



# RADIATION AND DUFOUR EFFECTS ON LAMINAR FLOW OF A ROTATING FLUID PAST A POROUS PLATE IN CONDUCTING FIELD

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## ABSTRACT

A theoretical investigation has been performed to describe the laminar flow of a rotating fluid past a porous plate in conducting field with variable temperature and variable concentration taking into account the chemical reaction, radiation and Dufour effects. The non-dimensional governing equations are solved numerically by using finite difference scheme. The effects of different physical parameters on velocity, temperature and concentration are presented and 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 effect.

## 1. INTRODUCTION

Radiation is the processes by which heat energy is transmitted from one place to another without the aid of any material medium. 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. Muthucumaraswamy and Visalakshi (2011) studied radiative flow and heat transfer past an exponentially accelerated vertical plate with uniform mass diffusion. Effects of thermal radiation and porosity on MHD mixed convection flow in a vertical channel using homotopy analysis method were also carried out by Srinivas and Muthuraj (2010). Raptis *et al.* (2003) studied the effects of radiation in an optically thin gray gas flowing past a vertical infinite plate in the presence of a magnetic field. Ananda and Varma (2010) studied radiation effect on MHD Couette flow with heat and mass transfer between two parallel plates. Raju *et al.* (2014) presented an analytical study of MHD free convective, dissipative boundary layer flow past a porous vertical surface in the presence of thermal radiation, chemical reaction and constant suction. Kumar (2013) discussed radiative heat transfer with MHD free convection flow over a stretching porous sheet in the presence of heat source subjected to power law heat flux. Ali *et al.* (2013) studied 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 (2013) discussed magneto hydrodynamic transient flow through a porous medium bounded by a hot vertical plate in the presence of radiation. Chandrakala (2011) analyzed radiation effects on flow past an impulsively started vertical oscillating plate with uniform heat flux. Chandra Reddy *et al.* (2016) studied the properties of free convective magneto-nanofluid flow past a moving vertical plate in the presence of radiation and thermal diffusion.

In a moving fluid, if heat and mass transfer occur simultaneously, the relations among the dynamic potentials and fluxes are of more considerable. It has been recognized that energy flux will be formed by temperature gradients as well as concentration gradients. The energy flux formed by a concentration gradient is treated as the diffusion-thermo effect or Dufour effect. Bhargava *et al.* (2009) considered cross diffusion effects on the fluctuating hydromagnetic flow under thermal and mass buoyancy. Thermo diffusion and chemical effects with simultaneous thermal and mass diffusion in mixed convection flow with ohmic heating were explained by Reddy and Varma (2011). Tsai and Huang (2009) studied theoretically heat and mass transfer consequences on Hiemenz flow in a porous boundary through a stretched surface under the occurrence of species diffusion and thermal diffusion. Narayana and Sibanda ((2010) discussed the sores and dufour effects thoroughly on a wavy surface in Darcy porous media. Seddeek (2004) established diffusion-thermo and thermal-diffusion influence on the flow over an accelerating surface with heat generation and blowing/suction for the particular case of mixed convection and changeable viscosity.

The topic of rotating flows has received wide interest in modern fluid dynamics research. Excellent treatises on this subject with applications in geophysics and planetary sciences have been in the literature since the early 1950s. The coupled effects of heat transfer and rotational hydrodynamics have largely been inspired by applications in chemical engineering and manufacturing processes in the chemical industry. Ganapathy (1994) presented a note on oscillatory Couette flows in a rotating system. Singh (2000) analyzed an oscillatory hydromagnetic Couette flow in a rotating system. Ghosh (1993) studied an unsteady hydromagnetic flow in a rotating channel with oscillating pressure gradient. Seth *et al.* (2014) analyzed oscillatory hydromagnetic Couette flow in a rotating system with induced magnetic field. Seth *et al.* (2013) discussed the effects of thermal radiation and rotation on unsteady hydromagnetic free convection flow past an impulsively moving vertical plate with ramped temperature in a porous medium.

