Effects of chemical, radiation and diffusion–thermo on a rotating laminar fluid past a porous plate

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Abstract— **In this paper, the combined effects of chemical reaction radiation and diffusion thermo have been studied on a rotating laminar flow through a porous medium in conducting field with variable temperature and variable concentration. Finite difference method has been employed to solve the governing equations numerically. The effects of various physical parameters like Grashof number, porosity, radiation, chemical reaction etc, on velocity, temperature and concentration are discussed with the help of graphs. Also the numerical values for local skin friction, Nusselt number and Sherwood number are recorded and analyzed. Increasing values of heat source parameter results in rising of the temperature, but it falls down in the case of heat sink parameter.**

Keywords- Laminar flow; Rotating fluid; Finite difference scheme; Thermal radiation and Dufour effects;

I. INTRODUCTION

When a body is hot, the energy of vibration of the atoms and molecules is sent out from it in the form of radiant heat waves. These waves when falling on another body induce the molecules to vibrate there and hence the body is heated up. In many fluid–particle flows, thermal radiation effects play an important role in altering the heat transfer characteristics. Raptis *et al.*[1]studied radiation effects on an optically thin gray gas flowing through a vertical infinite plate. Radiative flow past an exponentially accelerated vertical plate with uniform mass diffusion is studied by Muthucumaraswamy and Visalakshi [2]. Srinivas and Muthuraj [3] investigated the effects of thermal radiation and porosity on MHD mixed convection flow in a vertical channel using homotopy analysis method. Ananda and Varma [4] analysed the radiation effects on MHD couette flow with heat and mass transfer between two parallel plates. Raju *et al.* [5] presented an analytical study of MHD free convictive, dissipative boundary layer flow past a porous vertical surface in the presence of thermal radiation, chemical reaction and constant suction. Radiative heat transfer on MHD free convection flow in the presence of heat source subjected to power law heat flux over a porous sheet was considered by Kumar [6]. Ali *et al*. [7] considered the influence of thermal radiation on an unsteady free convection MHD flow of Brinkman type fluid in a porous medium with Newtonian heating. Ahmed and Kalita [8] discussed magneto hydrodynamic transient flow through a porous medium bounded by a hot vertical plate in the presence of radiation. Chandra Reddy *et al*. [9] studied the properties of free convective magneto-nanofluid flow past a moving vertical plate in the presence of radiation and thermal diffusion.

Energy flux will be formed by concentration gradients as well as temperature gradients. The energy flux formed by a concentration gradient is treated as the diffusion- thermo effect or Dufour effect. Bhargava *et al*. [10] considered cross diffusion effects on the fluctuating hydromagnetic flow under thermal and mass buoyancy. Reddy and Varma [11] explained the Soret and chemical effects in details with simultaneous thermal and mass diffusion in mixed convection flow with ohmic heating. Narayana and Sibanda [12] numerically discussed the soret and dufour effects thoroughly on a wavy surface in Darcy porous media. Seddeek [13] established the flow over an accelerating surface with heat generation and blowing/suction for the particular case of mixed convection in presence of diffusion-thermo and thermal-diffusion.

In modern fluid dynamics research, the concept of rotating flows have received wide applications. Outstanding discourses on this subject with applications in geophysics and planetary sciences have been in the works since 1950s. The combined effects of heat transfer and rotational hydrodynamics have mainly been motivated by the applications in chemical engineering and manufacturing processes in the chemical industry. Singh [14] analyzed an oscillatory hydromagnetic Couette flow in a rotating system.. Seth *et al.* [15] investigated oscillatory hydromagnetic Couette flow in a rotating system with induced magnetic field. Seth *et al*. [16] discoursed the effects of thermal radiation and rotation on unsteady hydromagnetic free convection flow past a moving vertical plate with ramped temperature in a porous medium. The influence of rotation and Hall current on mixed convection MHD flow past a porous medium in a vertical channel with the existence of thermal radiation was analysed by Singh and Pathak [17]. Ahmed and Sarmah [18] studied MHD transitory flow through an impulsively ongoing horizontal porous plate in a revolving system with Hall current. Seth *et al.* [19] examined the effect of rotation on unsteady hydromagnetic regular convection flow through impulsively moving vertical plate with ramped temperature in a porous medium with thermal diffusion and heat absorption. Malique and Sattar [20] presented the effects of variable properties and Hall current on steady MHD laminar convective fluid flow due to a porous rotating disk. Reddy *et al*.[21] examined rotational and thermal diffusion effects on magneto hydrodynamic mixed convection flow of heat absorbing/radiating visco - elastic fluid past a porous channel. Ananda [22] performed an investigation to describe the laminar flow of a rotating fluid past a porous plate with variable temperature and concentration in the presence of chemical reaction, radiation and Dufour effects.

