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ORIGINAL RESEARCH

Thermal and Thermo Diffusion Effects on Heat and Mass Transfer in a Viscous Couple Stress Fluid

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ABSTRACT

Thermal and thermo diffusion effect on viscous dissipating Couple stress fluid along a vertical plate has applications in various scientific and engineering domains particularly in petrochemical and metallurgical industries. This study aims to investigate the combined effects of thermal and thermo diffusion on the flow of heat and mass transfer in viscous couple stress fluid. The governing equations were transformed into coupled nonlinear ordinary differential equations using a suitable similarity variable. The resulting self-similar problems were solved by employing a shooting method embedded in MATLAB R2025a. The Nusselt number was found to increase with increase in the Soret number while it reduces as Dufour number increases. Sherwood number on the other hand decreases with an increase in the Soret number while it increases as Dufour number increases. Prandtl number causes a reduction in the fluid velocity and temperature. An increase in the values of Dufour number increases the velocity and temperature of the fluid, while it reduced the concentration. Higher values of the Soret number reduces the fluid velocity and temperature, but increased its concentration. Furthermore, enhancement in Eckert number Ec reduces the Nusselt number and increases the Sherwood number, while increment in the heat generation/absorption parameter increases the Nusselt number and reduces the Sherwood number. The embedded parameters have appreciable impact on the flow of heat and mass transport of the couple stress fluid.

Keywords: Couple stress fluid, Heat generation/absorption, Thermal diffusion, Thermo diffusion, Viscous dissipation

INTRODUCTION

Couple Stress Fluid is characterized by the complex rotational motion and interactions occurring at a microscale. It exhibits internal forces that lead to internal deformation. The fluid demonstrates a characteristic known as memory time scale or relaxation time (Bird et al., 2007). Furthermore,

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it has a wide range of applications across various fields, including biomedical engineering, industrial processes, etc. Based on these, Sreekala and Maruthi (2024) researched on thermal effects of a couple stress fluid flow in an elastic tube, they analyzed the effect of pliability on the peristaltic flow of a couple- stress fluid with nanoparticles in a cylindrical tube. The expressions for velocity and flux flow rate are determined by using homotopy perturbation method, in the process of long wave length and low Reynold's number approximations. Aamgeer et al., (2020) studied couple stress fluid flow due to slow steady oscillations of a permeable sphere, while Chandrashekhar (2023) presented couple stress fluid flow through a porous media past a solid sphere. Devakar et al., (2014) worked on analytical solution of Couple stress fluid flow with slip boundary condition. Laplace and Fourier transforms were used to establish the exact solutions of Stokes' first and second problems for an incompressible couple stress fluid in the work of Imran and Yousra (2019). A work on the rheology of peristaltic flow of couple stress fluid in an inclined tube was done by Abbas et al., (2022). Baba and Suripeddi (2024) studied entropy generation in the flow of two immiscible fluids (Couple-stress fluid and a viscous liquid) through a vertical wavy porous space. Kumar and Singh (2021) investigated stability within a Couple-stress magneto-fluid, while Siva et al., (2022) investigated the transient electromagnetohydrodynamic (EMHD) flow of a Couple stress fluid in a narrow/micro-fluidic channel. Opanuga et al., (2017) worked on Second law analysis of a reactive MHD Couple stress fluid through a porous medium. Peristalsis transport of MHD Couple stress fluid through a porous medium under the influence of heat transfer and slip effect was examined by Sankad and Nagathan (2017). Zahir et al., (2019) studied the Couple stress convective micropolar fluid flow in a hall MHD generator system using the Homotopy analysis method, and found that the primary velocity reduces with greater magnetic parameter, local Grashof number, hall parameter and Couple stress parameter. Nadeem and Akbar (2009) studied peristaltic flow of a Couple stress fluid with variable viscosity in an asymmetric channel. Rahmat et al., (2019) worked on peristaltic blood flow of Couple stress fluid suspended with nanoparticles under the influence of chemical reaction and activation energy. Suman and Shalini (2024) examined the effect of chemical reaction on MHD flow of Couple stress fluid over a stretchable inclined cylinder. Suresha et al., (2021) studied magnetized Couple stress fluid flow past a vertical cylinder under thermal radiation and viscous dissipation effect. Vinod et al., (2019) analyzed the effect of internal heat source on magneto-stationary convection of Couple stress fluid