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Singh and Pathak (2012) studied the effect of rotation and Hall current on mixed convection MHD flow through a porous medium in a vertical channel in the presence of thermal radiation. Ahmed and Sarmah (2011) considered MHD transient flow past an impulsively started horizontal porous plate in a rotating system with Hall current. Seth *et al.* (2013) analyzed the effect of rotation on unsteady hydromagnetic natural convection flow past an impulsively moving vertical plate with ramped temperature in a porous medium with thermal diffusion and heat absorption. Malique and Sattar (2005) 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.* (2016) presented thermal diffusion and rotational effects on magneto hydrodynamic mixed convection flow of heat absorbing/generating visco-elastic fluid through a porous channel.

## 2. MATHEMATICAL FORMULATION

The laminar flow of a rotating fluid past a porous plate in conducting field with variable temperature and variable concentration taking into account the chemical reaction, radiation and Dufour effects is considered. X-axis is taken 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 rigid body rotates with a uniform angular velocity  $\Omega$  about Y-axis. Initially at time  $t^* \leq 0$ , both the fluid and the plate were at rest with uniform temperature and concentration  $T_\infty$  and  $C_\infty$  respectively. 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 maintained at uniform temperature and concentration  $T_\infty$  and  $C_\infty$  respectively. Under these considerations the equations that govern the flow are as follows.

$$\frac{\partial u^*}{\partial t^*} + 2\Omega V^* = \nu \frac{\partial^2 u^*}{\partial y^{*2}} + g\beta_T (T^* - T_\infty) + g\beta_C (C^* - C_\infty) - \frac{\sigma B_0^2 u^*}{\rho} - \frac{\nu}{k} u^* \quad (1)$$

$$\frac{\partial V^*}{\partial t^*} - 2\Omega u^* = \nu \frac{\partial^2 V^*}{\partial y^{*2}} - \frac{\sigma B_0^2 V^*}{\rho} - \frac{\nu}{k} V^* \quad (2)$$

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

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

The corresponding initial and boundary conditions are

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

The non-dimensional quantities are as follows:

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

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

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

$$\text{Magnetic parameter } M = \frac{\sigma B_0^2 \nu}{\rho U_0^2},$$

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

$$\text{Permeability of the porous medium } K = \frac{k U_0^2}{\nu^2},$$

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

$$\text{Chemical reaction Parameter } Kr = \frac{K_l \nu}{U_0^2},$$

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

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

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

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

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

$$\frac{\partial u}{\partial t} + 2k_1^2 V = \frac{\partial^2 u}{\partial y^2} + Gr\theta + GmC - Mu - \frac{1}{K}u \quad (6)$$

$$\frac{\partial V}{\partial t} - 2k_1^2 u = \frac{\partial^2 V}{\partial y^2} - MV - \frac{1}{K}V \quad (7)$$

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

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

The corresponding initial and boundary conditions are

$$\left. \begin{aligned} &u = 0, V = 0, \theta = 0, C = 0 \quad \text{for all } y, t \leq 0 \\ &t > 0: u = e^{at}, V = e^{at}, \theta = t, C = t \quad \text{at } y = 0 \\ &u = 0, V = 0, \theta = 0, C = 0 \quad \text{as } y \rightarrow \infty \end{aligned} \right\} \quad (10)$$

## 3. 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:

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

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

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

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

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:

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

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

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

$$u(i_{\max}, j) = 0, \theta(i_{\max}, j) = 0, C(i_{\max}, j) = 0 \text{ for all } j$$

(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  $\theta(i, j+1)$  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  $\Delta t$  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:**

