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Unsteady MHD Free Convective Chemically Absorption Fluid Past an Impulsively Accelerated Plate with Thermal Radiation

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Abstract— ***A theoretical study on free convective heat and mass transfer flow of an electrically conducting incompressible viscous fluid past an impulsively accelerated permeable plate embedded in Darcian (thermal) absorption media in presence of thermal radiation and first order chemical reaction is presented in this paper. The governing equation of motions are first non-dimensionalised and then transformed into a set of ordinary differential equations by employing a suitable periodic transformations. The closed form of expression for velocity, temperature and concentration fields as well as skin- friction, Nusselt and Sherwood numbers are obtained in terms of various physical parameters present. It is observed that, the radiation absorption parameter increases the temperature as well velocity, but decelerates the heat transfer rate. It is also observed that, the chemical reaction parameter enhances both the heat as well as mass transfer rates.***
Keywords— ***MHD Free convection, Porous media, Thermal radiation, Chemical reaction, Radiation absorption***

Nomenclature

A Suction Parameter (a real positive constant)
B_0 Strength of the applied magnetic field
$\bar{C}$ Species concentration
c_p Specific heat at constant pressure
$\bar{C}_m$ Mean Species concentration at the plate
$\bar{C}_\infty$ Species concentration in the free stream
D_M Co-efficient of mass diffusion
D_T Co-efficient of thermal diffusion
Gm Thermal Grashof number
Gr Solutal Grashof number
k Thermal conductivity
Nu_R Nusselt number (Real part)
Pr Prandtl number
R Radiation parameter
S First-order Heat source/sink parameter
Sc Schmidt number
Sh_R Sherwood number (Real part)
Sr Soret number
t Time variable(Non-Dimensional)
$\bar{t}$ Time variable (Dimensional)
$\bar{T}$ Fluid temperature
$\bar{T}_m$ Mean Temperature at the plate
$\bar{T}_\infty$ Temperature in the free stream
u First component of fluid velocity (Non-Dimensional)

u_0 Mean plate velocity (Non-dimensional)

u_R Real part of u

$\overline{u}$ First component of fluid velocity (Dimensional)

U_0 Mean plate velocity (Dimensional)

y y – co-ordinate (Dimensional)

$\overline{y}$ y – Co-ordinate (Non-Dimensional)

v Second component of fluid velocity (Non-Dimensional)

$\overline{v}$ Second component of fluid velocity (Dimensional)

V_0 Mean suction velocity

Greek Symbols

β Thermal Coefficient of volumetric expansion

β^* Solutal Coefficient of volumetric expansion

ρ Fluid density

ν Kinematic coefficient of viscosity

θ Non-dimensional temperature

θ_R Real part of θ

ϕ Non-dimensional species concentration

ϕ_R Real part of ϕ

τ_R Non-dimensional skin friction (Real part)

ω Frequency of Oscillation

Subscripts

m Mean / Average condition

∞ Free stream conditions

I. INTRODUCTION

The analysis of MHD free convective flow involving mass transfer in porous medium has attracted the attention of many researchers due to its possible applications in varied fields of science and technology such as geophysics, soil technology, astrophysics, nuclear power reactors etc. Notwithstanding, in recent times, the study of MHD convective flow over heated or cooled plates becomes one of the fundamental problems of research. As many problems in nature are time dependent, unsteady free convection flow past an infinite or a semi-infinite plate has got an important place in research due to its significant technological applications. Hossain and Mandal [1] studied the effects of mass transfer and free convection on the unsteady MHD flow past a vertical porous plate with variable suction. Chamkha [2] studied the unsteady MHD convective heat and mass transfer flow past a moving semi- infinite vertical porous plate with heat absorption. The case of MHD free convection heat and mass transfer flow past a vertical flat plate embedded in a porous medium was considered by Alam and Rahman [3]. Pal and Talukdar [4] examined the combined effects of Joule heating and chemical reaction on unsteady magneto-hydrodynamic mixed convection of a viscous dissipative fluid over a vertical plate in porous media with thermal radiation. Recently, Ahmed et al. [5] investigated the case of unsteady MHD free convective mass transfer flow past an oscillating plate in presence of Soret effect. The science of thermal radiation has become of increasing importance in aerospace research
and design due to high temperatures associated with increased engine efficiencies. The pioneering work in the field of radiation was made by Cess [6]. The case of unsteady flow in presence of radiation and variable viscosity on a MHD free convection past a semi-infinite flat plate with an aligned magnetic field was studied by Seddeek [7]. Chamkha and Ben-Nakhi [8] studied the thermal radiation with Soret and Dufour effects on MHD mixed convection flow past a permeable surface immersed in a porous medium. Pal and Mondal [9]examined the effect of thermal radiation on MHD non-Darcy flow and heat transfer over a stretching sheet in presence of Ohmic dissipation.

The study of heat and mass transfer with chemical reaction is of considerable importance in the chemical and hydrometallurgical industries. A notable contribution in chemical reactions phenomena was made by Astarita [10]. Combined heat and mass transfer phenomena with chemical reaction have been studied by various researchers like Muthucumaraswamy and Ganesan [11], Chamkha [12], Raptis and Perdikis[13], Postelnicu [14] etc. The effects of thermal radiation and first order chemical reaction on a vertical oscillating plate were investigated separately by Manivannan et al. [15] and Muthucumaraswamy et al. [16].

The objective of the present study is to investigate two- dimensional unsteady free convective flow past an oscillating plate of an electrically conducting chemically absorption fluid in presence of thermal radiation and first order chemical reaction.

