CONVECTIVE MHD FLOW PAST AN IMPULSIVELY STARTED VERTICAL PLATE WITH PERIODIC TEMPERATURE AND CONCENTRATION IN PRESENCE OF THERMAL RADIATION AND CHEMICAL REACTION

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***Abstract*— This study investigated a two-dimensional unsteady MHD-free convection of a viscous, incompressible fluid past through an impulsively started vertical plate in the presence of thermal radiation and chemical reactions. The Laplace transform method is used to solve the second-order partial differential equations. The effect of various related parameters on the velocity field, temperature field, and concentration field are demonstrated graphically. The effects of the Nusselt number, Sherwood number, and skin friction for the influence of different parameters are also graphically visualized. It is noticed that the increment in Soret number hikes the fluid velocity and concentration. Also, the Hartmann number reduces the velocity of the fluid. Present work is important in various industrial and engineering sectors, such as chemical and power industries, glass production, steel rolling etc.**

***Keywords*— MHD; heat transfer; mass transfer; thermal radiation; thermal diffusion; chemical reaction**

I. INTRODUCTION

The rapid development of modern technology has led researchers to study the effects of heat and mass transfer as well as chemical reactions because of its substantial use in petroleum reservoirs, geothermal and geophysical engineering, and many industrial applications. Thermal MHD boundary layer flow has many uses in agriculture, engineering, petroleum, solar physics, geophysics, electronic engineering, and chemical engineering. Makinde and Sibanda (2008), Aydin and Kaya (2009), Rashad *et al.* (2011) and Gorla *et al.* (2010) have described mixed convection of heat and mass transfer flows under various circumstances. Kader and Yaglom (1994) have shown the law of heat and mass transfer in a completely turbulent wall flow. The effects of heat and mass transfer on the radiative flux of chemical reactions were studied by Muthucumaraswamy and Chandrakala (2006). Chamkha (1997a) discussed the hydromagnetic natural convective flow through an isothermal inclined surface adjacent to a porous medium. Chamkha (1996), Chamkha and Khaled (2000, 2001), Takhar *et al*. (2002b), Chamkha *et al*. (2006), Chamkha *et al.* (2011) and Wakif *et al*. (2020) are some authors who have investigated in this field.

Thermophoresis, or the Soret effect, is caused by a temperature gradient. It has been used in the manufacture of optical fibers using a vapor deposition process to separate various polymers. Ahmed (2010, 2012), Chamkha and Pop (2004), and Chamkha *et al*. (2006) described the effects of thermal diffusion, or Soret, on various MHD convections.

Thermal radiation has great significance in different industrial and space technology such as furnace design, the production of glass, electric power generation, solar power technology, nuclear engineering, astrophysical flows, etc. Chamkha (1997b), Chamkha *et al*. (2002), Muthucumaraswamy and Ganesan (2003), Makinde and Ogulu (2008), Kodidala *et al.* (2016), Ahmed and Sarmah (2009) analyzed the effect of thermal radiation on different heat and mass transfer flows. Seth *et al.* (2014) discussed the effects of Hall current and rotation on unsteady MHD natural convective flow with heat and mass transfer passing through an impulsively moving vertical plate in the presence of radiation and chemical reactions.

In most technical fields, chemical reactions occur between foreign substances and fluids. Depending on their occurrence, as an interface or a single phase, chemical reactions are classified into heterogeneous and homogeneous categories. These processes have numerous applications in different industries, such as food processing, glassware manufacturing, etc. Muthucumaraswamy and Ganesan (2001) showed how the first-order chemical reaction reacts in a fluid flowing with constant heat flux and mass transfer. Sarma *et al*. (2013b), Seth *et al*. (2014), Kishore *et al*. (2013a), Haile *and* Shankar, (2014), Magyari and Chamkha (2010) investigated the combined effect of the chemical reaction and thermal radiation considering different models of convective heat and mass transfer flow. Prakash *et al*. (2015) studied the effects of thermal diffusion and chemical reactions on a 3D MHD convective Couette flow. Damseh *et al*. (2009) studied the combined effects of heat absorption and first-order chemical reactions on micropolar fluid flowing over a uniformly stretched permeable surface.

The effect of heat and mass transfer from truncated cones in the presence of chemical reaction was presented by Chamkha *et al.* (2012). Recently, Jiang *et al.* (2022) have published studies on MHD flow with radiation, chemical reaction, and mass transfer in porous medium considering fractional Burgers' fluid. Krishna (2022) has recently made an analytical study of chemical reaction, Soret, Hall and ion slip effects on an MHD flow passing through an infinitely rotating vertical plate under the porous medium. Arulmozhi *et al.* (2022a) analyzed the radiative and chemically reactive effects on an MHD flow considering a nanofluid over a moving vertical plate. Postelnicu (2007) studied the impact of chemical reaction, Soret and Dufour on heat and mass transfer by natural convection from vertical surfaces in porous media.

