.02, 0.03, 0.04, \) and \( 0.10 \), with \( \text{Cu} \) and \( \text{Fe}_3\text{O}_4 \) suspended nanoparticles on the nanofluid temperature distributions and rate of heat transfer. Clearly, as both \( \text{Bi} \) and \( \phi \) rise, the rate of heat transfer, nanofluid temperature field \( \theta(\xi, \eta) \) and thermal boundary-layer thickness enhance. Therefore, adding of nanoparticles in the base fluid is responsible for the enhancement in thermal conductivity of the fluid.

![Figure 5. Impact of \( \lambda \) parameter on \( x \) and \( y \) velocity components](image1)

![Figure 6. Impact of \( \lambda \) parameter on \( x \) and \( y \) components of shear stress](image2)

The impact of heat generation parameter, \( \delta = -1.0, 0.5, -0.1, 0, 0.1, \) and \( 0.5 \), on the temperature profile and local Nusselt number is elucidated in fig. 10. With rising values of heat generation parameter, \( \delta \), the nanofluid temperature augments. This result is as per the expectations because any heat generated would cause an upgrade in the thermal energy of the nanofluid. The augment in nanofluid temperature has susceptibility to rise the thermal buoyancy
Figure 7. Impact of $\lambda$ parameter on $\theta$ and Nu profiles

Figure 8. Impact of Biot number on $\theta$ and Nu profiles

Figure 9. Aspects of Ec parameter on $\theta$ and Nu profiles
force. This gives higher buoyancy induced flow along the sphere surface. Moreover rising values of heat generation parameter leads to reduce the rate of heat transfer as given in terms of local Nusselt number. The difference in temperature profile $\theta$, Nusselt number, $\text{Nu}(\xi, 0)$, velocity profile $F'$, and $x$ and $y$ shear stresses i.e. $F''(\xi, 0)$, $V'(\xi, 0)$ with Cu and Fe$_3$O$_4$ nanoparticle, against $\xi$ for some various values of mixed convection parameter, $\gamma = 1, 2, 3, 4, 5$, are produced in figs. 11-13. From illustrated figures $\text{Nu}(\xi, 0)$, $F''(\xi, 0)$, and $V'(\xi, 0)$ augment as the mixed convection parameter, $\gamma$, rises this caused by descent of viscous and thermal boundary-layer thicknesses. Since the positive buoyancy force affects such a affirmative pressure gradient which makes the fluid motion accelerated inside the boundary-layer. Consequently descent the thickness of thermal and momentum boundary-layers and this in turn enlarge the shear stresses and heat transfer rate at the surface.

Figure 14 gives the influence of magnetic field parameter $M_g = 0, 0.1, 0.5, 1, 2, 5$, on $x$ and $y$ velocity component. Clearly magnetic field parameter reduces velocity components outlines. With the physical estimation, the currently phenomena is found as the magnetic field provides current in the conductive fluid, then it gives a resistive-type force (known as Lorentz force) on the fluid inside boundary-layer, which diminishes the fluid activity. This deficiency of the velocity distributions increases both of the velocity and thermal boundary-layer thicknesses which upgrades the $\text{Nu}(\xi, 0)$, $F''(\xi, 0)$, and $V'(\xi, 0)$. The surface shear stresses and rate of heat transfer are independent of magnetic field $M_g$ as $\xi = 0$ (at the motion start), after that the aspect of $M_g$ rises with $\xi$.

Conclusions

The impacts of unsteady mixed homogeneous and heterogeneous reactions, internal heat generation, convective boundary condition and magnetic field on a viscous flow, incompressible, and electrically conducting nanofluid in stagnation-point of rotating sphere was
Figure 12. Impact of $\gamma$ parameter on $x$ and $y$ components of shear stress

Figure 13. Impact of $\gamma$ parameter on $\theta$ and Nu profiles

Figure 14. Impact of $M_g$ parameter on $x$ and $y$ components of velocity
inspected. The problem was modeled due to Navier stokes equations with Boussinesq approximation and then the resulting governing flow equations have been treated numerically via the MATLAB routine bvp4c. We have illustrated, inter alia, an augment in the nanoparticle solid volume fraction leads to rise the species concentration and nanofluid velocity in the case of a Fe3O4-water nanofluid whereas it has an opposite impact on species concentration and nanofluid velocity in the case of a Au-water nanofluid. An increment in the volume fraction of the nanoparticles rises the nanofluid temperature. Internal heat generation parameter causes an augment in the nanofluid temperature. The species concentration is reduced by ascending in the homogeneous and heterogeneous reaction strength and the concentration at the sphere surface approaches zero as the homogeneous and heterogeneous reaction rate becomes higher. that the impact of the magnetic field parameter is to diminish the species concentration and the flow but boost the nanofluid temperature.

Nomenclature

\( A \) – unstediness parameter  
\( a, b \) – concentrations of chemical species  
\( c_v \) – specific heat, [Jkg\(^{-1}\)K\(^{-1}\)]  
\( D_a \) – diffusion coefficient of chemical specie \( a \)  
\( D_b \) – diffusion coefficient of chemical specie \( b \)  
\( Ec \) – Eckert number  
\( F \) – non-dimensional stream function  
\( k \) – thermal conductivity, [Wm\(^{-1}\)K\(^{-1}\)]  
\( K_c \) – homogeneous reaction parameter  
\( K_r \) – heterogeneous reaction parameter  
\( M_r \) – magnetic field parameter  
\( Nu \) – nusselt number  
\( Pr \) – prandtl number  
\( Re \) – reynolds number  
\( Sc \) – schmidt number  
\( T \) – dimensional temperature, [K]  
\( t \) – time, [s]  

\( u, v \) – velocity components, [ms\(^{-1}\)]  
\( x, y \) – cartesian co-ordinates, [m]  

\( \gamma \) – constant, [s\(^{-1}\)]  
\( \delta \) – ratio of diffusion coefficients  
\( \theta \) – dimensionless temperature  
\( \mu \) – dynamic viscosity, [kgm\(^{-1}\)s\(^{-1}\)]  
\( \nu \) – kinematic viscosity, [m\(^2\)s\(^{-1}\)]  
\( \rho \) – fluid density, [kgm\(^{-3}\)]  
\( \sigma \) – electrical conductivity, [Wm\(^{-1}\)K\(^{-1}\)]  
\( \phi \) – nanoparticles solid volume fraction  

Subscripts

\( x \) – conditions in the free stream  
\( f \) – fluid  
\( nf \) – nanofluid particle  
\( p \) – solid material  
\( w \) – conditions at the surface

References

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