II. MATHEMATICAL FORMULATION

The chemical reaction, radiation and Dufour effects are considered on a laminar flow of a rotating fluid throgh a porous plate in conducting field with variable temperature and variable concentration. X-axis is considered along the plate which is in vertical direction. Y-axis is taken normal to the surface of the plate. The plate as well as the fluid in a state of inelastic body revolves with a constant angular velocity Ω about Y-axis. Primarily at time $t^* \le 0$, both the fluid and the plate were at rest with uniform temperature and concentration T_∞ and C_∞ correspondingly. At time $t^* > 0$, the plate starts moving in X direction with uniform velocity $U_0 a^* t^*$. The temperature and concentration raises to $T_\infty + (T_s^* - T_\infty)\left(\frac{t^*}{t_0}\right)$ and $C_\infty + (C_s^* - C_\infty)\left(\frac{t^*}{t_0}\right)$ respectively. Later it is continued at uniform temperature and concentration T_∞ and C_∞ respectively. In these respects, the equations that govern the flow are given below.

$$\frac{\partial u^*}{\partial t^*} + 2\Omega V^* = \nu \frac{\partial^2 u^*}{\partial y^{*2}} + g\beta_T\left(T^* - T_\infty\right) + g\beta_C\left(C^* - C_\infty\right) - \frac{\nu}{k}u^* \tag{1}$$

$$\frac{\partial V^*}{\partial t^*} - 2\Omega u^* = \nu \frac{\partial^2 V^*}{\partial y^{*2}} - \frac{\nu}{k}V^* \tag{2}$$

$$\rho C_p \frac{\partial T^*}{\partial t^*} = k_T \frac{\partial^2 T^*}{\partial y^{*2}} + Q^*\left(T^* - T_\infty\right) - \frac{\partial q_r^*}{\partial y^*} + \frac{D_m k_T \rho}{C_s}\frac{\partial^2 C^*}{\partial y^{*2}} \tag{3}$$

$$\frac{\partial C^*}{\partial t^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} - K_l(C^* - C_\infty) \tag{4}$$

The corresponding initial and boundary conditions are

$$\left.\begin{array}{ll} u^* = 0,\ V^* = 0, T^* = T_\infty,\ \mathrm{C}^* = C_\infty & for\ all\quad y^*, t^* \le 0 \\ t^* > 0:\ u^* = U_0 a^* t^*, V^* = U_0 a^* t^*, \mathrm{T}^* = T_\infty + (T_s^* - T_\infty)\left(\frac{t^*}{t_0}\right), & \\ \mathrm{C}^* = C_\infty + (C_s^* - C_\infty)\left(\frac{t^*}{t_0}\right) & at\ y^* = 0 \\ u^* = 0,\ T^* = T_\infty,\ \mathrm{C}^* = C_\infty & as\ y^* \to \infty \end{array}\right\} \tag{5}$$

The non-dimensional quantities are as follows:

$$u = \frac{u^*}{U_0},\ V = \frac{V^*}{U_0} t = \frac{t^* U_0^2}{\nu},\ y = \frac{y^* U_0}{\nu},\ \theta = \frac{T^* - T_\infty}{T_s^* - T_\infty},$$

$$\mathrm{C} = \frac{C^* - C_\infty}{C_s^* - C_\infty},\ a = \frac{a^*\nu}{U_0^2},\ \frac{\partial q_r^*}{\partial y^*} = 4(T^* - T_\infty)I^*,$$