The novelty of the present study is to investigate the effects of thermal radiation, chemical reaction, and thermal diffusion on MHD free convective flow past an impulsively started vertical plate subjected to a periodic temperature and periodic concentration. In our problem, chemical reaction and thermal diffusion are introduced, which were not observed in the work of Kodidala *et al.* (2016). The concepts of periodic temperature and periodic concentration in the boundary restrictions are also newly introduced, and the term of frequency is added to the non-dimensional parameters, which is different from the work of Kodidala *et al.* (2016). In our present work, we have not considered the magnetic field to be very strong and for which the electron-atom collision become very low. As a consequence, the Hall and ion slip effects have no significant role in our flow model (Chamkha, 1997c; Krishna and Chamkha, 2019, 2020; Chamkha *et al.*, 2020, 2021; Veerakrishna *et al.*, 2018). The second-order differential equations are solved using the Laplace transform technique to find the solutions of temperature, concentration, and velocity fields. It also describes the effects of various pertinent parameters on Nusselt numbers, Sherwood numbers, and skin friction.

II. METHODS

A. Basic equations

This study examined the MHD-free convection of an incompressible, viscous, and conductive fluid under the effect of the chemical reaction. The plate under consideration is a non-conductive vertical plate with uniform mass and heat flux. The x-axis is taken along the direction of movement of the plate, and the y-axis is perpendicular to the plate. Based on the above situation, the flow equations for determining the velocity field, concentration field, and temperature field using Boussinesq's approximation can be considered as follows. The uniform magnetic field of intensity B_o is considered in the normal direction of the plate. The velocity, temperature, and magnetic field are all independent of the x-axis and dependent only on the y-axis. The energy dissipation due to frictional force and viscosity and the electric field due to the polarization of charges are all considered negligible.

We have considered air as a solvent or a diffusing medium. It is worthwhile to mention that for air, the electrical conductivity, and the magnetic permeability, are very small, which in turn makes the magnetic Reynolds number of the flow very small. This is the reason why the induced magnetic field is neglected. Also, the flow considered here is free convective. In the case of free convective flow, the fluid velocity, as well as the velocity gradient, are relatively small. On the basis of this, viscous dissipation and ohmic dissipation are neglected.

Figure 1 demonstrates our assumptions.

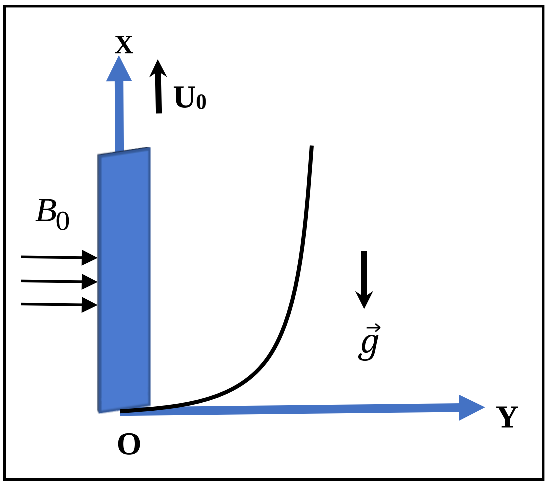

Figure 1: Physical structure of the problem.

Considering the above-mentioned assumptions, the governing equations of the problem are given as follows:

$$\vec{\nabla}.\vec{q}=0 \qquad (1)$$

$$\vec{\nabla}.\vec{B}=0 \qquad (2)$$

$$\rho\left[\frac{\partial \vec{q}}{\partial t}+(\vec{q}.\vec{\nabla})\vec{q}\right]=\rho\vec{g}+\vec{J}\times\vec{B}-\vec{\nabla}.p+\mu\nabla^2\vec{q} \qquad (3)$$

$$\rho C_p\left[\frac{\partial T}{\partial \bar{t}}+(\vec{q}.\vec{\nabla})T\right]=\kappa\nabla^2 T-\vec{\nabla}.\vec{q_r} \qquad (4)$$

$$\frac{\partial C}{\partial \bar{t}}+(\vec{q}.\vec{\nabla})C=D_M\nabla^2 C+D_T+\bar{Q}(C_\infty-C) \qquad (5)$$

$$\vec{J}=\sigma[\vec{E}+\vec{q}\times\vec{B}] \qquad (6)$$

$$\rho_\infty=\rho[1+\beta(T-T_\infty)+\bar{\beta}(C-C_\infty)] \qquad (7)$$

$$\vec{q_r}=-\frac{4\sigma^\star}{3\kappa^\star}\vec{\nabla}T^4 \qquad (8)$$

Ignoring the higher order terms, as the temperature difference is sufficiently small and using Taylor's series expansion, we have

$$T^4=4T_\infty^3 T-3T_\infty^4 \qquad (9)$$

Therefore, equation (8) gives

$$\vec{q_r}=-\frac{16T_\infty^3\sigma^\star}{3\kappa^\star}\vec{\nabla}T \qquad (10)$$

Equation (4) reduces to

$$\rho C_p\left[\frac{\partial T}{\partial \bar{t}}+(\vec{q}.\vec{\nabla})T\right]=\kappa\nabla^2 T+\frac{16T_\infty^3\sigma^\star}{3\kappa^\star}\nabla^2 T \qquad (11)$$