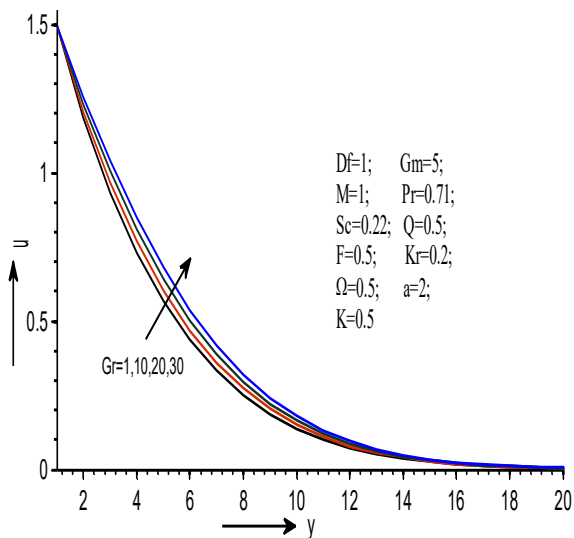
The dimensionless rate of mass transfer in terms of Sherwood number is given by

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

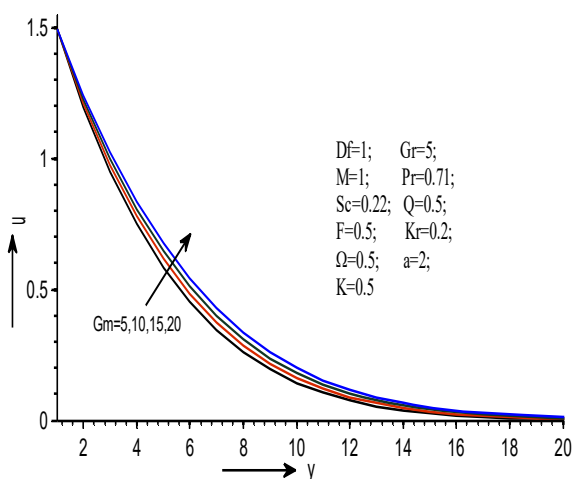
#### 4. RESULTS AND DISCUSSION

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 magnetic parameter on primary velocity and secondary velocity is illustrated in the figures 4, 5. The velocity falls down when the values of magnetic parameter increases. This is due to the application of transverse magnetic field, which has the tendency of reducing the velocity. This drag force is called as Lorentz force. The

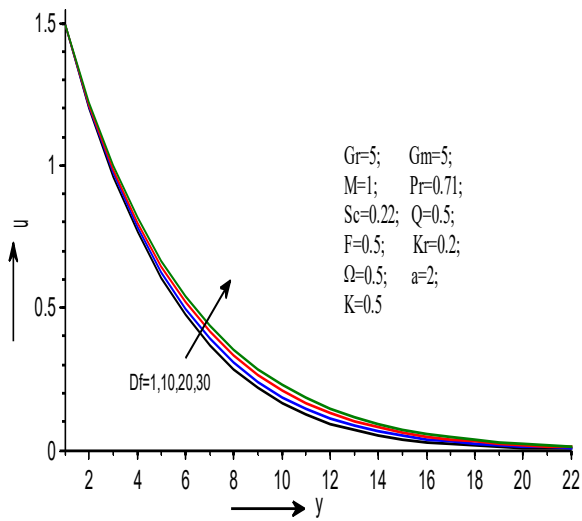
effect of porosity parameter on primary velocity and secondary velocity is illustrated in the figures 6, 7. The velocity enhances for increasing values of porosity parameter increases. Figures 8, 9 display the variations in primary and secondary velocities under the influence of rotation parameter. The 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 10. 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 11. 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 12. The variation in temperature under the influence of diffusion thermo effect is depicted in figure 13. The temperature grows for enhancing values of Dufour number. Figure 14 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 15. The existence of chemical reaction leads to decrease the concentration of the fluid.