Grashof number $Gr = \frac{\nu g\beta_T\left(T_s^* - T_\infty\right)}{U_0^3}$,

Modified Grashof number $Gm = \frac{\nu g\beta_C\left(C_s^* - C_\infty\right)}{U_0^3}$,

Rotation parameter $k_1^2 = \frac{\Omega\nu}{U_0^2}$,

Permeability of the porous medium $K = \frac{kU_0^2}{\nu^2}$,

Prandtl number $\Pr = \frac{\rho\nu C_p}{k_T}$,

Chemical reaction Parameter $Kr = \frac{K_l\nu}{U^2{}_0}$,

Heat absorption $Q = \frac{Q^*\nu^2}{k_T U_0^2}$,

Radiation parameter $F = \frac{4\nu I^*}{\rho C_p U_0^2}$,

Schmidt number $Sc = \frac{\nu}{D}$,

Dufour number $Df = \frac{D_m k_T(C_s^* - C_\infty)}{\nu C_s C_p(T_s^* - T_\infty)}$

Introducing the non-dimensional quantities the equations (1)-(4) reduces to following form

$$\frac{\partial u}{\partial t} + 2k_1^2 V = \frac{\partial^2 u}{\partial y^2} + Gr\,\theta + Gm\,C - M\,u - \frac{1}{K}u \tag{6}$$

$$\frac{\partial V}{\partial t} - 2k_1^2 u = \frac{\partial^2 V}{\partial y^2} - M\,V - \frac{1}{K}V \tag{7}$$

$$\frac{\partial\theta}{\partial t} = \frac{1}{\Pr}\frac{\partial^2\theta}{\partial y^2} + Q\theta - F\theta + Df\,\frac{\partial^2 C}{\partial y^2} \tag{8}$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} - KrC \tag{9}$$

The corresponding initial and boundary conditions are

$$\left.\begin{array}{ll} u = 0,\ V = 0,\ \theta = 0,\quad \mathrm{C} = 0 & for\,all\quad y, t \le 0 \\ t > 0:\ u = e^{at}, V = e^{at},\ \theta = t,\ \mathrm{C} = t & at\ \ y = 0 \\ u = 0,\ V = 0,\ \theta = 0,\quad \mathrm{C} = 0 & as\ y \to \infty \end{array}\right\} \tag{10}$$

III. METHOD OF SOLUTION

Equations (6)-(9) are linear partial differential equations and are to be solved with the initial and boundary conditions (10). In fact the exact solution is not possible for this set of equations and hence we solve these equations by finite-difference method. The equivalent finite difference schemes of equations for (6)-(9) are as follows:

$$\frac{u_{i,j+1}-u_{i,j}}{\Delta t}+2k_1^2V_{i,j}=Gr\,\theta_{i,j}+Gm\,C_{i,j}+\frac{u_{i-1,j}-2u_{i,j}+u_{i+1,j}}{(\Delta y)^2}-M\,u_{i,j}-\frac{1}{K}u_{i,j} \quad (11)$$

$$\frac{V_{i,j+1}-V_{i,j}}{\Delta t}-2k_1^2u_{i,j}=\frac{V_{i-1,j}-2V_{i,j}+V_{i+1,j}}{(\Delta y)^2}-M\,V_{i,j}-\frac{1}{K}V_{i,j} \quad (12)$$

$$\frac{\theta_{i,j+1}-\theta_{i,j}}{\Delta t}=\frac{1}{\Pr}\frac{\theta_{i-1,j}-2\theta_{i,j}+\theta_{i+1,j}}{(\Delta y)^2}+Q\theta_{i,j}-F\theta_{i,j}+Df\,\frac{C_{i-1,j}-2C_{i,j}+C_{i+1,j}}{(\Delta y)^2} \quad 13)$$

$$\frac{C_{i,j+1}-C_{i,j}}{\Delta t}=\frac{1}{Sc}\frac{C_{i-1,j}-2C_{i,j}+C_{i+1,j}}{(\Delta y)^2}-KrC_{i,j} \quad (14)$$