Equation (1) gives

$$\frac{\partial u'}{\partial \bar{x}}=0$$

$$u'=u'(\bar{y},\bar{t}) \qquad (12)$$

Equation (2) is trivially satisfied with

$$\vec{B}=B_o\hat{j}$$

Equation (3), (11) and (5) respectively reduces to

$$\frac{\partial u'}{\partial \bar{t}}=-\frac{\sigma B_o^2 u'}{\rho}+g[\beta(T-T_\infty)+\bar{\beta}(C-C_\infty)]+$$

$$\nu\frac{\partial^2 u'}{\partial \bar{y}^2} \qquad (13)$$

$$\rho C_p\left[\frac{\partial T}{\partial \bar{t}}\right]=\kappa\frac{\partial^2 T}{\partial \bar{y}^2}+\frac{16\sigma^\star T_\infty^3}{3\kappa^\star}\frac{\partial^2 T}{\partial \bar{y}^2} \qquad (14)$$

$$\frac{\partial C}{\partial \bar{t}}=D_M\frac{\partial^2 C}{\partial \bar{y}^2}+D_T\frac{\partial^2 T}{\partial \bar{y}^2}+\bar{Q}(C_\infty-C) \qquad (15)$$

The initial and boundary conditions are:

$$\forall\ \bar{y}\geq 0,\ u'=0,\ T=T_\infty, C=C_\infty;\ \bar{t}\leq 0$$

$$At\ \bar{y}=0:\ u'=U_o,\ T=T_\infty+(T_w-T_\infty)e^{i\bar{\omega}\bar{t}},$$

$$C=C_\infty+(C_w-C_\infty)e^{i\bar{\omega}\bar{t}};\ \bar{t}>0$$

$$\text{At},\ \bar{y}\to\infty: u'\to 0,\ T\to T_\infty,\ C\to C_\infty;\ \ \bar{t}>0 \qquad (16)$$

The non-dimensional quantities are as follows:

$$u = \frac{u'}{U_o},\ y = \frac{U_o \bar{y}}{\nu},\ t = \frac{\bar{t} U_o^2}{\nu},\ \omega = \frac{\bar{\omega}\nu}{U_o},\ \mathrm{Gr} = \frac{\nu g \beta (T_w - T_\infty)}{U_o^3},$$
$$\mathrm{Gm} = \frac{\nu g \bar{\beta}(C_w - C_\infty)}{U_0^3},\ \theta = \frac{(T - T_\infty)}{(T_w - T_\infty)},\ \phi = \frac{(C - C_\infty)}{(C_w - C_\infty)},$$
$$Pr = \frac{\mu C_p}{\kappa},\ Sc = \frac{\nu}{D_M},\ Sr = \frac{D_T(T_w - T_\infty)}{\nu(C_w - C_\infty)},\ M = \frac{\sigma B_0^2 \nu}{\rho U_0^2},$$
$$N = \frac{\kappa\kappa^\star}{4\sigma^\star T_\infty^3},\ Q = \bar{Q}\frac{\nu}{U_0^2}. \tag{17}$$

Now, from the Eqs. (13), (14) and (15), the non-dimensional governing equations are:

$$\frac{\partial u}{\partial t} = -Mu + Gr\theta + Gm\phi + \frac{\partial^2 u}{\partial y^2}, \tag{18}$$
$$\frac{\partial \theta}{\partial t} = \frac{\partial^2 \theta}{\partial y^2} R, \tag{19}$$
$$\frac{\partial \phi}{\partial t} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} + Sr\frac{\partial^2 \theta}{\partial y^2} - Q. \tag{20}$$

The corresponding boundary conditions are:

$$\text{For all}, y \geq 0:\ u = 0, \theta = 0, \phi = 0;\ t \leq 0$$
$$\text{At}\ y = 0: u = 1, \theta = e^{i\omega t},\ \phi = e^{i\omega t};\ t > 0$$
$$\text{At}\ y \to \infty:\ u \to 0, \theta \to 0, \phi \to 0;\ t > 0. \tag{21}$$

B. Method of solution:

The Eqs. (18), (19) and (20) are now solved using Laplace transform technique. Firstly, we apply Laplace on both the sides of the equations and get the following equations:

$$s\bar{\theta} = \Lambda\frac{d^2\bar{\theta}}{dy^2}, \tag{22}$$
$$s\bar{\phi} = \frac{1}{Sc}\frac{d^2\bar{\phi}}{dy^2} + Sr\frac{d^2\bar{\theta}}{dy^2} - Q\bar{\phi}, \tag{23}$$
$$s\bar{u} = -M\bar{u} + Gr\bar{\theta} + Gm\bar{\phi} + \frac{d^2\bar{u}}{dy^2}. \tag{24}$$

Now by applying inverse Laplace to the above Eqs. from (22) to (24) and also by using the related boundary conditions, the solutions of the temperature field, concentration field and the velocity field are obtained as given below:

$$\theta = e^{i\omega t}\psi_3, \tag{25}$$
$$\phi = \psi_1 + \lambda_1[A_1(\psi_3 - \psi_1) + A_2(\psi_4 - \psi_2)], \tag{26}$$
$$u = u_1 + u_2 + u_3 + u_4 + u_5. \tag{27}$$