II. MATHEMATICAL FORMULATION OF THE PROBLEM

A co-ordinate system ($\overline{x}$, $\overline{y}$) has been introduced, with its $\overline{x}$ -axis along the length of the plate in the upward vertical direction and $\overline{y}$ -axis perpendicular to the plate towards the fluid region. A uniform magnetic field of moderate strength is applied along positive $\overline{y}$ -axis and perpendicular to the plate. All fluid properties except possibly the hydrostatic pressure are supposed to be independent of length scale. The plate is subjected to a constant suction velocity. Using Boussinesq and boundary layer approximations, a two- dimensional fluid model has been developed in terms of a system of coupled partial differential equations, combined with two-point semi-open initio - boundary conditions as:

Continuity Equation

$$\frac{\partial \overline{v}}{\partial \overline{y}} = 0 \tag{1}$$

Momentum Equation

$$\frac{\partial \overline{u}}{\partial \overline{t}} + \overline{v}\frac{\partial \overline{u}}{\partial \overline{y}} = \nu \frac{\partial^2 \overline{u}}{\partial \overline{y}^2} + g\beta(\overline{T} - \overline{T}_\infty) + g\beta^*(\overline{C} - \overline{C}_\infty) - \left(\frac{\sigma B_0^{\ 2}}{\rho} + \frac{\nu}{\overline{K}}\right)\overline{u} \tag{2}$$

Energy Equation

$$\frac{\partial \overline{T}}{\partial \overline{t}} + \overline{v}\frac{\partial \overline{T}}{\partial \overline{y}} = \frac{k}{\rho c_p}\frac{\partial^2 \overline{T}}{\partial \overline{y}^2} - \frac{1}{\rho c_p}\frac{\partial \overline{q}_{r\overline{y}}}{\partial \overline{y}} + \frac{\overline{Q}_l}{\rho c_p}(\overline{C} - \overline{C}_\infty) - \frac{\overline{Q}}{\rho c_p}(\overline{T} - \overline{T}_\infty) \tag{3}$$

Species Continuity Equation

$$\frac{\partial \overline{C}}{\partial \overline{t}} + \overline{v}\frac{\partial \overline{C}}{\partial \overline{y}} = D_M \frac{\partial^2 \overline{C}}{\partial \overline{y}^2} - K_l(\overline{C} - \overline{C}_\infty) \tag{4}$$

The relevant initio - boundary conditions:

$$\left.\begin{array}{l}
\overline{u} = 0\ ,\ \overline{T} = \overline{T}_\infty,\ \overline{C} = \overline{C}_\infty, \text{ for every } \overline{y} \text{ and when } \overline{t} \le 0\ . \\
\overline{u} = U_0, \overline{T} = \overline{T}_\infty + A(\overline{T}_m - \overline{T}_\infty)\exp(i\overline{n}\overline{t}), \overline{C} = \overline{C}_\infty + A(\overline{C}_m - \overline{C}_\infty)\exp(i\overline{n}\overline{t}), \text{ at } \overline{y} = 0, \text{ when } \overline{t} > 0 \\
\overline{u} \to 0\ , \overline{T} \to \overline{T}_\infty\ ,\ \overline{C} \to \overline{C}_\infty\ , \text{ for } \overline{y} \to \infty\ , \text{ when } \overline{t} > 0
\end{array}\right\} \tag{5}$$

The constant suction velocity can be considered as:

$$\overline{v}(t) = -V_0 \tag{6}$$

The Rosseland approximate model, quantified the radiative heat flux for an optically thick boundary layer flow in a simplified differential form is considered as:

$$\overline{q}_r = -\frac{4\sigma^*}{3k^*}\frac{\partial \overline{T}^4}{\partial \overline{y}} \tag{7}$$

Where σ^* and k^* are the Stefan-Boltzmann constant and Rosseland mean absorption coefficient, respectively. Assuming that the temperature differences within the flow are sufficiently small, as such $\overline{T}^4$ may be expressed as a linear function of temperature $\overline{T}$ and expanding $\overline{T}^4$ in Taylor's series about $\overline{T}_\infty$ and neglecting higher order terms we thus get,

$$\overline{T}^4 \approx \overline{T}_\infty^{\ 4} + (\overline{T} - \overline{T}_\infty)4\overline{T}_\infty^{\ 3} = 4\overline{T}_\infty^{\ 3}\overline{T} - 3\overline{T}_\infty^{\ 4} \tag{8}$$

Using (8) and (7), equation (3) becomes,

$$\frac{\partial \overline{T}}{\partial \overline{t}} + \overline{v}\frac{\partial \overline{T}}{\partial \overline{y}} = \frac{k}{\rho c_p}\frac{\partial^2 \overline{T}}{\partial \overline{y}^2} + \frac{16\sigma^*\overline{T}_\infty^{\ 3}}{3\rho c_p k^*}\frac{\partial^2 \overline{T}}{\partial \overline{y}^2} + \frac{\overline{Q}_l}{\rho c_p}(\overline{C} - \overline{C}_\infty) - \frac{\overline{Q}}{\rho c_p}(\overline{T} - \overline{T}_\infty) \tag{9}$$

Introduce the following non-dimensional quantities as:

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$$y=\frac{\bar{y}V_0}{\nu},t=\frac{\bar{t}V_0^{\,2}}{\nu},u=\frac{\bar{u}}{U_0},v=\frac{\bar{v}}{V_0},\theta=\frac{\bar{T}-\bar{T}_\infty}{\bar{T}_m-\bar{T}_\infty},\phi=\frac{\bar{C}-\bar{C}_\infty}{\bar{C}_m-\bar{C}_\infty},M=\frac{\sigma B_0^{\,2}\nu}{\rho V_0^{\,2}},Gr=\frac{g\beta\nu(\bar{T}_m-\bar{T}_\infty)}{U_0V_0^{\,2}},K=\frac{V_0^{\,2}\bar{K}}{\nu^2},$$

$$Gm=\frac{g\beta^*\nu(\bar{C}_m-\bar{C}_\infty)}{U_0V_0^{\,2}},\ \omega=\frac{\bar{\omega}\nu}{V_0^{\,2}},\ \Pr=\frac{\nu\rho c_p}{k},Sc=\frac{\nu}{D_M},\ R=\frac{4\sigma^*\bar{T}_\infty^{\,3}}{kk^*},\ S=\frac{\bar{Q}\nu}{\rho c_pV_0^{\,2}},N_r=\frac{\bar{Q}_l\nu}{kV_0^{\,2}},F=\frac{\bar{K}_l\nu}{V_0^{\,2}}.$$