Here, the suffix i refer to y and j to time. The mesh system is divided by taking $\Delta y = 0.1$. From the initial condition in (10), we have the following equivalent:

$$u(i,0)=0,\ \theta(i,0)=0, C(i,0)=0 \ \ for\ all\ i \quad (15)$$

The boundary conditions from (10) are expressed in finite-difference form as follows

$$u(0,j)=at, \theta(0,j)=\frac{1}{1+t}, C(0,j)=\frac{1}{1+t} \ \ for\ all\ j$$
$$u(i_{\max},j)=0, \theta(i_{\max},j)=0, C(i_{\max},j)=0 \ \ for\ all\ j \quad (16)$$

(Here i_{max} was taken as 200)

The primary velocity at the end of time step viz, u(i, j+1)(i=1,200) is computed from (11) and the secondary velocity at the end of time step viz, V(i, j+1)(i=1,200) is computed from (12) in terms of velocity, temperature and concentration at points on the earlier time-step. After that θ (i, j +1) is computed from (13) and then C (i, j +1) is computed from (14). The procedure is repeated until t = 0.5 (i.e. j = 500). During computation Δt was chosen as 0.001.

Skin-friction:

The skin-friction in non-dimensional form is given by the relation

$$\tau=\left(\frac{du}{dy}\right)_{y=0}$$

Rate of heat transfer:

The dimensionless rate of heat transfer in terms of Nusselt number is given by

$$Nu=-\left(\frac{d\theta}{dy}\right)_{y=0}$$

Rate of mass transfer:

The dimensionless rate of mass transfer in terms of Sherwood number is given by

$$Sh=-\left(\frac{dC}{dy}\right)_{y=0}$$

IV. Results and Discussion

In the present work a representative set of graphical results for the velocity, temperature, concentration, local skin-friction coefficient, local Nusselt number (rate of heat transfer) and the local Sherwood number (rate of mass transfer) is presented and discussed for various parameters encountered in the governing equations of the problem. Figures 1 and 2 exhibit the velocity profiles with the effect of Grashof number for heat and mass transfer. It is noticed that the fluid velocity increases under the increment of both the cases of Grashof number and modified Grashof number. This is due to the presence of thermal and solutal buoyancy which has the tendency to increase the velocity. The variation in velocity under diffusion thermo effect is depicted in figure 3. The velocity grows when the values of Dufour number increases. The effect of porosity parameter on primary velocity and secondary velocity is illustrated in the figures 4,5. The velocity enhances for increasing values of porosity parameter increases. Figures 6,7 display the variations in primary and secondary velocities under the influence of rotation parameter. The primary velocity decreases for increasing values of rotation parameter but a reverse effect is observed in the case of secondary velocity. The effect of Prandtl number on temperature is presented in figure 8. It is seen that the surface temperature reduces with the increase in Prandtl number. The effect of heat source parameter and sink parameter on temperature is exhibited in figure 9. It reveals that the temperature falls down under the influence of heat absorption parameter whereas the temperature grows in the presence of heat generation. The central reason behind this effect is that the heat absorption causes a decrease in the kinetic energy as well as thermal energy of the fluid. Hence the momentum and thermal boundary layers get thinner in case of heat absorbing fluids. Increasing values of radiation parameter leads to decrease the temperature which is observed from figure 10. The variation in temperature under the influence of diffusion thermo effect is depicted in figure 11. The temperature grows for enhancing values of Dufour number. Figure 12 illustrates the influence of Schmidt number on the concentration. It is noticed that as the Schmidt number increases, there is a decreasing trend in the concentration field. Not much of significant contribution of Schmidt number is observed far away from the plate. The variation in species concentration in the presence of chemical reaction is exhibited in figure 13. The existence of chemical reaction leads to decrease the concentration of the fluid.