C. Nusselt number:

The rate of heat transfer at the plate in terms of Nusselt number is given by

$$\mathrm{Nu} = -\left[\frac{\partial\theta}{\partial y}\right]_{y=0} = \sqrt{\frac{\eta}{\pi t}} + e^{i\omega t}\sqrt{\eta i\omega}\ erfc\left(\sqrt{i\omega t}\right), \tag{28}$$

D. Sherwood number:

The rate of mass transfer at the plate in terms of Sherwood number is given by

$$Sh = -\left[\frac{\partial\phi}{\partial y}\right]_{y=0} = (1 - \lambda 1)e^{i\omega t}S_1 - \lambda_1 A_2 e^{c_1 t}S_2 + \lambda_1 A_1 e^{i\omega t}S_3 + \lambda_1 A_2 e^{c_1 t}S_4. \tag{29}$$

E. Skin Friction:

The viscous drag or the skin friction at the plate is given by

$$\tau = \left[\frac{\partial u}{\partial y}\right]_{y=0} = \tau_1 + \tau_2 + \tau_3 + \tau_4 + \tau_5 + \tau_6 + \tau_7 + \tau_8 + \tau_9 + \tau_{10} + \tau_{11}. \tag{30}$$

F. Results and discussion:

To visualize the impact of various parameters on the velocity field, temperature field, and concentration field and also to give a physical meaning to the problem, the calculated values are demonstrated in Figs. 2–15 in this section. We have adopted the following values for the different parameters: Prandtl number Pr = 0.71, thermal radiation $N = 2$, Hartmann number $M = 2$, Schmidt number Sc=0.6, Soret number $Sr = 0.78$, solutal Grashof number $Gm = 10$, Grashof number $Gr = 10$ and chemical reaction parameter $Q = 0.1$, frequency parameter ω=0.6.

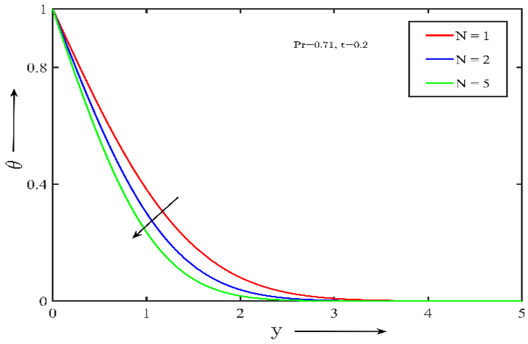

Figure 2: θ versus y for distinct values of N

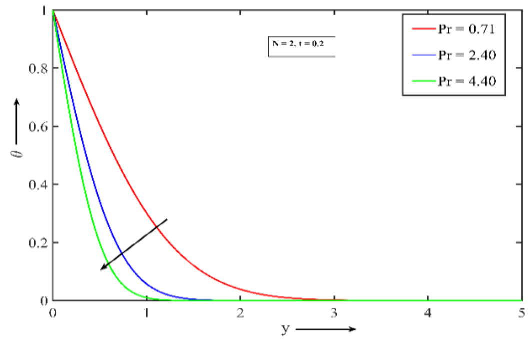

Figure 3: θ versus y for distinct values of Pr

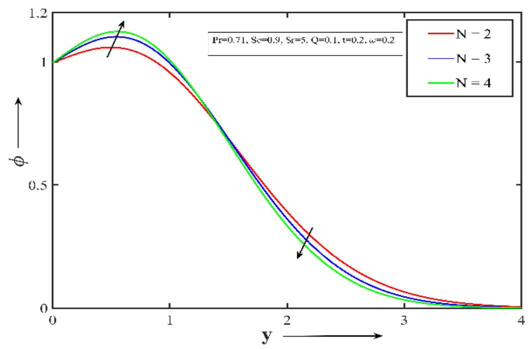

Figure 4: ϕ versus y for distinct values of N

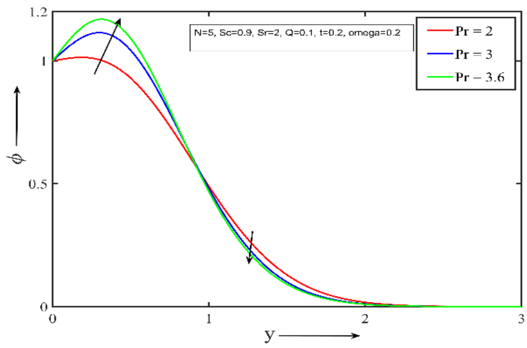

Figure 5: ϕ versus y for distinct values of Pr

The influence of the thermal radiation parameter and Prandtl number on the fluid temperature is presented in Figs. 2 and 3. As the thermal radiation parameter rises, the fluid temperature falls gradually, as visualized in Fig. 2. Figure 3 shows that the increment in the Prandtl number decreases the fluid temperature. As the Prandtl number is the ratio of viscous diffusivity to thermal diffusivity, an increment in the Prandtl number infers a decrease in the thermal diffusivity. Hence, the rise in thermal diffusivity raises the fluid temperature. Figures 4–8 reveal the changes in fluid concentration due to the effects of some related parameters. The upsurge in thermal radiation and Prandtl number decreases the fluid concentration. But interestingly, the fluid concentration tends to decrease afterwards, i.e., it takes a reverse turn, which