The corresponding non-dimensional form of equations (2), (9) and (4) respectively become,

$$\frac{\partial u}{\partial t}-\frac{\partial u}{\partial y}=\frac{\partial^2 u}{\partial y^2}+Gr\theta+Gm\phi-M^*u \qquad (10)$$

$$\Pr\left(\frac{\partial\theta}{\partial t}-\frac{\partial\theta}{\partial y}\right)=\lambda\frac{\partial^2\theta}{\partial y^2}+N_r\phi-S\theta \qquad (11)$$

$$Sc\left(\frac{\partial\phi}{\partial t}-\frac{\partial\phi}{\partial y}\right)=\frac{\partial^2\phi}{\partial y^2}-FSc\phi \qquad (12)$$

Where, $M^*=M+\frac{1}{K}$ (say)

The non-dimensional initio - boundary conditions are:

$$\left.\begin{array}{l} u=0,\ \theta=0,\ \phi=0,\ \text{for every } y \text{ when } t\le 0\\ u=1,\ \theta=A\exp(i\omega t),\ \phi=A\exp(i\omega t),\ \text{at } y=0 \text{ when } t>0\\ u\to 0,\theta\to 0,\ \phi\to 0,\ \text{for } y\to\infty \text{ when } t>0 \end{array}\right\} \qquad (13)$$

III. METHOD OF SOLUTION

To, get a closed analytical form of solutions we prefer to use the technique of normal mode method. For purely an oscillating flow, the form of solutions for expressions (8), (9) and (10) can be considered as:

$$u(y,t)=u_0(y)\exp(i\omega t),\quad \theta(y,t)=\theta_0(y)\exp(i\omega t),\ \phi(y,t)=\phi_0(y)\exp(i\omega t) \qquad (14)$$

On using the forms of (14), expressions (10), (11), (12) and (13) give,

$$\frac{d^2u_0}{dy^2}+\frac{du_0}{dy}-(M_1+i\omega)u_0=-Gr\theta_0-Gm\phi_0 \qquad (15)$$

$$\lambda\frac{d^2\theta_0}{dy^2}+\Pr\frac{d\theta_0}{dy}-i\omega\Pr\theta_0=-N_r\phi \qquad (16)$$

$$\frac{d^2\phi_0}{dy^2}+Sc\frac{d\phi_0}{dy}-(F+i\omega)\phi_0=0 \qquad (17)$$

With initio – boundary conditions as:

$$\left.\begin{array}{l} u_0=0,\theta_0=0,\phi_0=0,\ \text{for every } y \text{ when } t\le 0.\\ u_0=1,\theta_0=1,\ \phi_0=1,\ \text{at } y=0 \text{ when } t>0\\ u_0\to 0,\theta_0\to 0,\phi_0\to 0,\ \text{for } y\to\infty,\ \text{when } t>0 \end{array}\right\} \qquad (18)$$

The real part of expressions for non-dimensional concentration, temperature and velocity of fluid particles in the boundary layer are thus calculated and expressed in closed form as:

$$\phi_R(y,t)=\exp(-a_1y)\cos(\omega t-b_1y) \qquad (19)$$

$$\theta_R(y,t)=(c_1e\exp(-a_1y)+d_1e\exp(-a_2y))\cos(\omega t)-(c_2e\exp(-a_1y)+d_2e\exp(-a_2y))\sin(\omega t) \qquad (20)$$

$$\begin{aligned}u_R(y,t)&=(e_5\exp(-a_1y)+e_7\exp(-a_2y))\cos(\omega t)-(e_6\exp(-a_1y)+e_8\exp(-a_2y))\sin(\omega t)\\&+e_9\exp(-a_3y)\cos(\omega t-b_3y)-e_{10}\exp(-a_3y)\sin(\omega t-b_3y).\end{aligned} \qquad (21)$$

Skin- friction at the plate:

The real part of the non-dimensional skin-friction co-efficient at the plate is obtained as:

$$\tau_R = \left(\frac{\partial u_R}{\partial y}\right)_{y=0} = \tau_a \cos(\omega t) + \tau_b \sin(\omega t) \cdot \quad (22)$$

Rate of heat transfer coefficient:

The real part of the rate of heat transfer coefficient in terms of the Nusselt number is given as,

$$Nu_R = -\frac{1}{Pr}\left(\frac{\partial \theta_R}{\partial y}\right)_{y=0} = Nu_1 \cos(\omega t) + Nu_2 \sin(\omega t) \quad (23)$$

Rate of mass transfer coefficient:

The real part of the rate of mass transfer coefficient in terms of the Sherwood number is

$$Sh_R = -\frac{1}{Sc}\left(\frac{\partial \phi_R}{\partial y}\right)_{y=0} = a_1 \cos(\omega t) - b_1 \sin(\omega t) \quad (24)$$

IV. RESULTS AND DISCUSSION

The present paper deals with the problem of two- dimensional unsteady flow of a viscous chemically absorption fluid past an impulsively accelerated plate embedded in porous media with thermal radiation, first order chemical reaction and oscillating plate temperature and concentrations. Numerical results for the velocity temperature and concentration functions with friction co-efficient, rate of heat and mass transfer are calculated by using a normal mode method for different values of the parameters such as *Pr, Gr*, *Gm*, *Sr*, *Sc*, *S*, *F*, *R*, *M*, *K*, u_0, ω, *y* and t. In this study, water is taken as a primary fluid (solvent), whose Prandtl number (*Pr*) is consider as 7.0 at 25^0 C or $298K$ and 1 atmosphere of pressure. To produce a substantial effect on mass diffusion, some fluids considered as secondary (solute) such as Helium (*He)*, Water vapour (H_2O), Ammonia (NH_3) and Carbon dioxide (CO_2) are diffused through air. The Schmidt number (*Sc*) of the corresponding secondary species are taken as respectively 0.30, 0.60, 0.78, 0.98 and the Prandtl number of the diffused fluids are all considered as 7.0. In figures 1 and 2, the parametric effect of thermal radiation (*R*) and radiation absorption (N_r) on the temperature profiles (θ_R,y) for a set of fixed values of *Pr*=7.0, *F*=0.5, ω =0.1, *t*=0.1, *Sc*=0.60 as well as *R* =0.15 (for fig. 2) and N_r =0.1(for fig. 1) are depicted schematically. Due to increase in values of both *R* and N_r, the temperature of the fluid particles near the plate surface are found to be increasing, which is in accordance with the fact that, the increase in the respective parametric values affected in the growth of the thermal boundary layer thereby increase the values of θ_R. Figure 3 present graphically the influence of chemical reaction parameter (*F*) on the concentration ϕ_R against normal distances *y* for a set of fixed values of *Sc*=0.60, ω =0.2, *t*=0.1. Due to increase in values of *F*, constituents in higher concentration zone (adherent to the plate) moves towards the species in lower concentration zone (free stream region), which results in dropping the thickness of the concentration boundary layer and thus decrease the values of ϕ_R.