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under magnetic field modulation. The effect of magnetic nanoparticles on Couple stress fluid flow between two parallel squeezing and expanding surfaces was examined in the study by Mahesh et al., (2020). The work of Olajuwon and Oahimire (2013) looked at the effect of thermal diffusion and chemical reaction on heat and mass transfer in an MHD micro-polar fluid with heat generation, while Makinde (2010) studied MHD heat and mass transfer over a moving vertical plate with a convective surface boundary condition. Norfifah et al., (2010) looked at flow and heat transfer over an unsteady stretching sheet in a micropolar fluid. Vajravelu et al., (2016) considered the influence of hall current on MHD flow and heat transfer over a slender stretching sheet in the presence of variable fluid properties. Ganeswara and Bhaska (2010) worked on Soret, Dufour, and viscous dissipation effects on steady MHD free convection flow past a semi- infinite moving vertical plate in a porous medium. Most of the previous works have not considered the combined effect of viscous dissipation and heat generation/absorption on the flow of Couple stress fluid over a stretching plate. But they occur in many chemical and mechanical application processes.

This study aims to investigates the impact of thermal and thermo diffusion on heat and mass transfer in a viscous couple stress fluid with heat generation and absorption along a vertical plate. The work of Srinivasacharya and Kaladhar (2011a) was extended to include the heat generation/absorption and viscous dissipation. The shooting method in MATLAB R2025a was employed to solve the nonlinear problem. The effects of couple stress fluid parameter, Soret and Dufour numbers are examined and are displayed through graphs. The results obtained are compared with relevant results in the existing literature.

MATERIALS AND METHODS

Consider a two-dimensional mixed convective heat and mass transfer along a semi-infinite vertical plate embedded in a free stream of couple stress fluid with velocity u_∞. Choose the coordinate system such that x-axis is along the vertical plate and y-axis normal to the plate. The plate is maintained at a uniform wall temperature T_w and concentration C_w. These values are assumed to be greater than the ambient temperature T_∞ and concentration C_∞ at any arbitrary reference point in the medium (inside the boundary layer). Figure 1 below shows the diagrammatic representation of the model.

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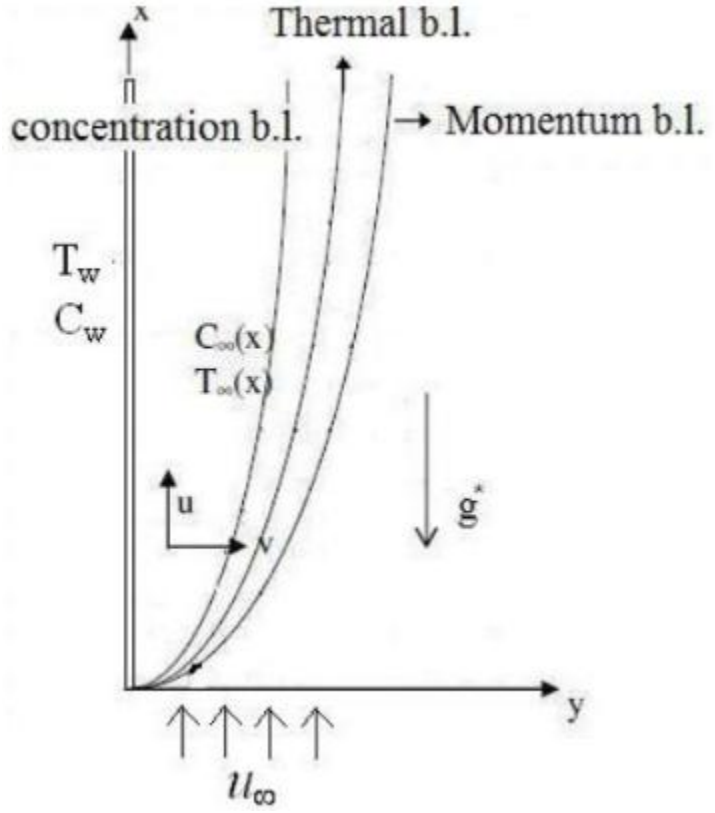


Figure 1: Schematic of the model

Viscous dissipation and heat generation/absorption are incorporated into the governing equations of the flow, heat and mass transfer of Srinivasacharya and Kaladhar (2011a). The modified model is given as:

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0 \tag{1}$$

$$u\frac{\partial}{\partial x}+v\frac{\partial u}{\partial y}=v\frac{\partial^2 u}{\partial y^2}-\frac{\eta_1\partial^4 u}{\rho\partial y^4}+g\left[\beta_T\left(T-T_\infty\right)+\beta_C\left(C-C_\infty\right)\right] \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{DK_T}{\rho C_P}\frac{\partial^2 C}{\partial y^2}+\frac{\mu}{\rho C_P}\left(\frac{\partial u}{\partial y}\right)^2+\frac{\theta_0}{\rho C\rho}\left(T-T_\infty\right) \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}+\frac{DK_T}{T_m}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