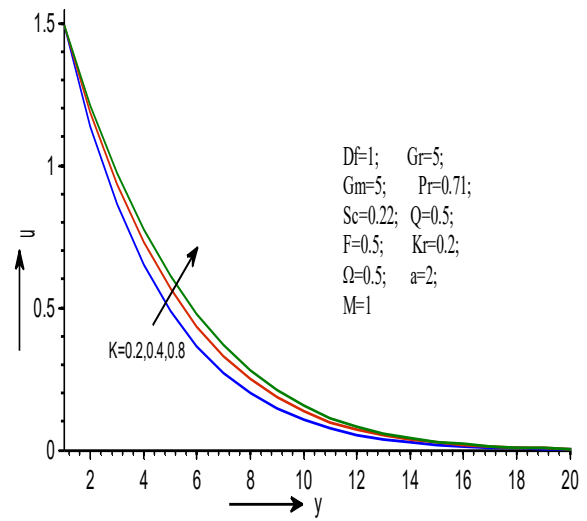
**Fig.1** Effect of Grashof number on primary velocity



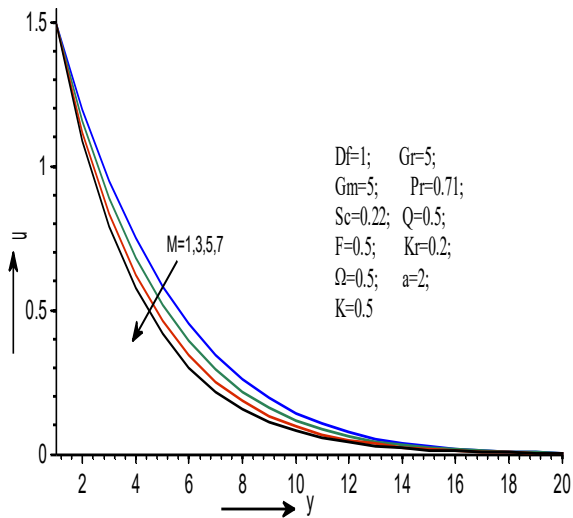
**Fig. 2** Effect of modified Grashof number on primary velocity



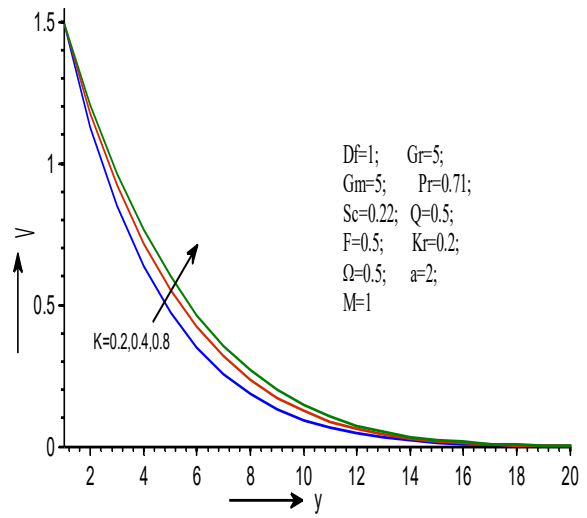
**Fig. 3** Effect of Dufour number on primary velocity



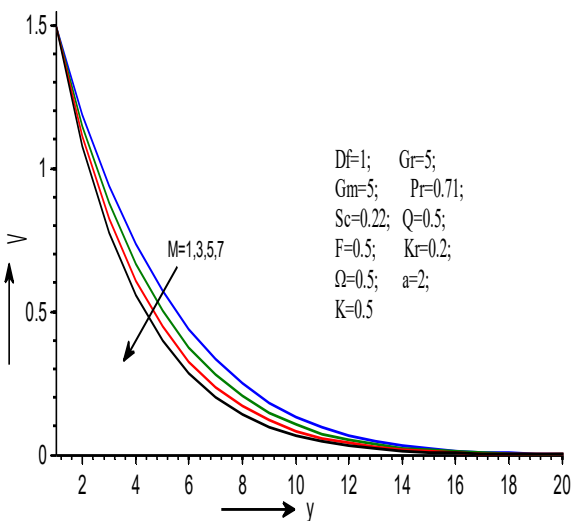
**Fig. 6** Effect of porosity parameter on primary velocity



