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Casson Fluid Flow Over A Vertical Porous Plate Under The Existence Of Cross Diffusion Effects In Conducting Field

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Abstract
An attempt has been made to examine the flow characteristics of Casson fluid flow along a vertical porous plate under the consideration of diffusion thermo and thermal diffusion effects. The influence of heat generation, thermal radiation and chemical reaction is also studied. The governing equations pertinent to the flow are solved by applying finite differene scheme. The effects of related physical parameters on the velocity, temperature and concentration profiles are discussed through graphical presentations. Further the nature of skin-friction, Nusselt number and Sherwood number is analyzed and presented numerically in the tabular form. The influence of thermal diffusion leads to enhance and the existence of chemical reaction diminishes the species concentration.

Keywords: *Casson fluid, Soret number, Dufour number, Thermal radiation, Chemical reaction and Conducting field.*

1. Introduction
The study of characteristics of non-Newtonian fluids is one of the important and interesting topics for scholars and scientists having direct or indirect affiliation with the field of fluid science. Non-Newtonian fluids have nonlinear relationship between strain rate and stress while in Newtonian fluid it is in linear mode. On the other hand, fluid flow properties are different in any way from that of the Newtonian fluid is called a non-Newtonian fluid. Some examples of non-Newtonian fluids are salt solutions, molten polymers, ketchup, custard, toothpaste, starch suspensions, paints, blood and shampoo.

It is an important scientific discovery to note that, in real industrial applications, non-Newtonian fluids are more significant due to their applications in petroleum drilling, polymer engineering, certain separation processes, manufacturing of foods and paper and some other industrial processes [1]. Due to the nonlinearity between the stress and the rate of strain for non-Newtonian fluids, it is difficult to express all those properties of several non-Newtonian fluids in a single constitutive equation. This has called on the attention of researchers to analyze the flow dynamics of non-Newtonian fluids. Consequently, several non-Newtonian fluid models have been designed depending on various physical parmeters. Pramanik [2] studied and established Casson fluid flow and heat transfer past an exponentially porous stretching surface in presence of thermal radiation. Qasim and Noreen [3] considered heat transfer in boundary layer flow in a casson fluid over permeable shrinking sheet with viscous dissipation. Das et al. [4] analyzed Newtonian heating effect on unsteady hydromagnetic Casson fluid flow past a flat plate with heat and mass transfer. Chandra Reddy et al. [5-8] considered and analyzed MHD boundary layer flows of a visco-elastic fluid as well as Rivlin-Ericksen fluid past a porous plate with different parameters and boundary conditions. Ananda Reddy et al [9] discussed radiation and Dufour effects on laminar flow of a rotating fluid past a porous plate in conducting field. Rama Mohan Reddy et al. [10] studied thermal diffusion and Joule-heating effects on magnetohydrodynamic

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free-convective, heat-absorbing/ generating, viscous-dissipative Newtonian fluid with variable temperature and concentration. Sidda Reddy et al. [11] examined thermal diffusion and Joule heating effects on MHD radiating fluid embedded in porous medium. Harinath Reddy et al. [12] considered Joule heating and radiation absorption effects on MHD convective and chemically reactive flow past a porous plate. Kataria and Patel [13] examined radiation and chemical reaction effects on MHD Casson fluid flow past an oscillating vertical plate embedded in porous medium. Yabo et al. [14] analyzed combined effects of thermal diffusion and diffusion-thermo effects on transient MHD natural convection and mass transfer flow in a vertical channel with thermal radiation. Mehmood et al. [15] discussed the effects of thermal-diffusion and diffusion-thermo on oblique stagnation point flow of couple stress Casson fluid over a stretched horizontal riga plate with higher order chemical reaction. Sharma and Mishra [16] established a Mathematical model of MHD micropolar fluid flow with thermal-diffusion and diffusion-thermo effects. Srinivasa Raju [17] considered combined influence of thermal diffusion and diffusion thermo on unsteady hydromagnetic free convective fluid flow past an infinite vertical porous plate in presence of chemical reaction. Srinivasacharya et al. [18] examined Soret and Dufour effects on mixed convection along a wavy surface in a porous medium with variable properties.
In view of the above literature we have considered combined influence of thermal diffusion and diffusion thermo effects on Casson fluid past a vertical plate embedded with porous medium. The influence of heat generation, thermal radiation and chemical reaction is also taken into consideration.