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where u, v are the velocity components in the x and y directions respectively. μ is the coefficient of thermal viscosity, g is the acceleration due to gravity, ρ is the density, β_T is the coefficient of thermal expansion, β_C is the coefficient of solutal expansion, α is the thermal diffusivity, D is the mass diffusivity , C_p is the specific heat capacity, C_∞ is the ambient concentration, T_m is the mean fluid temperature , K_T is the thermal diffusion ratio and η_1 is the couple stress fluid term. Energy equation (3) has the Dufour (diffusion- thermo) effect, and heat generation/absorption effect while the concentration equation (4) has the soret (thermal-diffusion) effect, respectively.

The boundary conditions are

$$u = 0, v = 0, C = C_w, V_x = U_{y,} \qquad \text{at} \qquad y = 0 \tag{5}$$

$$u \to u_\infty, T \to T_\infty, C \to C_\infty, \qquad \text{as} \qquad y \to 0 \tag{6}$$

The subscript w and ∞ indicate the condition at the wall and at the outer edge of the boundary layer respectively.

In view of the continuity equation (1), we introduce the stream function by

$$u = \frac{\partial \psi}{\partial y}, \quad v = -\frac{\partial \psi}{\partial y} \tag{7}$$

Substituting Equation (7) in Equations (2) - (4) and then using the following local similarity transformations

$$\eta = \frac{y}{x}\mathrm{Re}_x^{\frac{1}{2}}, \; u = u_\infty f'(\eta), \quad v = -\frac{1}{2}\sqrt{\frac{u_x v}{x}}\left[f(\eta) - \eta f'(\eta)\right], \; \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \quad \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty} \tag{8}$$

After the similarity transformation of equation (1) - (4) and boundary conditions (5) and (6), the following nonlinear system differential equation (9) – (11) are obtained:

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$$f''' + \frac{1}{2} f f'' + g_s \theta + g_c \phi - Caf^{v} = 0 \tag{9}$$

$$\theta'' + \frac{1}{2} \Pr f \theta' + D_f \Pr \phi'' + \Pr Ec \left(f''\right)^2 + \Pr Q\theta = 0 \tag{10}$$

$$\phi'' + \frac{1}{2} S_c f \phi' + S_c S_r \phi'' = 0 \tag{11}$$

Boundary conditions (5) and (6) in terms of f, θ and ϕ becomes

$$\left.\begin{array}{lllll} f(0)=0 & f'(0)=0 & f''(0)=0 & \theta(0)=1 & \phi(0)=1 \\ f'(\infty)=1 & f''(\infty)=0 & \theta(\infty)=0 & \phi(\infty)=0 & \end{array}\right\} \tag{12}$$

where $S_c = \frac{\upsilon}{D}$ is the Schmidt number, $\Pr = \frac{\upsilon}{\alpha}$ is the Prandtl number, $\mathrm{Re}_x = \frac{u_\infty x}{\upsilon}$ is the local Reynolds number, $S_r = \frac{DK_T(T_w - T_\infty)}{\upsilon T_m (C_w - C_\infty)}$ is the Soret number, $D_f = \frac{DK_T(C_w - C_\infty)}{\upsilon C_S c_p (T_w - T_\infty)}$ is the Dufour number, $Gr_x = \frac{g\beta_T (T_w - T_\infty) x^3}{\upsilon^2}$ is the local temperature Grashof number, $Gc_x = \frac{g\beta_C (C_w - C_\infty) x^3}{\upsilon^2}$ is the local mass Grashof number, $C_\alpha = \frac{\eta_1}{\mu x^2} \mathrm{Re}_x$ is the local couple stress parameter, $g_s = \frac{Gr_x}{\mathrm{Re}_x^{\,2}}$ is the temperature buoyancy parameter and $g_c = \frac{Gc_x}{\mathrm{Re}_x^{\,2}}$ is the mass buoyancy parameter, $\alpha = \frac{k}{\rho c_p}$ is the thermal diffusivity number, $\upsilon = \frac{\mu}{\rho}$ is the kinematic viscosity, $Ec = \frac{u_\infty{}^4}{c_p (T_w - T_\infty)}$ is the Eckert number, $Q = \frac{Q_0}{u_\infty \rho c_p}$ is the heat generation/absorption parameter, $\lambda = \frac{u_\infty \mu^2}{\rho k (T_w - T_\infty)}$ is the viscous dissipation parameter, local Nusselt number is $Nu_x = \frac{x q_w}{k(T_w - T_\infty)}$, and local Sherwood number is $Sh_x = \frac{x q_w}{D(C_w - C_\infty)}$.