Figures 4 to 8, demonstrate how the main flow rate have been regulated by the presence of the pertinent parameters like thermal radiation (*R*), radiation absorption (N_r), magnetic field parameter (*M*), permeability parameter (*K*) and chemical reaction parameter (*F*) respectively in presence of a set of fixed values of *Pr*=7.0, ω =0.2, *t* =0.1, *Sc*=0.60, *Gr*=20, S=0.2,*Gm*=10, $u_0 = 1.0$ as well as *R*=0.15 N_r=0.2 (for figures 4, 6.7,8), M=0.5 (for figures 4, 5.7,8), *K*=0.5 (for figures 4, 5.6,8) and *F*=0.5 (for figures 4, 5.6,7) . It is observed that, the flow velocity u_R increases as the values of *R*, N_r and *K* increase, while u_R is found decreasing due to increase in *M* and *F*. The increase in *R* and N_r increases the thermal buoyancy forces near the plate, which thus increase the values of u_R near the plate region. Again, as the values of *K* increase, the drag force decreases this increases the flow rate and the value of the velocity u_R. On the other hand, an increase in value of *F* decreases the concentration near the plate, which results in decreasing the mass buoyancy force and thus decreases the value of u_R. Also, the presence of *M* generates a resistive force named Lorentz force which acts against the flow and thus decelerate the flow rate and the values of u_R automatically decrease. It is interesting to observe that, the velocity profile attained its maximum peak near the plate, which is found to be died out away from the plate; this is in parity with the fact that, the effect of the buoyancy forces near the plate is more than at a distance far away from the plate.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Fig. 9 shows the influence of thermal radiation (*R*) on the skin-friction profile (τ_R, N_r) for a set of fixed values of *Pr*=7.0, ω =0.3, *t* =0.1, *Sc*=0.60, *Gr*=15, *Gm*=10, *K*=0.5 and $u_0 = 1.0$. It is observed that, τ_R decreasing due to increase in *R,* while it is found increasing as N_r increases. Fig. 10 depicts the effect of chemical reaction parameter (*F*) on the Sherwood number profile (Sh_R, *t*) for a set of fixed values of *Sc*=0.60, ω =0.2. Due to presence of *F*, there exists a transfer of species from higher concentration zone to lower concentration zone, which thus accelerate the mass transfer rate, results of which increase the values of Sh_R. The influence of thermal radiation (*R*) and chemical reaction parameter (*F*) on the Nusselt number profiles (Nu_R, N_r) are demonstrated in figures 11 and 12 for a set of fixed values of *Pr*=7.0, *F*=0.5, ω =0.1, *t*=0.1, *Sc*=0.60 as well as *R* =0.15 (for fig. 12) and N_r =0.1(for fig. 11) respectively. It is observed that, the rate of heat transfer accelerates due to increase in *F* and N_r, while the heat transfer flow rate decelerates as the values of *R* increase.

V. CONCLUSIONS

An unsteady two-dimensional free convective flow of a Newtonian electrically conducting incompressible viscous fluid through an impulsively accelerated vertical plate immersed in Darcian porous media in presence of thermal radiation and first order chemical reaction with radiation absorption effect is considered for study. The outcome of the study can be concluded as:

A. The presence of Chemical reaction parameter decreases the concentration near the plate, while the Sherwood number is seen to increase by the increase of chemical reaction parameter.
B. The temperature profiles increase with an increase in values of thermal radiation and absorption parameters.
C. The fluid velocity found increasing due to increase in values of thermal radiation, radiation absorption and permeability parameters, while the increase of magnetic and chemical reaction parameters is to decrease the velocity of the fluid particles.
D. The skin-frictional effect increases due to increase in radiation parameter, but the thermal radiation is found decreasing the effect of plate friction.
E. The Sherwood number increases due to increase in chemical reaction parameter.
F. The Nusselt number increases with increase in values of chemical reaction parameter, while the Nusselt number decreases due to increase in thermal radiation and radiation absorption parameters.

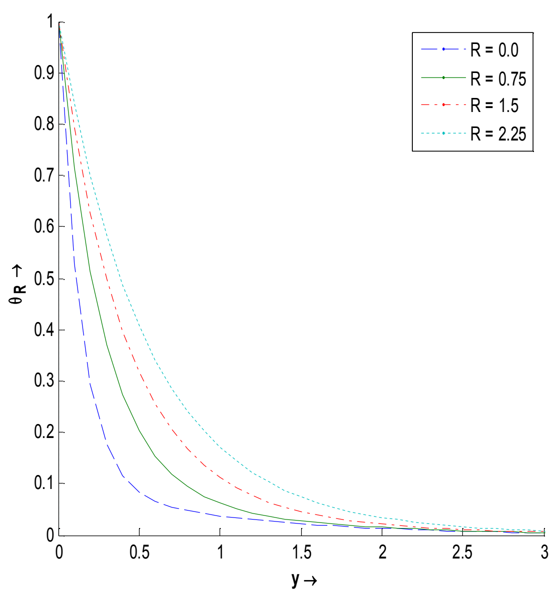

Fig. 1 Graph showing variation of temperature agaist normal distance for change in values of thermal radiation.