2. Formulation of the problem

An unsteady two-dimensional Casson fluid of an incompressible, viscous, electrically conducting fluid over a vertical porous plate moving with constant velocity is considered. The impacts of thermo diffusion and diffusion thermo effects in the presence of radiation, heat generation and chemical reaction is also considered. An incompressible viscous fluid is passing through a flat porous sheet coinciding with plane y = 0. Cartesian coordinate system is selected such that the x – axis is parallel to the surface and y axis is perpendicular to the surface. The fluid occupies a half space y>0. A constant magnetic field B_0 is applied in the y-direction as shown in Figure 1. Compared to applied magnetic field, magnetic Reynolds number is considered to be very small so that the induced magnetic field is negligible. The surface temperature of the plate oscillates with small amplitude about a non-uniform mean temperature. The fluid is supposed to have constant properties excluding for the influence of the density variations with temperature and concentration which are considered only in the body force term.

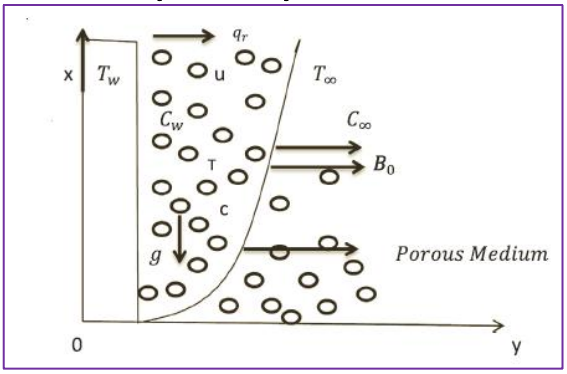

Figure1: Physical model of the problem

The rheological equation of state for an isotropic flow of a Casson fluid can be expressed as:

$$\tau_{ij} = \begin{cases} 2\left(\mu_B + \dfrac{P_y}{\sqrt{2\pi}}\right)e_{ij}, & \pi > \pi_c \\ 2\left(\mu_B + \dfrac{P_y}{\sqrt{2\pi_c}}\right)e_{ij}, & \pi < \pi_c \end{cases} \tag{1}$$

In the above equation, $\pi = e_{ij}e_{ij}$, where $e_{ij}$is the (i , j)th component of deformation rate. This indicates that π is the product of deformation rate with itself. Also, $\pi_c$is a critical value of this product based on the non-Newtonian model, μ_B is the plastic dynamic viscosity of the non-Newtonian fluid and P_y is the yield stress of the fluid.
Equations governing the unsteady boundary layer flow of the Casson fluid are

$$\frac{\partial u^*}{\partial t^*} = \left(1+\frac{1}{\gamma}\right)\frac{\partial^2 u^*}{\partial y^{*2}} + g\beta\left(T^* - T^*_\infty\right) + g\beta^*\left(C^* - C^*_\infty\right) - \frac{\sigma B_0^2}{\rho}u^* - \frac{\nu}{K^*}u^* \tag{2}$$

$$\frac{\partial T^*}{\partial t^*} = \frac{\kappa}{\rho Cp}\frac{\partial^2 T^*}{\partial y^{*2}} - \frac{1}{\rho Cp}\frac{\partial q_r^*}{\partial y^*} + \frac{Q_0}{\rho Cp}\left(T^* - T^*_\infty\right) + \frac{D_m k_T}{C_s C_p}\frac{\partial^2 C^*}{\partial y^{*2}} \tag{3}$$

$$\frac{\partial C^*}{\partial t^*} = D_M\frac{\partial^2 C^*}{\partial y^{*2}} - K_r^*\left(C^* - C^*_\infty\right) + \frac{D_T K_t}{T_m}\frac{\partial^2 T^*}{\partial y^{*2}} \tag{4}$$

Equations (2),(3) and (4) refers momentum equation, energy and species equation respectively where u is the velocity of the fluid, γ is Casson

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parameter, Q_0 is the heat source/sink parameter, Q_l is the radiation absorption parameter, D_M is the molecular diffusivity, k is thermal conductivity, C is mass concentration, t is time, ν is the kinematics viscosity, g is the gravitational constant, β and β* are the thermal expansions of fluid and concentration, ρ is density, Cp is the specific heat capacity at constant pressure, D_T is coefficient of mass diffusivity, D_m is the coefficient of heat diffusivity, K_t is thermal diffusion ratio, Tm mean fluid temperature, T_∞ free stream temperature of the surrounding fluid, C_∞ free stream concentration, T fluid temperature, C fluid concentration, q_r is the radiative flux, B_0 is the magnetic field and K_r is the chemical reaction rate constant.