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Method of solution

The governing equations (9) – (11) along sides their boundaries conditions in equation (12) are solved by employing shooting method embedded in MATLAB R2025a computational software. From equations (9) - (11) we have equations (13) - (15)

$$f^{v} = \frac{1}{C_a}\left(f''' + \frac{1}{2} ff'' + g_s\theta + g_c\phi \right) \tag{13}$$

$$\theta'' = -\frac{\Pr}{\left(1 - \Pr D_f S_c S_r\right)}\left(\frac{1}{2} f\theta' - \frac{1}{2} D_f S_c f\phi' + Ecf''^2 + Q\theta \right) \tag{14}$$

$$\phi'' = S_c C_r - \frac{1}{2} S_c f\phi' + \frac{S_c S_r \Pr}{\left(1 - \Pr D_f S_c S_r\right)}\left(\frac{1}{2} f\theta' - \frac{1}{2} D_f S_c f\phi' + Ecf''^2 + Q\theta \right) \tag{15}$$

Let $f = y_1,\quad f' = y_2,\quad f'' = y_3,\quad f''' = y_4.\quad f^{iv} = y_5,\quad f^{v} = y_5'$ (16)

$\theta = y_6 \qquad \theta' = y_7 \qquad \theta'' = y_7' \qquad \phi = y_8 \qquad \phi' = y_9 \qquad \phi'' = y_9'$ (17)

By applying transformation in equations (13) - (17) to equations (9) - (12), we have the system of first order differential equations in (18) – (20) and the new boundary conditions in equation (21).

$$y_5' = \frac{1}{C_a}\left(y_4 + \frac{1}{2} y_1 y_3 + g_s y_6 + g_c y_8 \right) \tag{18}$$

$$y_7' = -\frac{\Pr}{\left(1 - \Pr D_f S_c S_r\right)}\left(\frac{1}{2} y_1 y_7 - \frac{1}{2} D_f S_c y_1 y_9 + Ecy_3^{\,2} + Qy_6 \right) \tag{19}$$

$$\phi'' = -\frac{1}{2} S_c y_1 y_9 + \frac{S_c S_r \Pr}{\left(1 - \Pr D_f S_c S_r\right)}\left(\frac{1}{2} y_1 y_7 - \frac{1}{2} D_f S_c y_1 y_9 + Ecy_3^{\,2} + Qy_6 \right) \tag{20}$$

$$\left.\begin{array}{lllll} y_1(0) = 0 & y_2(0) = 0 & y_3(0) = 0 & y_6(0) = 1 & y_8(0) = 1 \\ y_2(\infty) = 1 & y_3(\infty) = 0 & y_6(\infty) = 0 & y_8(\infty) = 0 & \end{array}\right\} \tag{21}$$

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RESULTS

The results obtained after solving the dimensionless equations by BVP4C method in MATLAB R2025a, are well presented in the tables and the graphs which shows the impact of various pertinent parameters on each distribution. The accuracy of our current results is validated in Table 1 by setting the Eckert number and the heat generation/absorption parameter to zero, solving, and comparing the results with that of Srinivasacharya and Kaladhar (2011a). This is because when the Eckert number and the heat generation/absorption parameter are set to zero, the model becomes exactly as that of Srinivasacharya and Kaladhar (2011).

Table 2 provides computed values of the Nusselt and Sherwood numbers when the values of the various parameters are varied. The velocity, temperature, and concentration profiles of the fluid are represented by Figures 2 to 17 below.

Table 1: Validation of the result for different values D_f and S_r of when

$\Pr = 0.71, C_\alpha = 1.00, S_c = 0.71, g_s = 1.00, g_c = 0.10, Q = 0, Ec = 0$

D_f	S_r	Srinivasacharya and Kaladhar (2011)		This present study	
		Nu_x	Sh_x	Nu_x	Sh_x
2.00	0.03	0.2610	0.2256	0.2610	0.2256
1.00	0.06	0.2868	0.2220	0.2868	0.2220
0.60	0.10	0.2966	0.2198	0.2966	0.2198
0.40	0.15	0.3014	0.2179	0.3014	0.2179
0.15	0.40	0.3074	0.2101	0.3074	0.2101
0.10	0.60	0.3087	0.2043	0.3087	0.2043
0.06	1.00	0.3098	0.1928	0.3098	0.1928
0.03	2.00	0.3111	0.1642	0.3111	0.1642