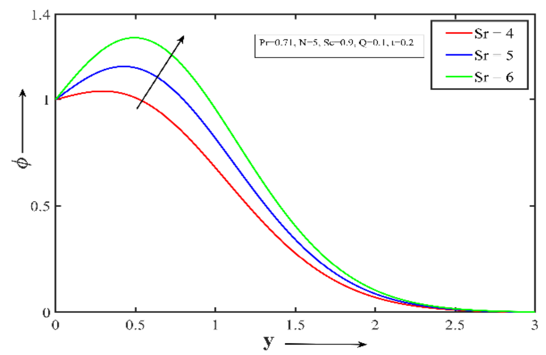

Figure 6: ϕ versus y for distinct values of Sr

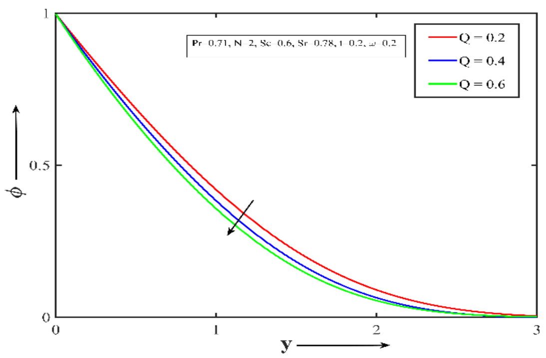

Figure 7: ϕ versus y for distinct values of Q

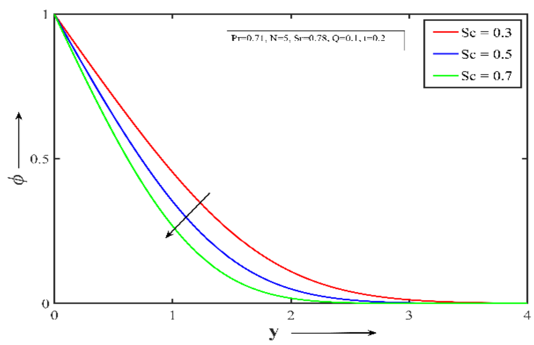

Figure 8: ϕ versus y for distinct values of Sc

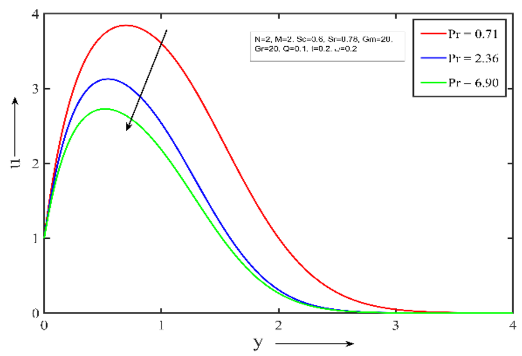

Figure 9: u versus y for distinct values of Pr

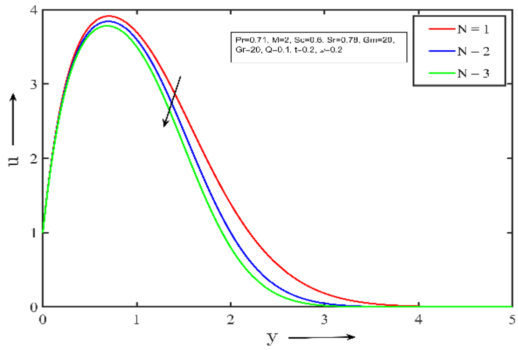

Figure 10: u versus y for distinct values of N

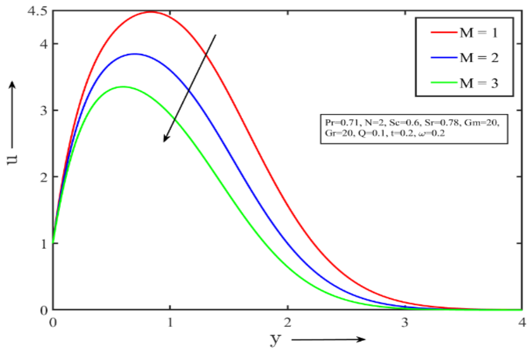

Figure 11: u versus y for distinct values of M

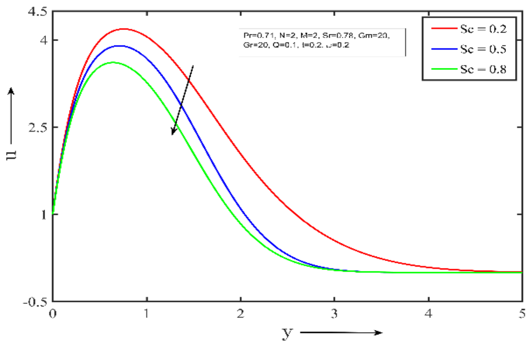

Figure 12: u versus y for distinct values of Sc

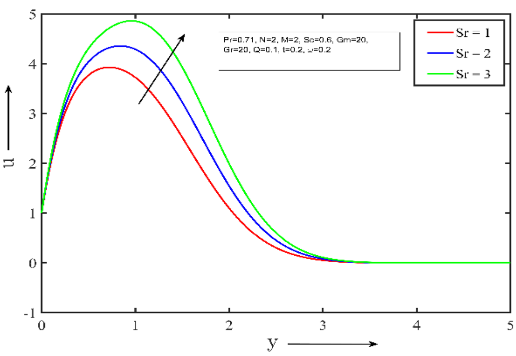

Figure 13: u versus y for distinct values of Sr

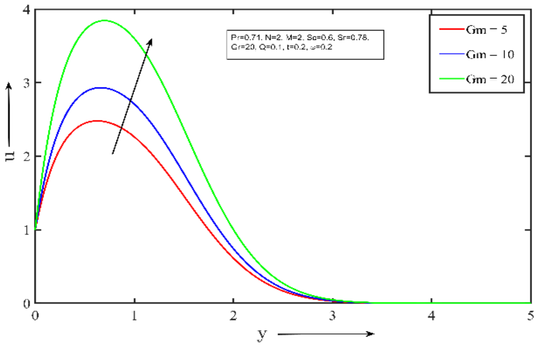

Figure 14: u versus y for distinct values of Gm

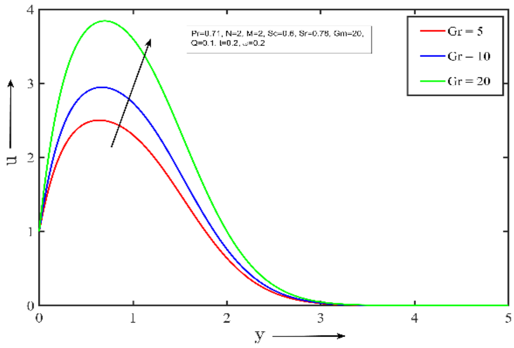

Figure 15: u versus y for distinct values of Gr

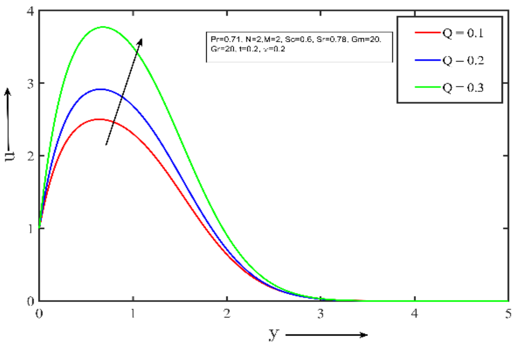

Figure 16: u versus y for distinct values of Q

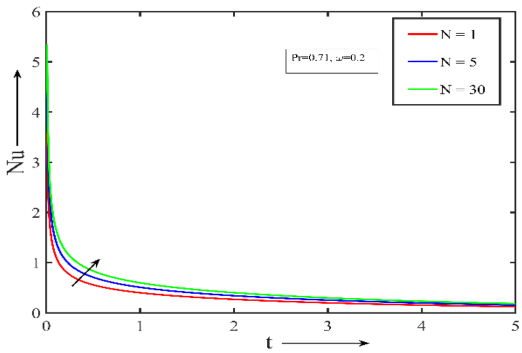

Figure 17: Nu versus t for distinct values of N

is depicted in Figs. 4-5. The upswing in the thermal diffusion or Soret parameter results in the growth of fluid concentration, which is reflected in Fig. 6. The Soret number is related to the temperature gradient; hence, higher values of the Soret parameter cause an enhancement in the temperature gradient, which results in an increase in the fluid concentration. Figures 7 and 8 clearly show the impact of the chemical reaction and Schmidt number on the concentration field of the fluid. The escalation in both parameters caused the fluid concentration to fall gradually. Figure 8 simulates that fluid concentration is dropped for increasing Schmidt number. Here, it is worth mentioning that an increase in Schmidt number lowers the mass diffusivity of the species, which decreases the boundary layer thickness for concentration. Thus, the fluid concentration rises with the increase in mass diffusivity and falls with the decrement in mass diffusivity.

Figures 9–16 illustrate the impact of the Prandtl number, thermal radiation, Hartmann number, Schmidt number, Soret number, solutal Grashof number, Grashof number, and chemical reaction parameters on the fluid velocity. The hike in the Prandtl number, thermal radiation, Hartmann number, and Schmidt number declines the fluid velocity, which is observed in Figs. 9 to 12. Again, an increase in the Hartmann number decelerates the flow, which is reflected in Fig. 10. With the enhancement in Hartmann's number, the magnetic Lorentz force also gets increased, which results in the decrement of the fluid velocity. Figures 12-15 demonstrate that the fluid velocity steadily rises with the increase in the parameters like Soret number, modified Grashof number, Grashof number and Chemical reaction.