The respective boundary conditions for the velocity, temperature and concentration are:

$$u^* = U, \quad T^* = T_\infty^* + \varepsilon\left(T_w^\infty - T_\infty^*\right)e^{n^*t^*},$$

$$C^* = C_\infty^* + \varepsilon\left(C_w^* - C_\infty^*\right)e^{n^*t^*} \quad \text{at } y^* = 0 \tag{5}$$

$$u^* \to 0, \quad T^* \to T_\infty^*,$$

$$C^* \to C_\infty^*, \quad \text{as} \quad y^* \to \infty$$

The temperature differences present in the flow are assumed sufficiently small so that T^*can be expressed as a linear function of T^* using Taylor's series to expand T^{*4}about the free stream temperature T_∞^*. Higher-order terms were neglected. This leads in the following approximation.

$$\frac{\partial q_r^*}{\partial y^*} = -4a^*\sigma^*(T_\infty^* - T^{*4}) \text{ and}$$

$$T^{*4} \cong 4T_\infty^{*3}T^* - 3T_\infty^{*4} \tag{6}$$

The following dimensionless quantities are introduced

$$u=\frac{u^*}{U}, \quad y=\frac{Uy^*}{v}, \quad t=\frac{Ut^*}{v}, \quad \theta = \frac{T^*-T_\infty^*}{T_w^*-T_\infty^*},$$

$$C = \frac{C^*-C_\infty^*}{C_w^*-C_\infty^*}, \quad Q=\frac{Q_0 v}{\rho C_p U^2}, \quad K=\frac{K^* u_0^2}{v^2}$$

$$P_r=\frac{\mu C_p}{k}, \quad M=\frac{\sigma B_0^2 v}{\rho U^2}, \quad G_r=\frac{v\beta g(T_w^*-T_\infty^*)}{U^2},$$

$$G_c = \frac{v\beta^* g(C_w^*-C_\infty^*)}{U^3} \quad K_r=\frac{K_r^* v}{U_0^2}, S_c=\frac{v}{D},$$

$$R=\frac{16a^*v\sigma^*T_\infty^{*3}}{\rho C_p U^2}, Df = \frac{D_m k_T (C_w^* - C_\infty^*)}{\nu C_s C_p (T_w^* - T_\infty^*)}$$

$$\mu = v\rho, \quad s_o = \frac{D_\varepsilon K_t U^2}{T_m v^2}(T_w^* - T_\infty^*) \tag{7}$$

The thermal radiation heat flux gradient may be expressed as follows

$$-\frac{\partial q_r}{\partial y^*}=4a\sigma^*(T_\infty^* - T^{*4}) \tag{8}$$

Considering the temperature difference by assumption within the flow are sufficiently small such that T^{*4}may be expressed as a linear function of the temperature. This is attained by expanding inT^{*4}Taylor's series about $T^{*4}$and ignoring higher order terms

$$T^{*4} \cong 4T_\infty^{*3}T^* - 3T_\infty^{*4} \tag{9}$$

Using equations (8) and (9) and substituting the dimensionless variables (7), equations (2) - (4) are reduced to the following dimensionless form.

$$\frac{\partial u}{\partial t}=\left(1+\frac{1}{\gamma}\right)\frac{\partial^2 u}{\partial y^2} + G_r\theta + G_c C - \left(M + \frac{1}{K}\right)u \tag{10}$$

$$\frac{\partial\theta}{\partial t} = \frac{1}{P_r}\frac{\partial^2\theta}{\partial y^2} - R\theta + Q\theta + Df\frac{\partial^2 C}{\partial y^2} \tag{11}$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} - KrC + So\frac{\partial^2\theta}{\partial y^2} \tag{12}$$

The corresponding boundary conditions are

$$u = 1, \theta = 1 + \varepsilon e^{nt}, C = 1 + \varepsilon e^{nt} \text{ at } y = 0$$

$$u \to 0, \quad \theta \to 0, \ C \to 0 \quad as \quad y \to \infty \tag{13}$$

where $G_r$is thermal Grashof number,$P_r$is the Prandtl number, $k_r$is the chemical reaction parameter, R is the thermal radiation conduction number, M is Hartmann number, $G_c$is the mass Grashof number, Q is the heat source parameter, D_f is the Dufour number and So is the Soret number.