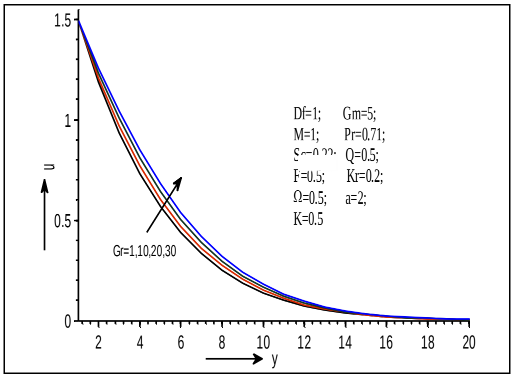

Figure 1. Effect of Grashof number on primary velocity

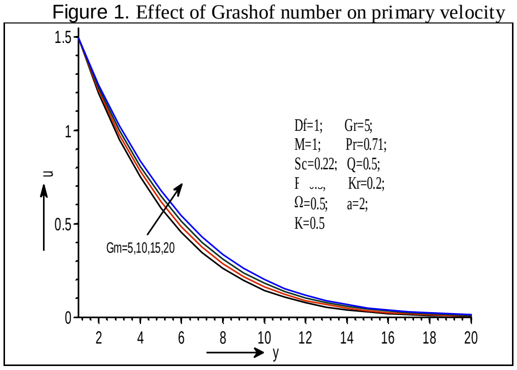

Figure 2. Effect of modified Grashof number on primary velocity

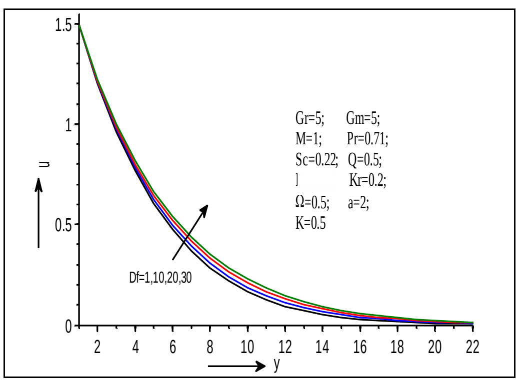

Figure 3. Effect of Dufour number on primary velocity

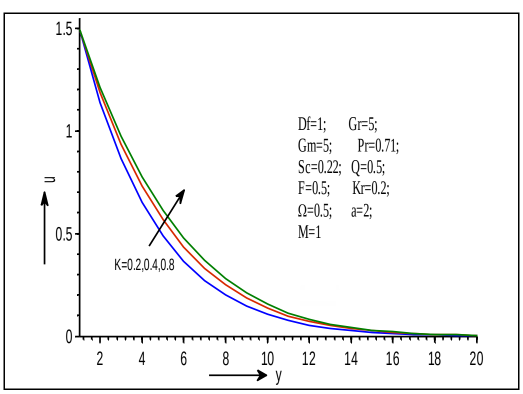

Figure 4. Effect of porosity parameter on primary velocity

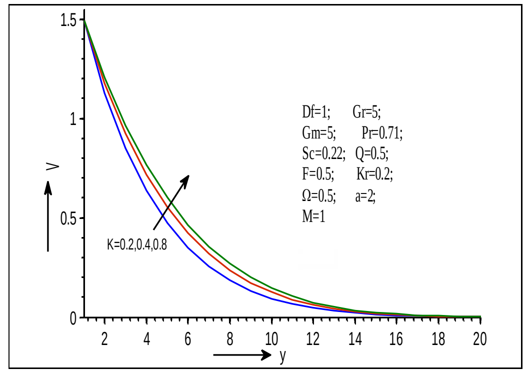

Figure 5. Effect of porosity parameter on secondary velocity

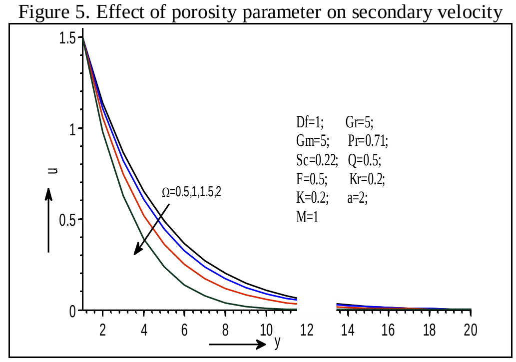

Figure 6. Effect of rotation parameter on primary velocity

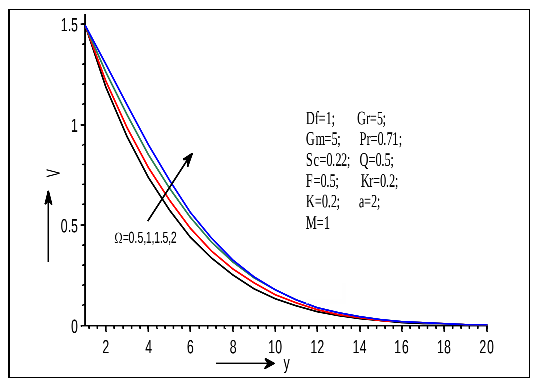

Figure 7. Effect of rotation parameter on secondary velocity

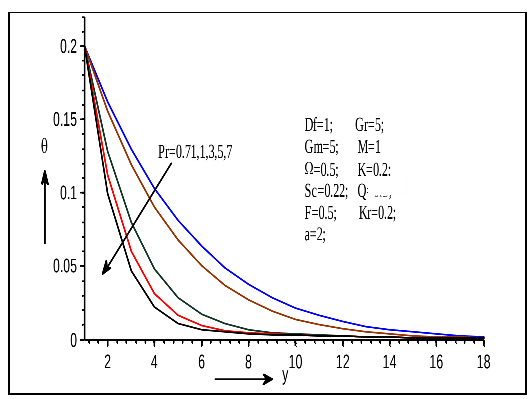

Figure 8. Effect of Prandtl number on temperature

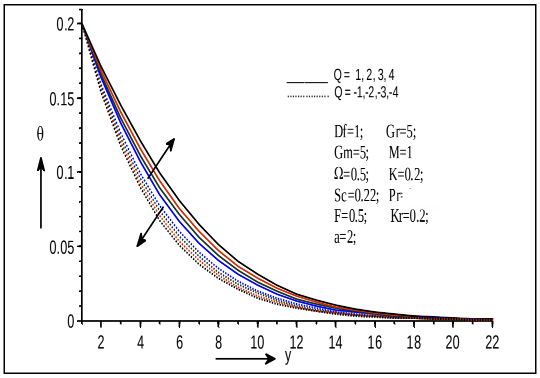

Figure 9. Effect of heat source and sink parameters on temperature

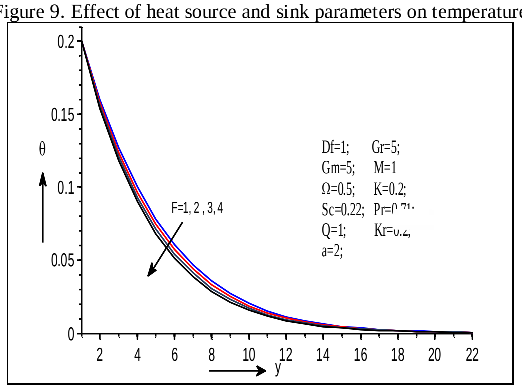

Figure 10. Effect of radiation parameter on temperature

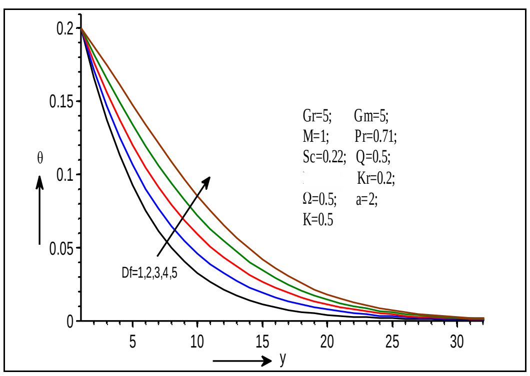

Figure 11. Effect of Dufour number on temperature

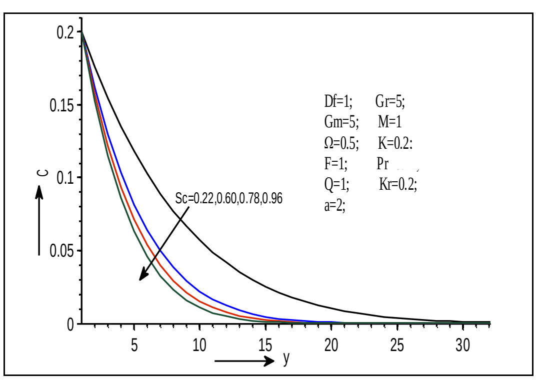

Figure 12. Effect of Schmidt number on concentration

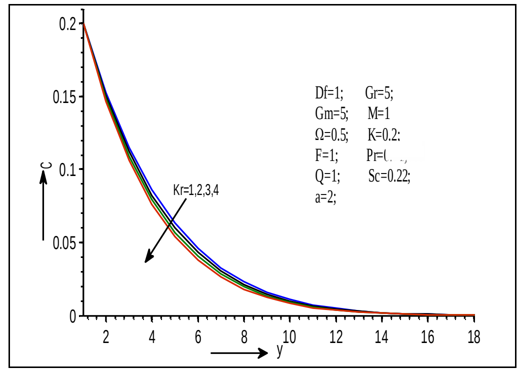

Figure 13. Effect of chemical reaction parameter on concentration