Table 2: Computational values of Nusselt and Sherwood numbers for the couple stress fluid

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D_f	S_r	Pr	Q	Ec	S_c	g_S	g_c	C_α	Nu_x	Sh_x
0.05	0.50	0.71	0.05	0.2	0.22	1.0	0.1	0.2	0.2380	0.2350
1.00									0.1957	0.2427
2.00									0.1421	0.2518
0.05	1.00								0.2380	0.2289
	2.00								0.2380	0.2169
	0.50	2.00							0.2576	0.2253
		3.00							0.2471	0.2241
		0.71	0.10						0.1940	0.2408
			0.50						0.3791	0.1790
			0.05	0.4					0.1521	0.2458
				0.6					0.0547	0.2579
				0.2	0.40				0.2368	0.2827
					0.60				0.2357	0.3268
					0.22	2.00			0.2356	0.2537
						3.00			0.1846	0.2748
						1.0	0.2		0.2369	0.2384
							0.5		0.2303	0.2482
							0.1	0.3	0.2364	0.2313
								0.5	0.2328	0.2261

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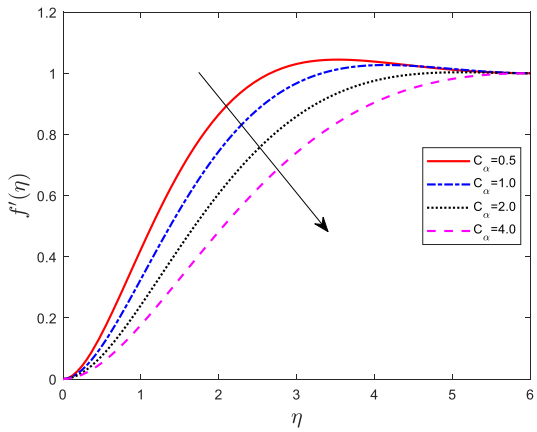


Figure 2: Effect of Couple stress parameter C_α on velocity $f'(\eta)$

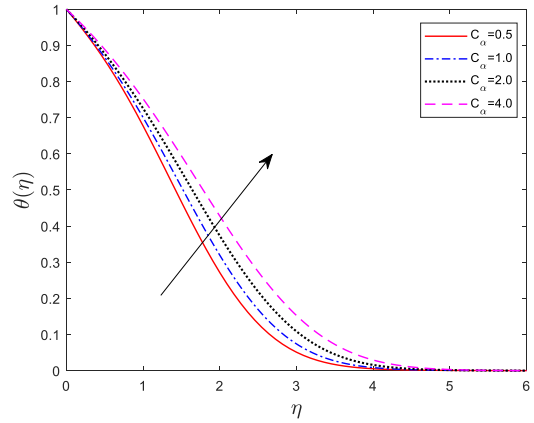


Figure 3: Effect of Couple stress parameter (C_α) on temperature $\theta(\eta)$

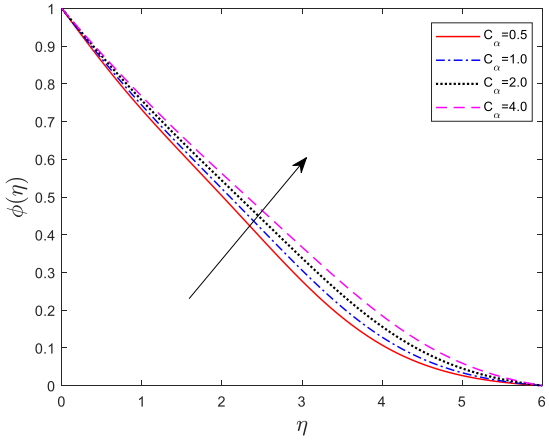


Figure 4: Effect of Couple stress parameter (C_α) on concentration ϕ_η

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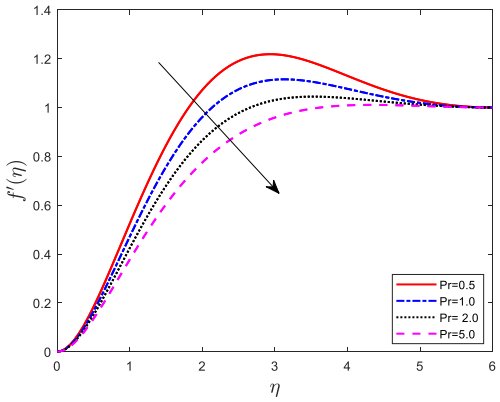