3. Method of solution:

The above linear partial differential equations (10)-(12) are to be solved with the initial and boundary conditions (13). 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 (10)-(12) are as follows:

$$\frac{u_{i,j+1} - u_{i,j}}{\Delta t} = \left(1 + \frac{1}{\gamma}\right)\frac{u_{i-1,j} - 2u_{i,j} + u_{i+1,j}}{(\Delta y)^2} + Gr\,\theta_{i,j} + Gc\,C_{i,j} - M\,u_{i,j} - \frac{1}{K}u_{i,j} \tag{14}$$

$$\frac{\theta_{i,j+1} - \theta_{i,j}}{\Delta t} = \frac{1}{\Pr}\frac{\theta_{i-1,j} - 2\theta_{i,j} + \theta_{i+1,j}}{(\Delta y)^2} + Q\theta_{i,j} - R\theta_{i,j} + Df\,\frac{C_{i-1,j} - 2C_{i,j} + C_{i+1,j}}{(\Delta y)^2} \tag{15}$$

$$\frac{C_{i,j+1} - C_{i,j}}{\Delta t} = \frac{1}{Sc}\frac{C_{i-1,j} - 2C_{i,j} + C_{i+1,j}}{(\Delta y)^2} + S_0\frac{\theta_{i-1,j} - 2\theta_{i,j} + \theta_{i+1,j}}{(\Delta y)^2} - KrC_{i,j} \tag{16}$$

Here, the suffix i corresponds to y and j to time. The mesh system is divided by taking Δy = 0.1. From (13), the equivalent initial condition is

$$u(i,0) = 0, \theta(i,0) = 0, C(i,0) = 0 \quad \forall\, i \tag{17}$$

and the equivalent boundary conditions are

$$u(0,j)=at,\theta(0,j)=1+\varepsilon e^{nt},\quad C(0,j)=1+\varepsilon e^{nt}\ \ for\ all\ j$$
$$u(i_{\max},j)=0,\theta(i_{\max},j)=0,\quad C(i_{\max},j)=0\ \ for\ all\ j \qquad (18)$$

(Here i_{max} was taken as 200)

The velocity at the end of time step viz, u(i, j+1)(i=1,200) is computed from (14) in terms of velocity, temperature and concentration at points on the earlier time-step. After that θ (i, j +1) is computed from (15) and then C (i, j +1) is computed from (16). 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

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

4. Results and Discussion:

The effects of Soret and Dufour numbers on unsteady MHD Casson fluid flow over a vertical plate in the presence of radiation and chemical reaction has been studied. The equations governing the non-Newtonian flow are solved by using finite difference method and numerical solutions are obtained. The effects of the relevant parameters on the flow fields are investigated and discussed through graphs and tables.

Figure (2) shows the effect of thermal Grashof number (***Gr)*** on velocity profiles in the boundary layer. As anticipated, it is observed that an increase in ***Gr*** leads to increase in the values of velocity due to enhancement in buoyancy force. Here the positive values of ***Gr*** resemble the cooling of the surface. Also, as Grashof number increases, the peak values of the velocity increased rapidly close to the porous plate and then decays gradually at the free stream velocity.

Figure (3) depicts typical velocity profiles in the boundary layer for various values of the Solutal Grashof number (***Gc)***, while all other parameters are kept at some fixed values. The velocity distribution attains a distinctive maximum value in the vicinity of the plate surface and then decrease properly to approach the free stream value. As expected, the fluid velocity increases and the peak value more distinctive due to increase in the concentration buoyancy effects represented by ***Gc***. The influence of the Casson parameter (γ) on the velocity profiles are shown in the figure (4). It is observed that when the Casson parameter increases, the velocity increased and after some time reverse trend is observed. This happens because the momentum boundary layer thickness Increases with increasing Casson parameter but the thermal boundary layer thickness decreases in this case.