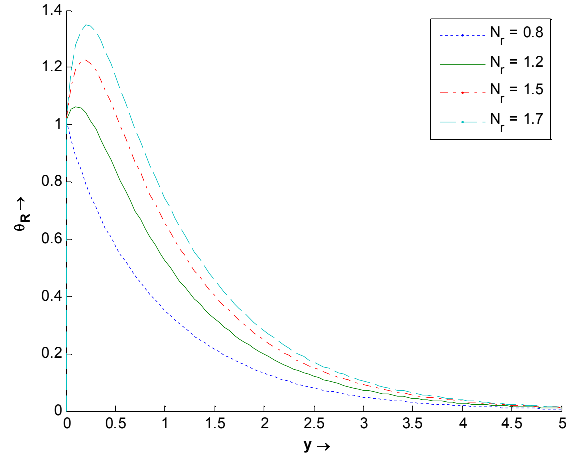

Fig. 2 Graph showing variation of temperature agaist normal distance for change in values of radiation absorption parameter.

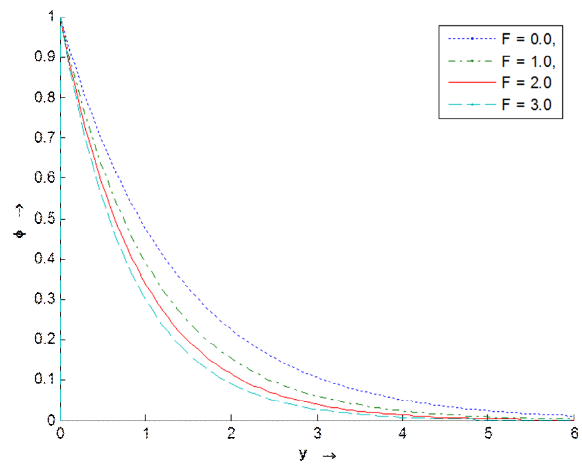

Fig. 3 Graph showing variation of concentration agaist normal distance for change in values of chemical reaction parameter.

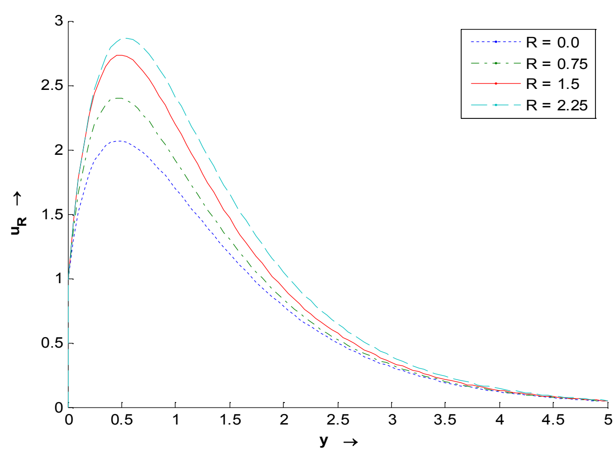

Fig. 4 Graph showing variation of velocity agaist normal distance for change in values of thermal radiation parameter.

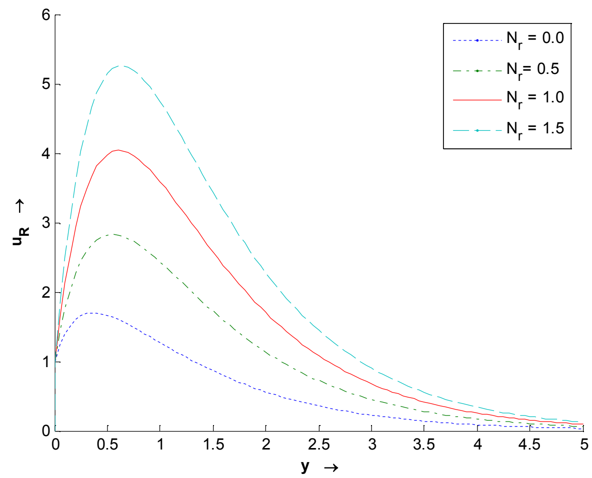

Fig. 5 Graph showing variation of velocity agaist normal distance for change in values of radiation absorption parameter.

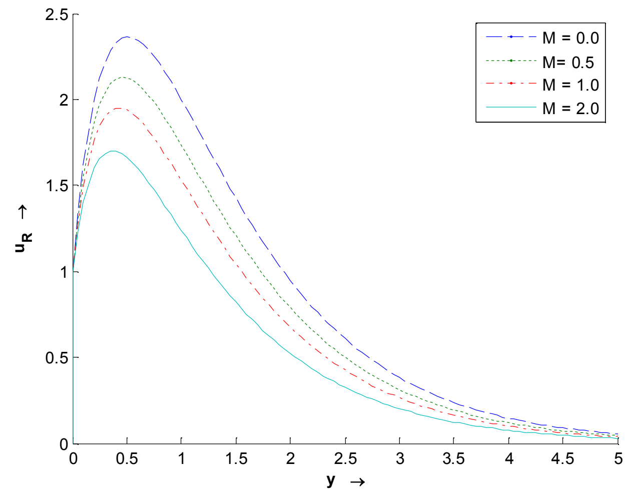

Fig. 6 Graph showing variation of velocity agaist normal distance for change in values of magnetic field parameter.

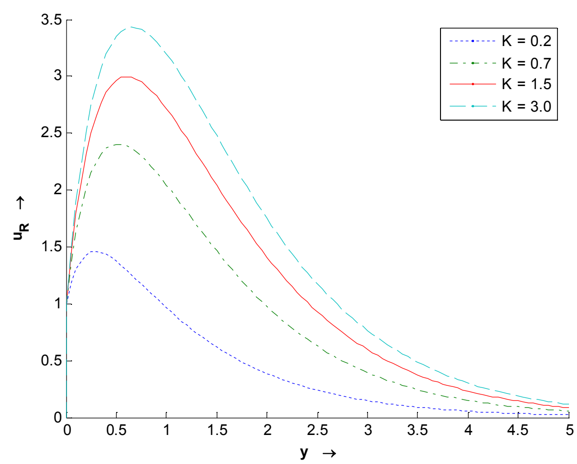

Fig. 7 Graph showing variation of velocity agaist normal distance for change in values of permeability parameter.