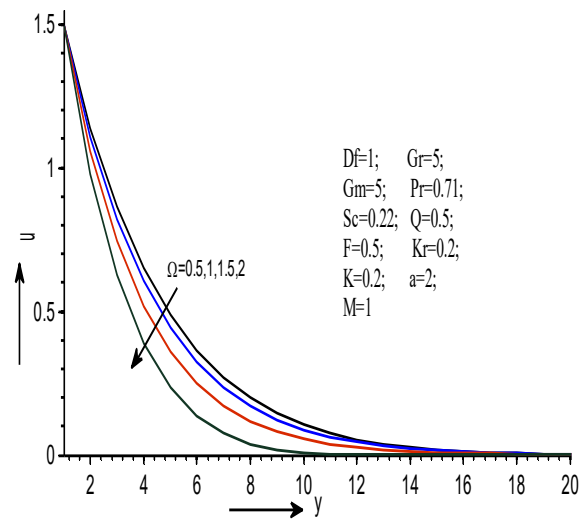
**Fig. 4** Effect of magnetic parameter on primary velocity



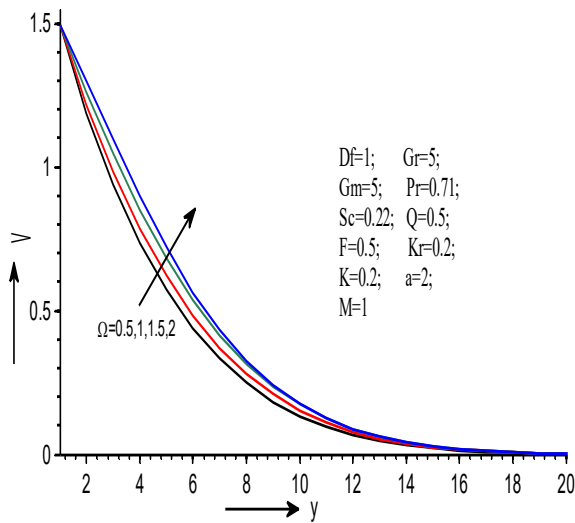
**Fig. 7** Effect of porosity parameter on secondary velocity



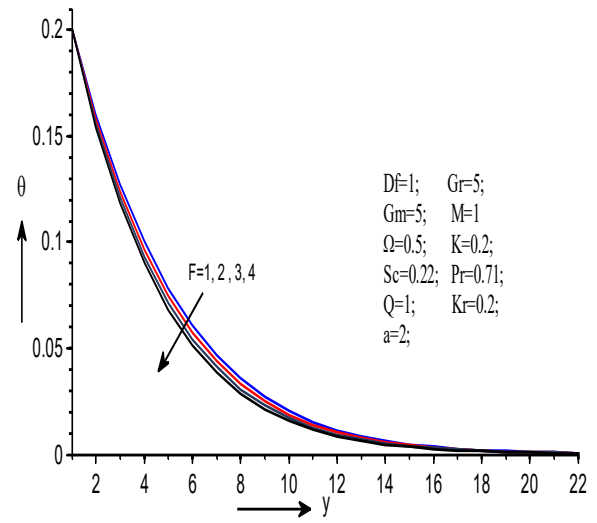
**Fig. 5** Effect of magnetic parameter on secondary velocity