The effect of magnetic field on velocity profiles in the boundary layer is depicted in Figure (5). From this figure it is seen that the velocity starts from minimum value at the surface and increases till it attains the peak value and then starts decreasing until it reaches to the minimum value at the end of the boundary layer for all the values of magnetic field parameter. The effect of magnetic field is more prominent at the point of peak value. The presence of magnetic field in an electrically conducting fluid introduces a force called the Lorentz force, which acts against the flow if the magnetic field is applied in the normal direction. This type of resisting force slows down the fluid velocity as shown in this figure.

Figure (6) shows the velocity profiles for different values of the permeability parameter ***K***. It is noticed that the velocity increases with an increase in the permeability parameter. From Figure (7), it is observed that an increase in the Prandtl number results in the decrease of the thermal boundary layer thickness and in general lower average temperature within the boundary layer. The reason is that smaller values of *Pr* are equivalent to increasing the thermal conductivities, and therefore heat is able to diffuse away from the heated plate more rapidly than for higher values of *Pr*.

Figure (8) depicts the temperature profiles for different values of the heat source parameter *Q*. It is noticed that an increase in the heat source parameter *Q* results in an increase in temperature within the boundary layer. From Figure (9), it is seen that the temperature decreases as the radiation parameter *R* increases. This result qualitatively agrees with the expectations, since the effect of radiation is to decrease the rate of energy transport to the fluid, thereby decreasing the temperature of the fluid. The effect of Dufour number on the temperature of the flow is displayed in the figure (10). It is observed that the increment in the Dufour number resulted in the increase of the temperature of the fluid flow.

Figure (11) displays the effect of Schmidt number Sc on the concentration profiles. As the Schmidt number increases the concentration decreased.

Figure (12) represents the changes in concentration profiles for different values of Soret number. It is observed that the concentration fields decreased with an increasing the Soret number. Figure (13) represents the effect of chemical reaction parameter on concentration profiles. It is observed that the concentration decreases with an increasing chemical reaction parameter.