Figure 5: Effect of prandlt (p_r) on velocity $f'(\eta)$

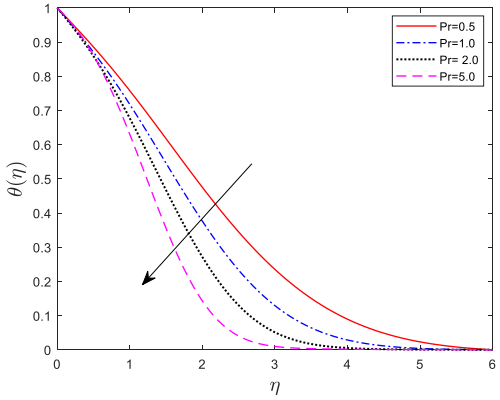


Figure 6: Effect of Prandlt $_r(\mathrm{Pr})$ on temperature

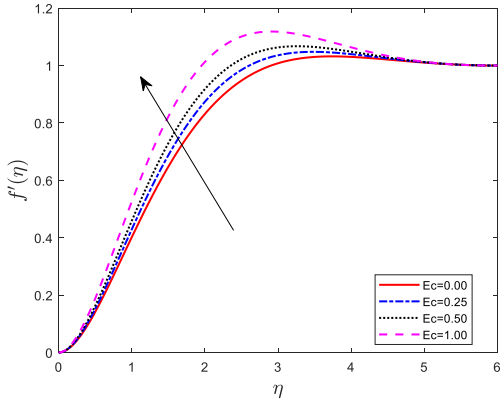


Figure 7: Effect of Eckect number Ec on velocity $f'(\eta)$

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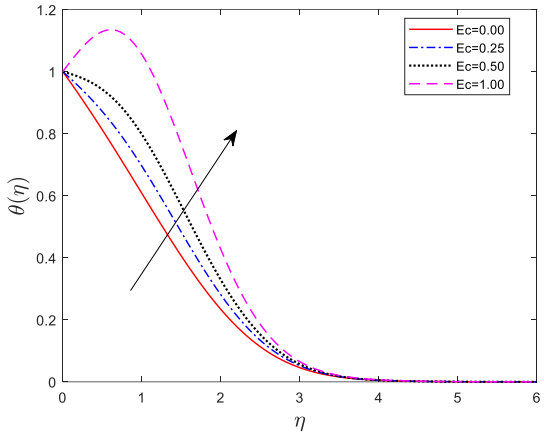