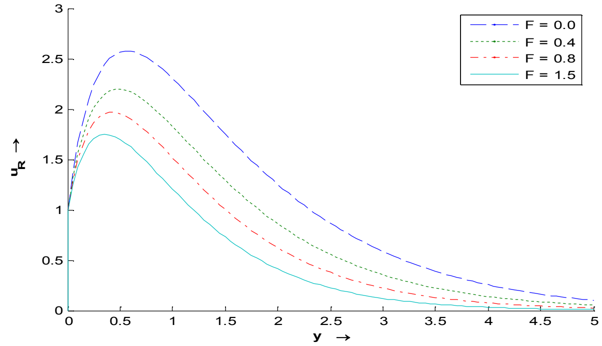

Fig. 8 Graph showing variation of velocity agaist normal distance for change in values of chemical reaction parameter.

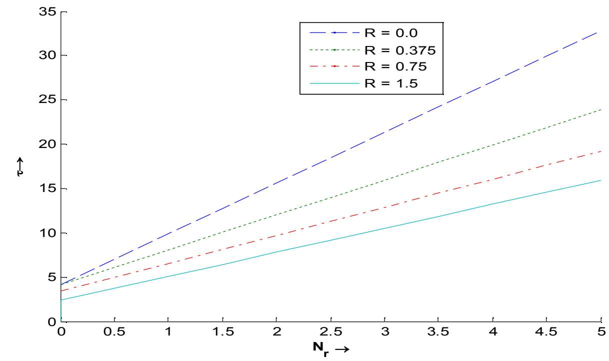

Fig. 9 Graph showing variation of skin-friction agaist radiation absorption parameter for change in values of thermal radiation parameter.

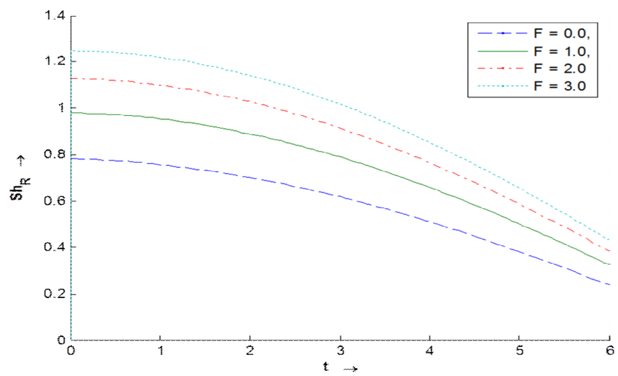

Fig. 10 Graph showing variation of Sherwood number agaist time for change in values of chemical reaction parameter.

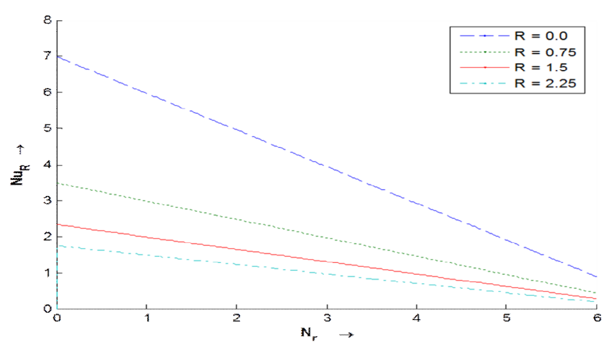

Fig. 11 Graph showing variation of Nusselt number agaist radiation absorption parameter for change in values of thermal radiation parameter.

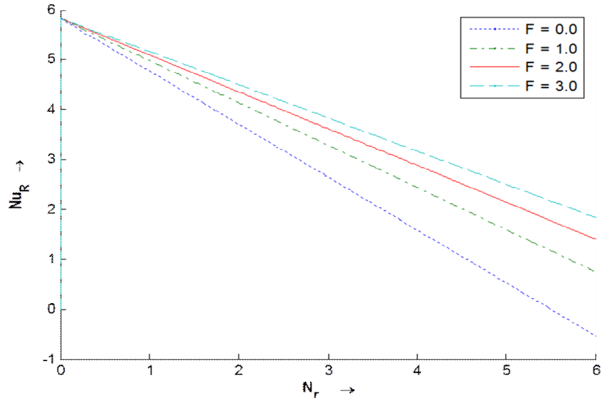

Fig. 12 Graph showing variation of Nusselt number agaist radiation absorption parameter for change in values of thermal radiation parameter.

Appendixes

$$\alpha_1 = \frac{1}{2}\left[Sc + \frac{\sqrt{Sc}}{\sqrt{2}}\sqrt{\left((Sc+4F)+\sqrt{(Sc+4F)^2+16n^2}\right)}\right], \beta_1 = \frac{\sqrt{Sc}}{2\sqrt{2}}\sqrt{\left(\sqrt{((Sc+4F)^2+16n^2}-(Sc+4F)\right)}$$

$$a_1 = \lambda(\alpha_1^{\ 2} - \beta_1^{\ 2}) - \Pr\alpha_1,\ a_2 = 2\alpha_1\beta_1\lambda - \Pr\beta_1 - n\Pr,\ \gamma_1(y) = -\frac{N_r\Pr}{a_1^{\ 2}+a_2^{\ 2}}(a_1\cos(\beta_1 y) - a_2\sin(\beta_1 y)),$$

$$\gamma_2(y) = \frac{N_r\Pr}{a_1^{\ 2}+a_2^{\ 2}}(a_2\cos(\beta_1 y) + a_1\sin(\beta_1 y)), \alpha_2 = \frac{1}{2\lambda}\left[\Pr + \frac{\sqrt{\Pr}}{\sqrt{2}}\sqrt{\left((\Pr+4S\lambda)+\sqrt{(\Pr+4S\lambda)^2+16n^2\lambda^2}\right)}\right],$$

$$\beta_2 = \frac{\sqrt{\Pr}}{2\sqrt{2}\lambda}\sqrt{\left(\sqrt{(\Pr+4S\lambda)^2+16n^2\lambda^2}-(\Pr+4S\lambda)\right)}\ a_3 = \alpha_2^{\ 2} - \beta_2^{\ 2} - \alpha_2 - M^*u_0, a_4 = 2\alpha_2\beta_2 - b_2 - nu_0,$$