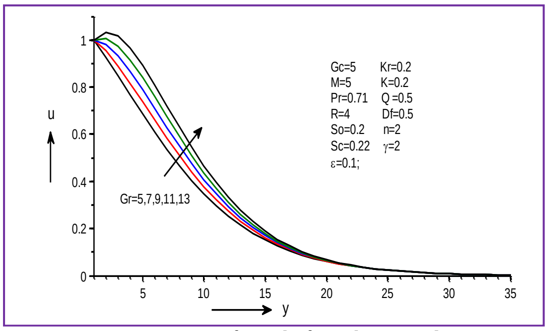

Figure 2: Impact of Grashof number on velocity

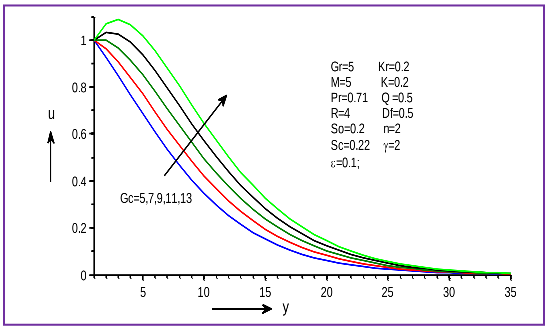

Figure 3: Impact of modified Grashof number on velocity

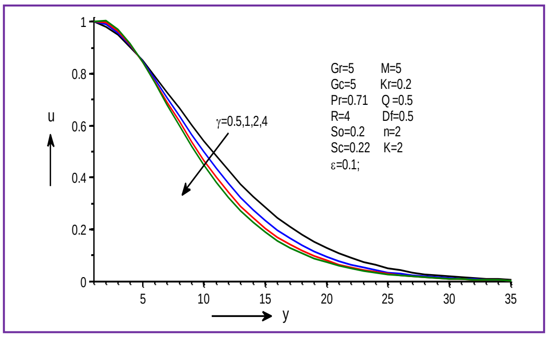

Figure 4: Impact of Casson parameter on velocity

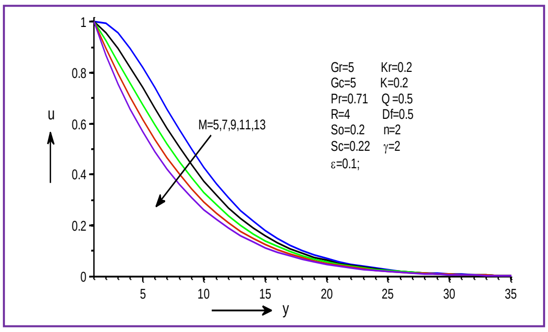

Figure 5: Impact of magnetic parameter on velocity

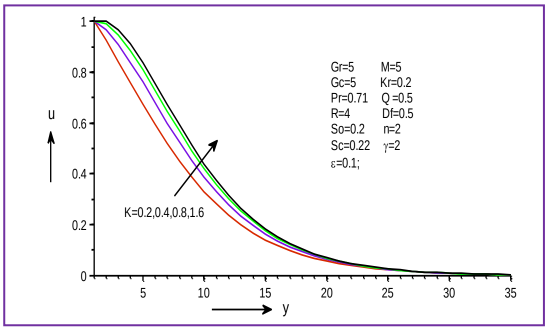

Figure 6: Impact of porosity parameter on velocity

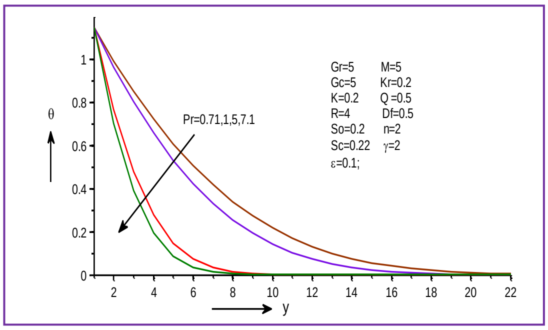

Figure 7: Impact of Prandtl number on temperature

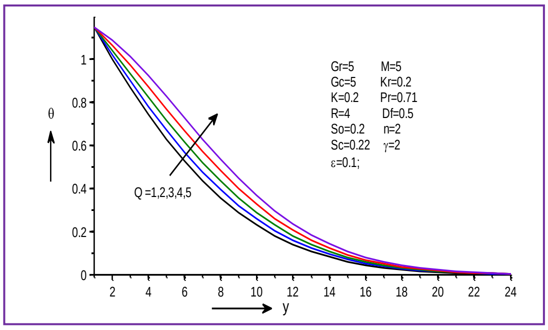

Figure 8: Impact of heat source on temperature

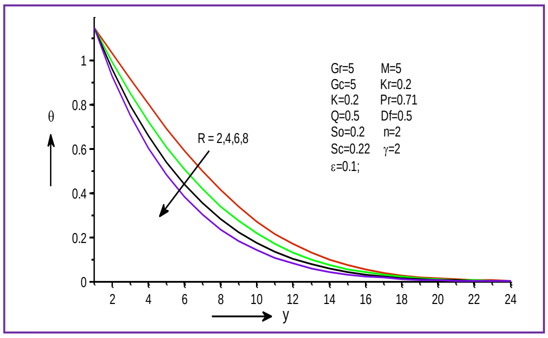

Figure 9: Impact of thermal radiation on temperature

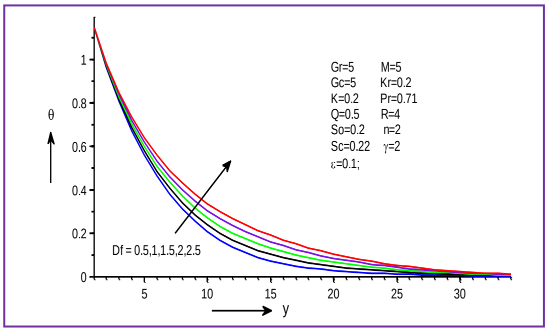

Figure 10: Impact of Dufour number on temperature

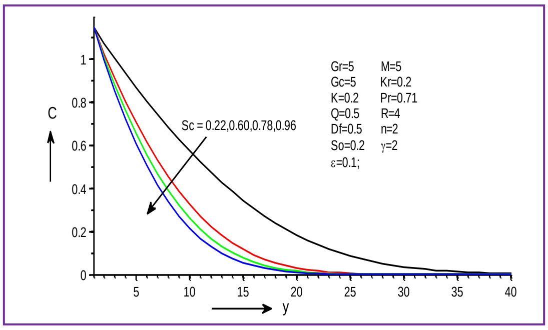

Figure 11: Impact of Schmidt number on concentration

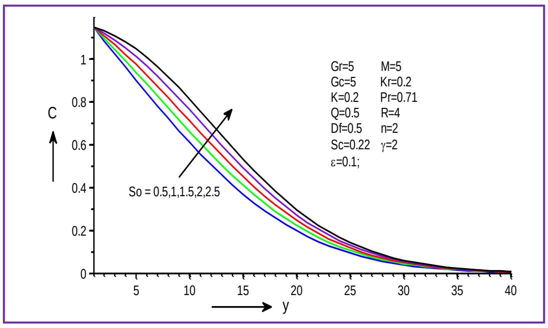

Figure 12: Impact of thermal diffusion on concentration

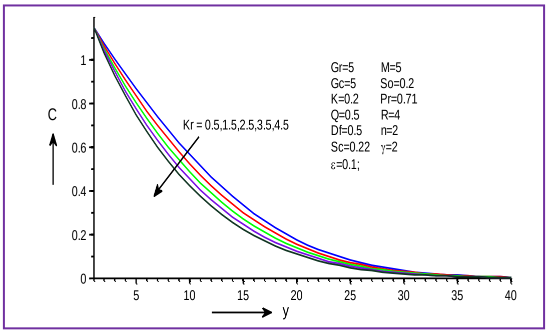

Figure 13: Impact of chemical reaction on concentration

Table 1 presents the numerical values of physical quantities namely, skin friction coefficient, Nusselt number and Sherwood number towards various flow controlling parameters i.e. Dufour effect parameter, heat source parameter, permeability parameter, Soret number, Schmidt number, Grashof number, modified Grashof number, Chemical reaction, Casson fluid parameter, Prandtl number and magnetic field. In particularly this table is used to study the effect of Dufour effect parameter, heat source parameter, chemical reaction parameter, Schmidt number and magnetic field on skin friction coefficient parameter. Physically, the negative value of skin friction coefficient means the amount of drag force offered by vertical porous plate to the fluid particles. In absolutely sense it is noticed that skin friction source as inciting nature towards Soret number, Grashof number, modified Grashof number, Casson fluid parameter, permeability parameter and Prandtl number. Dufour effect parameter and Prandtl number leads to increase the Nusselt number and decreases the Sherwood number. When chemical reaction parameter, Soret number and Schmidt number increases, Sherwood number is increased.