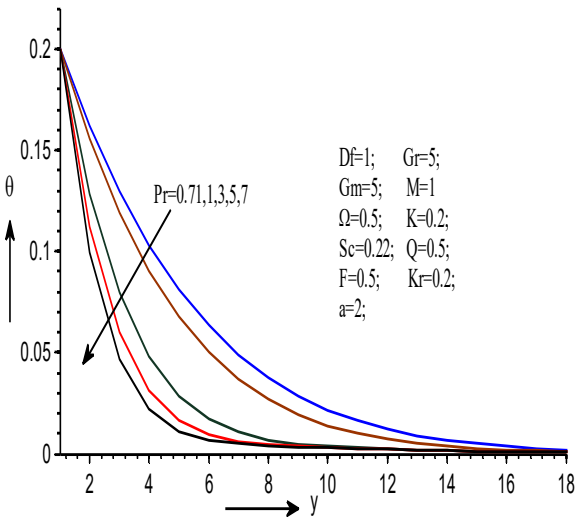
**Fig. 8** Effect of rotation parameter on primary velocity



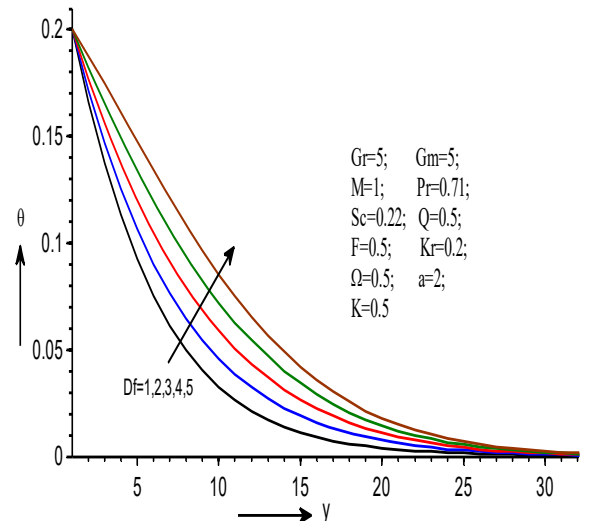
**Fig. 9** Effect of rotation parameter on secondary velocity



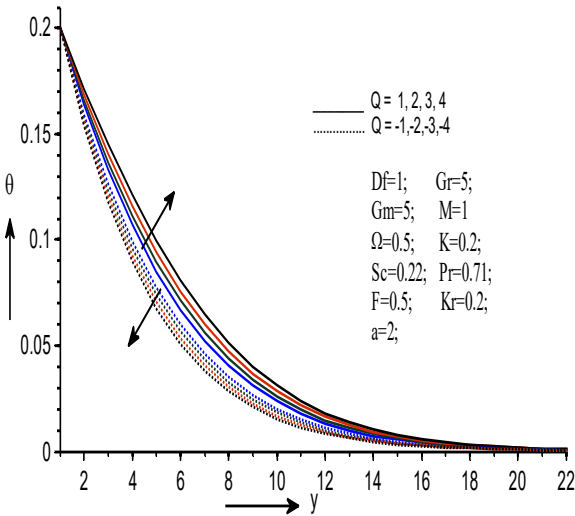
**Fig. 12** Effect of radiation parameter on temperature



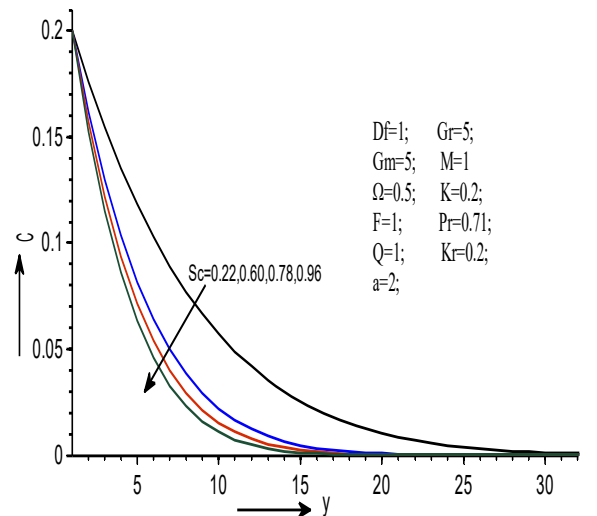
**Fig. 10** Effect of Prandtl number on temperature