The variations in skin friction under the impact of the physical parameters are observed with the help of numerical values from Table 1. The primary skin friction as well as secondary skin friction decreases for increased values of Grashof number and modified Grashof number but a reverse trend is seen in the case of porosity parameter. The primary skin friction increases under the influence of rotation parameter and the secondary skin friction enhances when the values of rotation parameter are increased. Table 2 presents the effects of Prandtl number, heat source parameter, radiation parameter and Dufour number on skin friction and Nusselt number. The primary skin friction as well as secondary skin friction decreases for increased values of radiation parameter but an opposite nature is found in the case of diffusion thermo effect. The rate of heat transfer rises for increasing values of Prandtl number, radiation parameter and Dufour number and decreasing values of heat source parameter. Sherwood number increases under the influence of chemical reaction and Schmidt number which can be seen from Table 3.

Table 1: Variations in skin friction under the influence of Grashof number modified Grashof number, porosity and rotation parameters.

Gr	Gm	K	Ω	τ_x	τ_y
5	**5**	**1.2**	**2.2**	**3.9445**	**0.0049**
6	5	1.2	2.2	3.7070	0.0036
7	5	1.2	2.2	3.4695	0.0024
5	6	1.2	2.2	4.7479	0.2227
5	7	1.2	2.2	4.6309	0.1669
5	5	2.2	2.2	3.0392	0.0015
5	5	3.2	2.2	3.1400	0.0016
5	5	1.2	3.2	3.1162	0.0015