Table: 1 Numerical values for Skin friction, Nusselt number and Sherwood number for different values of parameters

Df	Q	Gr	Gc	γ	Pr	M	τ	Nu
0.2	0.1	10	5	0.5	0.7	0.2	-3.0959	0.2704
0.4							-3.3028	0.4659
0.6							-3.6956	0.6006
	0.2						-4.5626	0.0042
	0.4						-3.9068	0.0038
	0.6						-3.5039	0.0034
		1					-1.0154	0.2704
		5					-2.2066	0.2704
		10					-3.6948	0.2704
			1				-2.4358	0.2704
			5				-3.6948	0.2704
			10				-5.2687	0.2704
				0.2			-3.5263	0.2704
				0.4			-3.3401	0.2704
				0.6			-2.9108	0.2704
					0.7		-3.6947	0.2704
					1		-3.5810	0.3213
					7.1		-2.8084	0.8500
						1	-3.6945	0.2704
						3	-3.5972	0.2704
						5	-3.5045	0.2704

Table 2: Impact of chemical reaction, Soret number and Schmidt number on Sherwood number

Kr	So	Sc	Sh
0.2			0.5995
0.4			0.8391
0.6	0.6		0.9322
	0.8		2.5848
	1		2.8962
		0.22	2.1076
		0.60	2.5300
		0.78	3.2733

5. Conclusion:

The summarized points of this study can be stated as follows:

- The velocity of the fluid increases when the values of Grashof number, modified Grashof number and porosity parameter increased whereas it comes down in the case of magnetic parameter and Casson parameter.
- The temperature of the fluid enhances for increasing values of heat source parameter and Dufour number whereas a reverse trend is

found in the case of Prandtl number and radiation parameter.

- The influence of thermal diffusion leads to enhance and the existence of chemical reaction diminishes the species concentration.
- Dufour effect parameter and Prandtl number leads to increase the Nusselt number and decreases the Sherwood number.
- When chemical reaction parameter, Soret number and Schmidt number increases, Sherwood number is increased.

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