Figures 17 and 18 show that the rise in thermal radiation and the Prandtl number lead to a decline in the Nusselt number. With an increment in the thermal radiation, Prandtl number, and Soret number, the

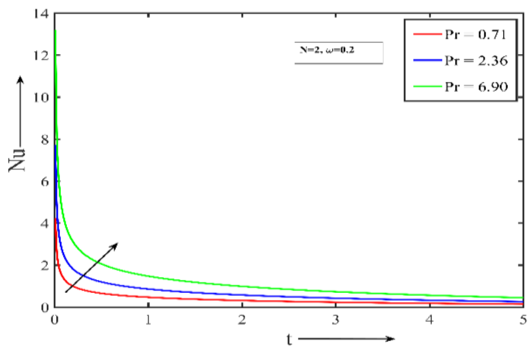

Figure 18: Nu versus t for distinct values of Pr

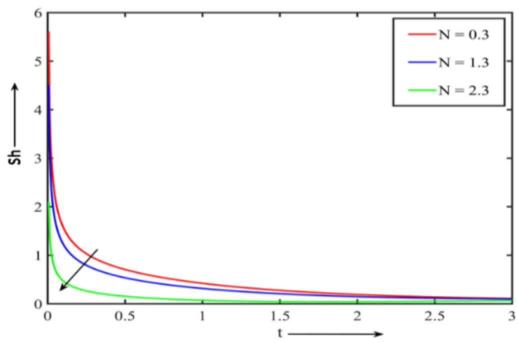

Figure 19: Sh versus t for distinct values of N

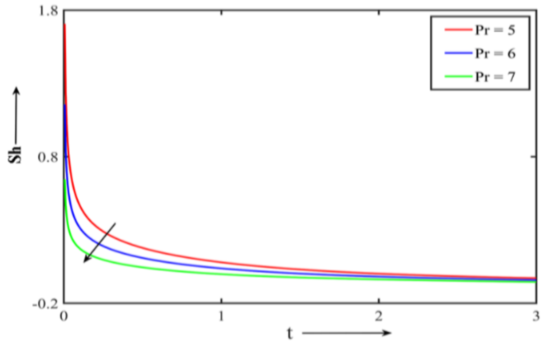

Figure 20: Sh versus t for distinct values of Pr

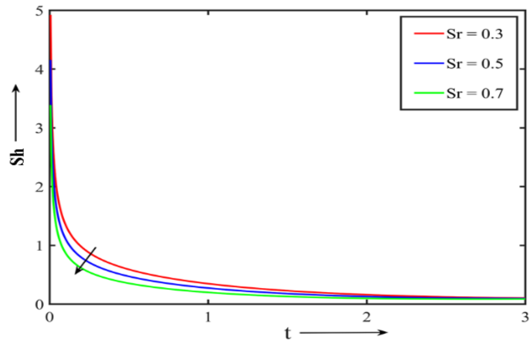

Figure 21: Sh versus t for distinct values of Sr

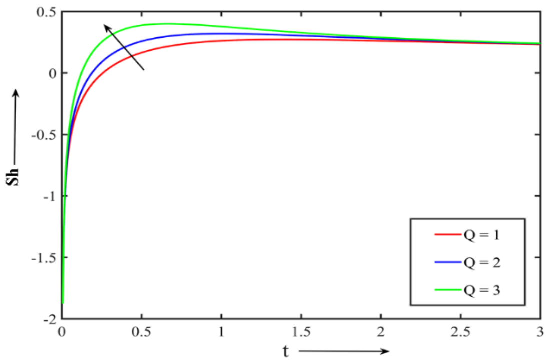

Figure 22: Sh versus t for distinct values of Q

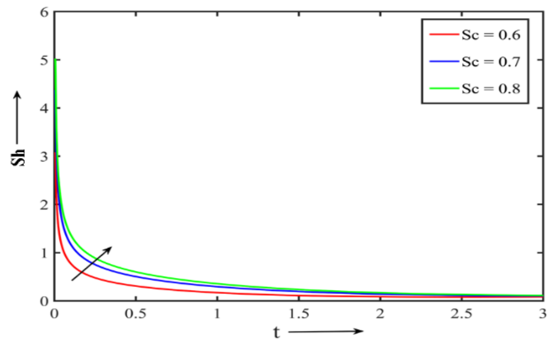

Figure 23: Sh versus t for distinct values of Sc

Sherwood number falls gradually. Again, the rise in the chemical reaction parameter and Schmidt number causes a decline in the Sherwood number. The variation in the viscous drag for the different parameters is discussed in Figs. 24–27. The enhancement in the thermal radiation, Hartmann number, and chemical reaction parameters results in a decrease in skin friction, but a reverse action has been noticed afterwards, as depicted in Figs. 24–26. The growth in the Soret number reduces the skin friction, and its nature alters subsequently, as demonstrated in Fig 27.