5	5	1.2	4.2	3.1264	0.0014

Table 2: Variations in skin friction and Nusselt number under the influence of Prandtl number, heat source parameter and radiation parameter.

Pr	Q	F	Df	τ_x	τ_y	Nu
2	1	0.22	1	2.2134	0.0111	2.4191
5	1	0.22	1	1.4054	0.0379	5.4853
2	1	0.22	1	1.2533	0.0471	2.5026
2	4	0.22	1	2.3633	0.0031	1.0803
2	1	0.60	1	2.8319	0.1587	1.0492
2	1	0.94	1	2.7366	0.1254	1.0498
2	1	0.22	1	2.9820	0.0847	1.1477
2	1	0.22	3	3.7820	0.5178	1.6451

Table 3: Effect of chemical reaction parameter and Schmidt number on skin friction and Sherwood number

Kr	Sc	Sh
3	1	0.8081
6	1	1.3198
3	1	0.1903
3	3	0.9918

V. CONCLUSIONS

The prominent observations of this study are:

- The velocity and temperature profiles have grown when the values of Dufour number increased
- The temperature of the fluid increased for growing values of heat source parameter however a reverse tendency is established in the case of heat sink parameter.
- Increasing values of radiation parameter led to decrease in the temperature
- The presence of chemical reaction led to the decrement in the concentration of the fluid.
- The skin friction increased when the values of rotation parameter are increased.

The rate of heat transfer raised up for growing values of Prandtl number, radiation parameter and Dufour number and falling values of heat source parameter.

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