Figure 8: Effect of Eckect number Ec on temperature $\theta(\eta)$

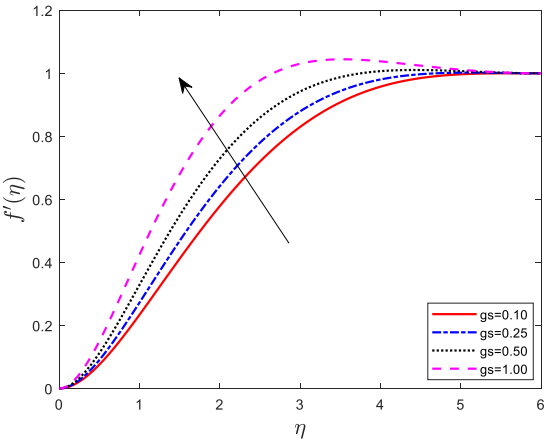


Figure 9: Effect of Temperature buoyancy (g_s) on velocity $f'(\eta)$

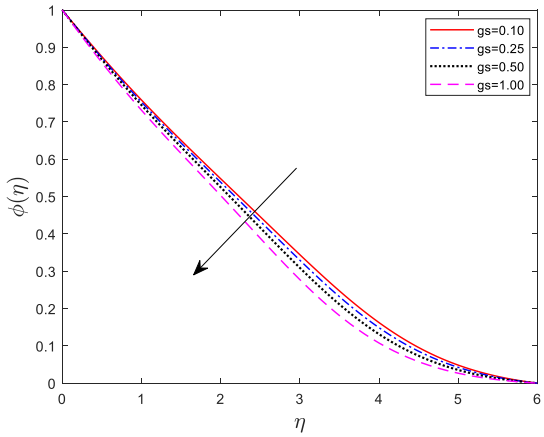


Figure 10: Effect of Temperature buoyancy (g_s) on concentration $\phi(\eta)$

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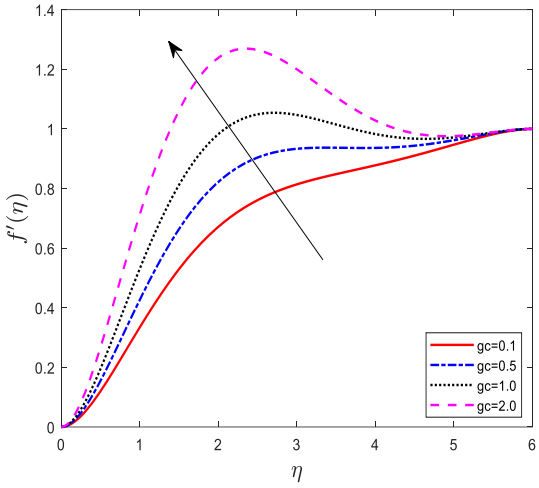


Figure 11: Effect of Mass buoyancy (g_c) on velocity $f'(\eta)$

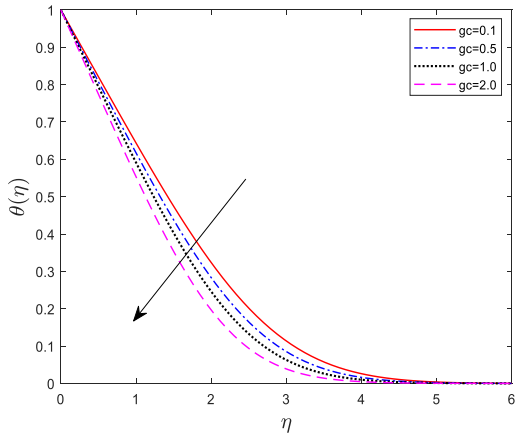
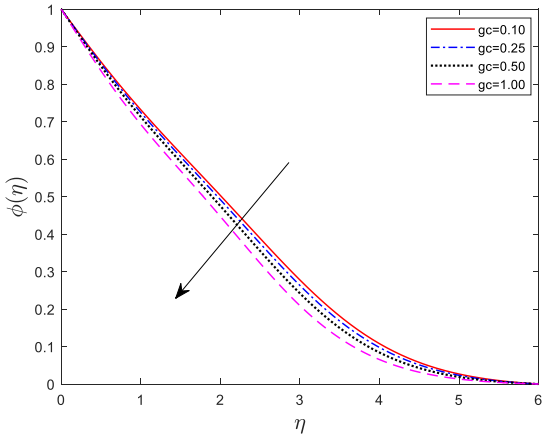


Figure 12: Effect of Mass buoyancy (g_c) on temperature



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Figure 13: Effect of Mass bouyancy (g_c) on oncentration $\phi(\eta)$

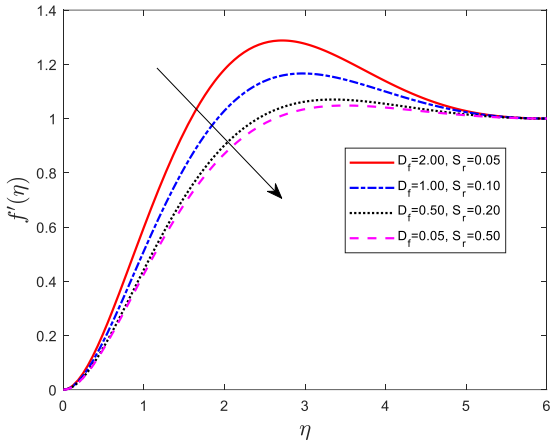


Figure 14: Effect of Dufour number (D_f) and Soret S_r number on velocity $f'(\eta)$

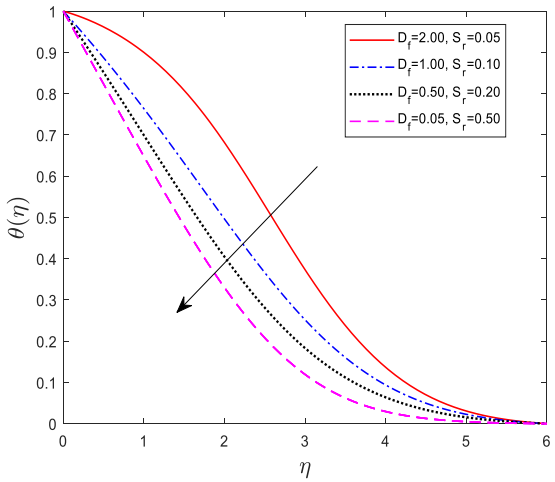


Figure 15: Effect of Dufour number (D_f) and Soret number S_r on temperature $\theta(\eta)$