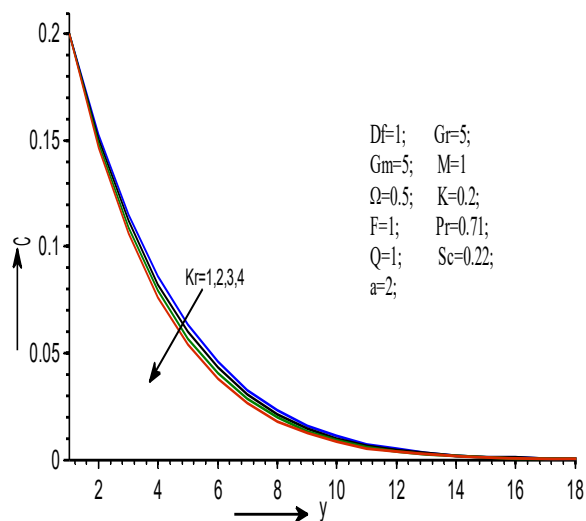
**Fig. 13** Effect of Dufour number on temperature



**Fig. 11** Effect of heat source and sink parameters on temperature



**Fig. 14** Effect of Schmidt number on concentration



**Fig. 15** Effect of chemical reaction parameter on concentration

**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	$\tau_x$	$\tau_y$	Nu
2	1	0.22	1	2.2134	0.0111	2.4191
4	1	0.22	1	1.5995	0.0288	4.4674
5	1	0.22	1	1.4054	0.0379	5.4853
2	1	0.22	1	1.2533	0.0471	2.5026
2	3	0.22	1	2.4729	0.0020	1.8595
2	4	0.22	1	2.3633	0.0031	1.0803
2	1	0.60	1	2.8319	0.1587	1.0492
2	1	0.78	1	2.7950	0.1488	1.0496
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	2	3.2820	0.1713	1.2472
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
5	1	1.2738
6	1	1.3198
3	1	0.1903
3	2	0.4004
3	3	0.9918

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 magnetic field parameter and 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, magnetic parameter, porosity parameter and rotation parameter.

Gr	Gm	M	K	$\Omega$	$\tau_x$	$\tau_y$
5	5	3	1.2	2.2	3.9445	0.0049
6	5	3	1.2	2.2	3.7070	0.0036
7	5	3	1.2	2.2	3.4695	0.0024
8	5	3	1.2	2.2	3.1321	0.0012
5	6	3	1.2	2.2	4.7479	0.2227
5	7	3	1.2	2.2	4.6309	0.1669
5	8	3	1.2	2.2	4.5138	0.0565
5	5	4	1.2	2.2	1.2790	0.0100
5	5	5	1.2	2.2	1.4619	0.0142
5	5	6	1.2	2.2	1.7387	0.0183
5	5	3	2.2	2.2	3.0392	0.0015
5	5	3	3.2	2.2	3.1400	0.0016
5	5	3	4.2	2.2	3.2403	0.0018
5	5	3	1.2	3.2	3.1162	0.0015
5	5	3	1.2	4.2	3.1264	0.0014
5	5	3	1.2	8.2	3.1369	0.0013

## 5. CONCLUSIONS

The notable points of this study are as follows:

- The primary velocity of the fluid increases when the values of rotation parameter increased and the secondary velocity decreases in the same case.
- The temperature of the fluid enhances for increasing values of heat source parameter whereas a reverse trend is found in the case of heat sink parameter.
- The existence of chemical reaction leads to decrease the concentration of the fluid.
- 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.
- The rate of heat transfer rises for increasing values of Prandtl number, radiation parameter and Dufour number and decreasing values of heat source parameter.

## ACKNOWLEDGEMENT

Authors are very much thankful to the reviewers for their valuable comments and constructive suggestions who certainly helped to improve the quality of the manuscript.

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