$$\delta_1 = (A-\gamma_1)\cos(\beta_2 y) - \gamma_2\sin(\beta_2 y), \delta_2 = \gamma_2\cos(\beta_2 y) + (A-\gamma_1)\sin(\beta_2 y),$$

$$\xi_1(y) = -\frac{Gr}{a_3^{\ 2}+a_4^{\ 2}}(a_3\cos(\beta_2 y) - a_4\sin(\beta_2 y)), \xi_2(y) = \frac{Gr}{a_3^{\ 2}+a_4^{\ 2}}(a_4\cos(\beta_2 y) + a_3\sin(\beta_2 y)),$$

$$a_5 = \alpha_2^{\ 2} - (\beta_1+\beta_2)^2 - \alpha_2 - M^*u_0,\ a_6 = (2\alpha_2 - 1)(\beta_1+\beta_2) - nu_0,$$

$$b_1(y) = a_5\cos(\beta_1+\beta_2)y - a_6\sin(\beta_1+\beta_2)y,\ b_2(y) = a_6\cos(\beta_1+\beta_2)y + a_5\sin(\beta_1+\beta_2)y,$$

$$\xi_3(y) = -\frac{GrN_r\Pr(a_1b_1 - a_2b_2)}{(a_1^{\ 2}+a_2^{\ 2})(a_5^{\ 2}+a_6^{\ 2})}, \xi_4(y) = \frac{GrN_r\Pr(a_1b_2 + a_2b_1)}{(a_1^{\ 2}+a_2^{\ 2})(a_5^{\ 2}+a_6^{\ 2})}, a_7 = \alpha_1^{\ 2} - \beta_1^{\ 2} - \alpha_1 - M^*u_0, a_8 = 2\alpha_1\beta_1 - \beta_1 - nu_0,$$

$$b_3 = a_7\cos(\beta_1 \mathrm{y}) - a_8\sin(\beta_1 \mathrm{y}), b_4 = a_8\cos(\beta_1 \mathrm{y}) + \mathrm{a}_7\sin(\beta_1 \mathrm{y}),\ \xi_5(y) = \frac{GrN_r\Pr(a_1b_3 - a_2b_4)}{(a_1^{\ 2}+a_2^{\ 2})(a_7^{\ 2}+a_8^{\ 2})}, \xi_5(y) = -\frac{GrN_r\Pr(a_1b_4 + a_2b_3)}{(a_1^{\ 2}+a_2^{\ 2})(a_7^{\ 2}+a_8^{\ 2})},$$

$$\xi_7(y) = -\frac{AGm(a_7\cos(\beta_1 y) - a_8\sin(\beta_1 y))}{a_7^{\ 2}+a_8^{\ 2}}, \xi_8(y) = \frac{AGm(a_8\cos(\beta_1 y) + a_7\sin(\beta_1 y))}{a_7^{\ 2}+a_8^{\ 2}}, \xi_9(y) = \xi_5(y) + \xi_7(y),$$

$$\xi_{10}(y) = \xi_6(y) + \xi_8(y),\ \xi_{11}(y) = \xi_1(y) + \xi_3(y),\ \xi_{12}(y) = \xi_2(y) + \xi_4(y), \alpha_3 = \frac{1}{2}\left[1 + \frac{1}{\sqrt{2}}\sqrt{\left(1+4M^* + \sqrt{(1+4M^*)^2+16n^2\lambda^2}\right)}\right],$$

$$\beta_3 = \frac{1}{2\sqrt{2}}\left[\sqrt{\sqrt{(1+4M^*)^2+16n^2\lambda^2}-(1+4M^*)}\right]\ \tau_{a1}(y) = \frac{AGm(\alpha_1a_7 + \beta_1a_8)}{a_7^{\ 2}+a_8^{\ 2}},$$

$$\tau_{b1}(y) = \frac{AGm(\alpha_1a_8 - \beta_1a_7)}{a_7^{\ 2}+a_8^{\ 2}}, \tau_{a2}(y) = \frac{\alpha_2a_3Gr}{a_3^{\ 2}+a_4^{\ 2}} + \frac{\alpha_2N_rGr(a_1a_5 - a_2a_6)}{(a_1^{\ 2}+a_2^{\ 2})(a_5^{\ 2}+a_6^{\ 2})}, \tau_{b2}(y) = \frac{\alpha_2a_4Gr}{a_3^{\ 2}+a_4^{\ 2}} + \frac{\alpha_2N_rGr(a_1a_6 + a_2a_5)}{(a_1^{\ 2}+a_2^{\ 2})(a_5^{\ 2}+a_6^{\ 2})}$$

$$\tau_{a3}(y) = \frac{\beta_2a_4Gr}{a_3^{\ 2}+a_4^{\ 2}} + \frac{(\beta_1+\beta_2)N_rGr(a_1a_6 + a_2a_5)}{(a_1^{\ 2}+a_2^{\ 2})(a_5^{\ 2}+a_6^{\ 2})}, \tau_{b3}(y) = -\frac{\beta_2a_3Gr}{a_3^{\ 2}+a_4^{\ 2}} - \frac{(\beta_1+\beta_2)N_rGr(a_1a_5 + a_2a_6)}{(a_1^{\ 2}+a_2^{\ 2})(a_5^{\ 2}+a_6^{\ 2})},$$

$$\tau_{a4}(y)=-\alpha_3\left(A+\frac{a_7 AGm}{a_7^2+a_8^2}+\frac{a_3 Gr}{a_3^2+a_4^2}+\frac{N_r Gr(a_1a_5-a_2a_6)}{(a_1^2+a_2^2)(a_5^2+a_6^2)}\right),\tau_{b4}(y)=-\alpha_3\left(\frac{a_4 Gr}{a_3^2+a_4^2}+\frac{aA_8 Gm}{a_7^2+a_8^2}+\frac{N_r Gr(a_1a_6+a_2a_5)}{(a_1^2+a_2^2)(a_5^2+a_6^2)}\right),$$