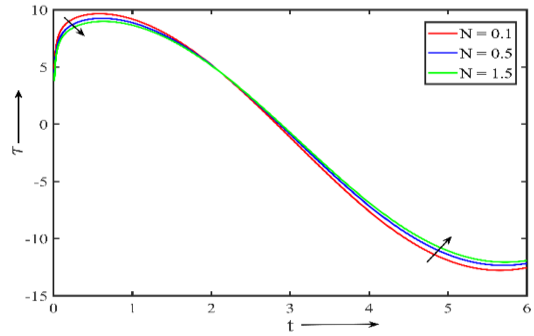

Figure 24: τ versus t for distinct values of N

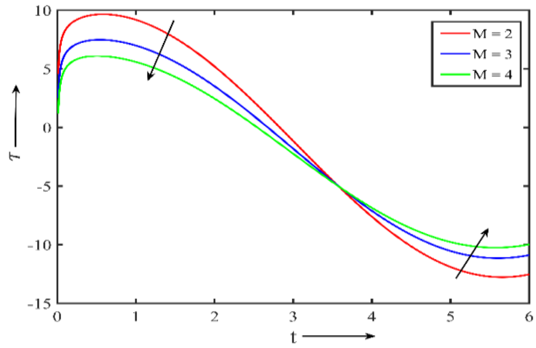

Figure 25: τ versus t for distinct values of M

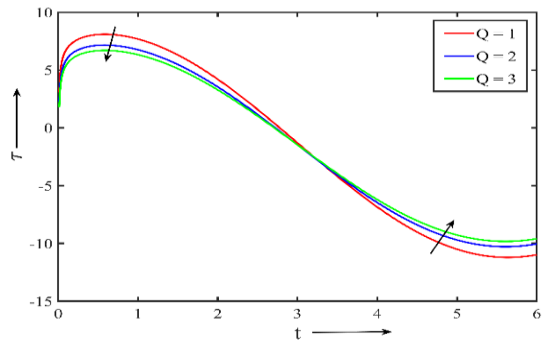

Figure 26: τ versus t for distinct values of Q

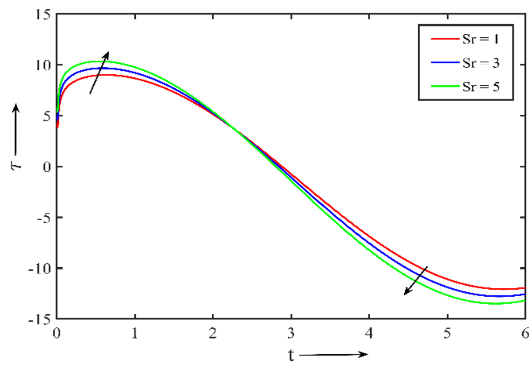

Figure 27: τ versus t for distinct values of Sr

III. COMPARISON OF RESULTS

In order to validate our results, we have compared some of our results with the work of Kodidala *et al*. (2016). After comparing Figs. 2 and 3 of our problem with Figs. 13 and 14, respectively, in the work of Kodidala *et al*. (2016), it is noticed that both figures are uniform and lead to an identical outcome. That is, the Prandtl number and radiation parameter lower the fluid temperature in both cases.

IV. CONCLUSION

1. Thermal radiation and the Prandtl number reduce the temperature of the fluid.
2. Fluid concentration increases due to high thermal radiation and Soret number but decreases with chemical reaction parameters and a high Schmidt number.
3. Due to the influence of heat radiation and the Prandtl number, the speed of the fluid slows down.
4. As the Soret parameter increases, the fluid velocity will increase.
5. Thermal radiation and the Prandtl number reduce the heat transfer coefficient of the plate.
6. As the thermal radiation parameter, Prandtl number, and Soret number increase, the mass transfer rate of the entire plate decreases, and the growing chemical reaction parameter and Schmidt number increase the mass transfer rate of the whole plate.
7. The viscous resistance of the plate gets reduced by the effects of heat radiation, Prandtl number, and Soret number. It is interesting to note that this behavior reverses afterwards.
8. The effect of the chemical reaction raises skin friction, but it shows a decreasing nature afterwards.

NOMENCLATURE

$\vec{q}$ = Fluid velocity
p = Fluid pressure
$\vec{g}$ = Gravitational acceleration vector
t = Time
ω = Frequency parameter
ρ = Fluid density
C = Fluid concentration
Pr = Prandtl number
Gr = Thermal Grashof number
D_M = Mass diffusivity
κ = Thermal conductivity
κ^* = mean absorption co-efficient
Sc = Schmidt number
T = Fluid temperature
Uo = Plate velocity
T_∞ = Undisturbed temperature
Sr = Soret number
C_∞ = Fluid concentration at a distant
ρ_∞ = Free stream density
β = Co-efficient of solutal expansion
μ = Co-efficient of viscosity
D_T = Molar thermal diffusivity
Mw = Mass flux
ν = Kinematic viscosity
Cp = specific heat at constant pressure
M = Magnetic field parameter
Gm = Solutal Grashof number
N = Radiation parameter
σ^* = Stefan Boltzmann constant
$\overrightarrow{q_r}$ = Radiative heat flux vector

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