$$\tau_{a5}(y)=-\beta_3\left(\frac{a_4 Gr}{a_3^2+a_4^2}+\frac{a_8 AGm}{a_7^2+a_8^2}+\frac{N_r Gr(a_1a_6+a_2a_5)}{(a_1^2+a_2^2)(a_5^2+a_6^2)}\right),\tau_{b5}(y)=-\beta_3\left(A+\frac{a_3 Gr}{a_3^2+a_4^2}+\frac{a_7 AGm}{a_7^2+a_8^2}+\frac{N_r Gr(a_1a_5-a_2a_6)}{(a_1^2+a_2^2)(a_5^2+a_6^2)}\right),$$

$$\tau_{a6}(y)=-\frac{a_4\beta_2 Gr}{a_3^2+a_4^2}-\frac{a_8 b_1 AGm}{a_7^2+a_8^2}+\frac{N_r Gr(a_1a_6+a_2a_6)(\beta_1+\beta_2)}{(a_1^2+a_2^2)(a_5^2+a_6^2)}\ \tau_{b6}(y)=\frac{a_3\beta_2 Gr}{a_3^2+a_4^2}+\frac{a_7 b_1 AGm}{a_7^2+a_8^2}+\frac{N_r Gr(a_1a_5-a_2a_6)(\beta_1+\beta_2)}{(a_1^2+a_2^2)(a_5^2+a_6^2)},$$

$$\tau_a=\tau_{a1}+\tau_{a2}+\tau_{a3}+\tau_{a4}+\tau_{a5}+\tau_{a6}\ \tau_b=\tau_{b1}+\tau_{b2}+\tau_{b3}+\tau_{b4}+\tau_{b5}+\tau_{b6},$$

$$Nu_1(y)=-\frac{a_2\beta_1 N_r}{a_1^2+a_2^2}+\frac{a_2(\beta_1+\beta_2)N_r}{a_1^2+a_2^2}-\frac{a_1\alpha_1 N_r}{a_1^2+a_2^2}+a_2\left(A+\frac{a_1 N_r}{a_1^2+a_2^2}\right),\ Nu_2(y)=-\frac{a_1\beta_1 N_r}{a_1^2+a_2^2}+\frac{a_1(\beta_1+\beta_2)N_r}{a_1^2+a_2^2}-\frac{a_2\alpha_1 N_r}{a_1^2+a_2^2}-\frac{a_2\alpha_2 N_r}{a_1^2+a_2^2}+\beta_2.$$

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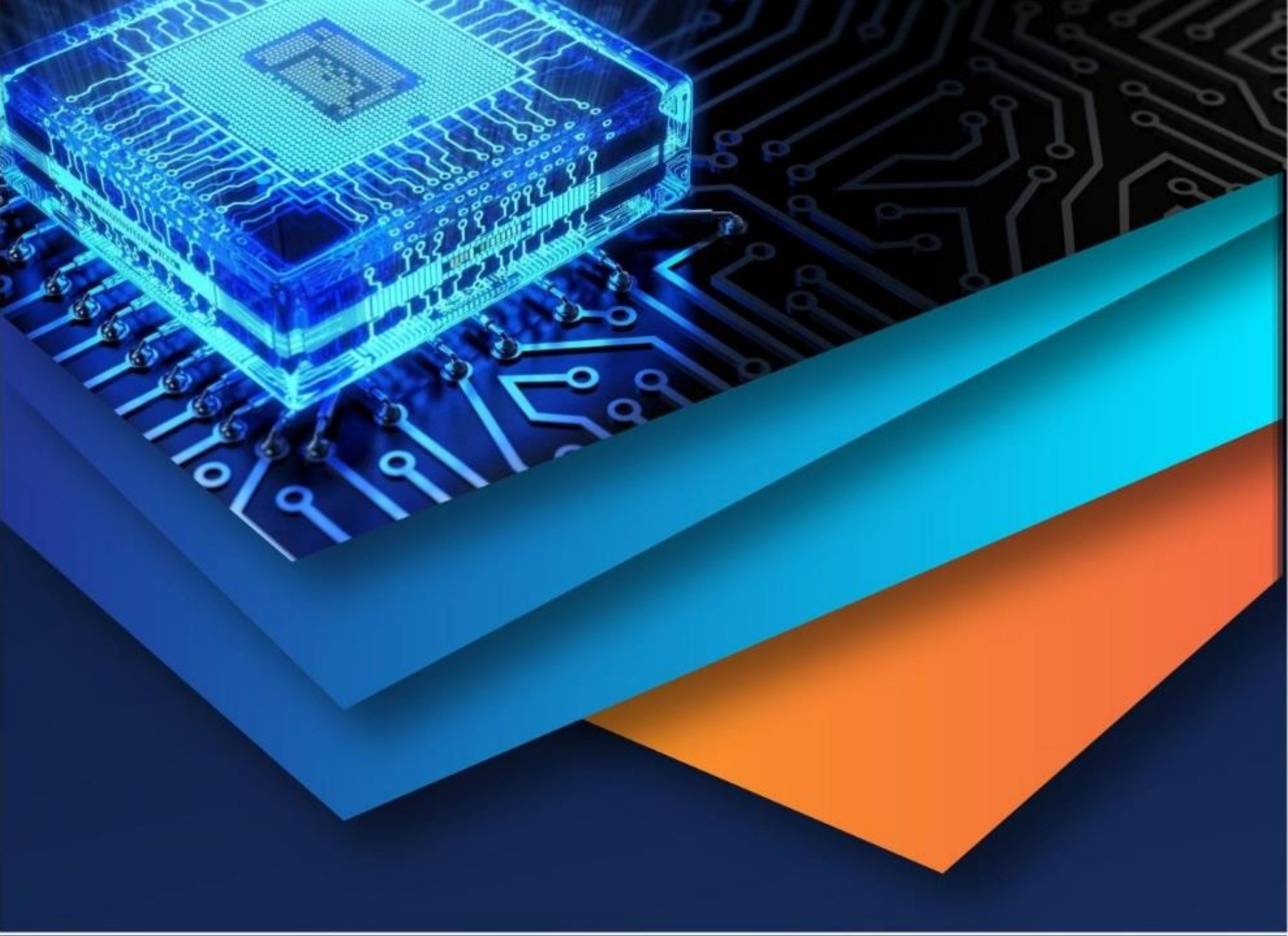

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