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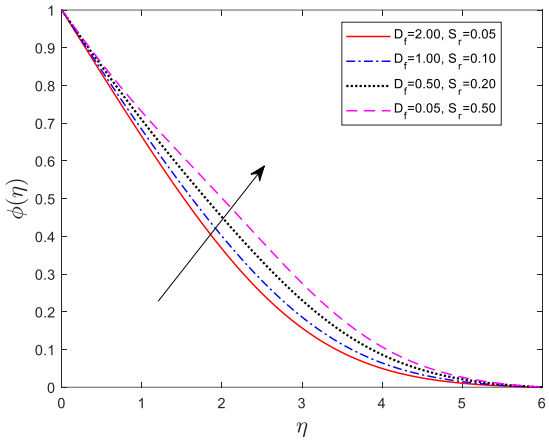


Figure 16: Effect of Dufour number (D_f) and Soret S_r number on concentration $\phi(\eta)$

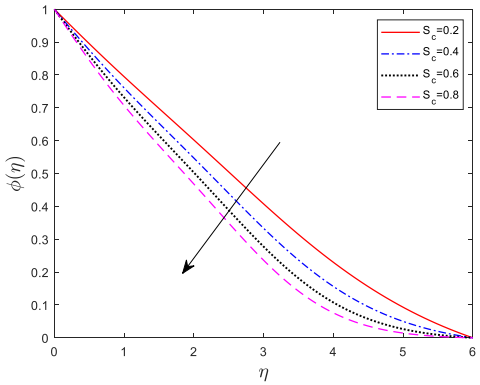


Figure 17: Effect of Schmidt number (S_c) on concentration $\phi(\eta)$

DISCUSSION

The results indicate that an increase in the couple stress parameter leads to a reduction in fluid velocity near the wall due to enhanced resistance to deformation, while velocity increases further away from the wall. Conversely, temperature and concentration profiles increase with higher couple stress parameter, indicating enhanced energy and mass transport due to intensified microstructural interactions within the fluid.

The observed decrease in both velocity and temperature profiles with increasing Prandtl number is attributed to the fact that fluids with higher Prandtl numbers possess lower thermal diffusivity and relatively higher viscosity. This leads to a reduction in both thermal and momentum boundary layer thicknesses, thereby suppressing fluid motion and heat transfer within the boundary layer

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(Schlichting and Gersten, 2017). Similarly, an increase in the Eckert number results in a reduction in the velocity profile, which may be associated with enhanced viscous dissipation effects that convert kinetic energy into internal energy, thereby influencing flow resistance (Oyelakin et al., 2021; Hayat et al., 2018).

There was also an increase in the temperature buoyancy parameter which enhanced the velocity distribution due to stronger buoyancy forces arising from thermal gradients. However, the concentration profile decreased as intensified fluid motion promoted rapid mixing and transport, thereby reducing concentration levels near the boundary layer (Srinivasacharya and Kaladhar, 2011b; Makinde, 2010).

It was also observed that increasing the mass buoyancy parameter enhanced the velocity near the plate due to increased buoyancy-driven flow. However, the velocity decreased farther away from the wall as the boundary layer developed. Meanwhile, both temperature and concentration profiles decreased, and this can be attributed to improved convective transport and reduced diffusion effects within the fluid (Bestman, 2013; Makinde, 2010).

An increase in the Dufour number led to an enhancement in both velocity and temperature profiles due to the additional heat flux generated by concentration gradients (diffusion-thermo effect). Conversely, the concentration profile decreased as thermal energy increased. On the other hand, increasing the Soret number reduced both velocity and temperature profiles due to increased resistance to flow and redistribution of thermal energy. However, the concentration profile increased because temperature gradients enhance mass diffusion (Bejan, 2013; Makinde, 2010).

An increase in the Schmidt number resulted in a decrease in concentration profiles. This is because higher Schmidt numbers correspond to lower mass diffusivity, which restricts species diffusion and causes the concentration boundary layer to become thinner, thereby reducing overall concentration distribution within the fluid (Schlichting and Gersten, 2017).

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CONCLUSION

This research examined the effect of thermophoresis properties in convective flow of couple stress fluid past a vertical plate. The nonlinear ordinary differential equations were numerically solved by employing the shooting method embedded in MATLAB computational software. The following statements can be deduced from this study:

i. An increase in temperature buoyancy and mass buoyancy enhanced the velocity but reduced the temperature profile and concentration profile.
ii. Enhancement of Prandtl number was seen to reduce the velocity profile and temperature profile.
iii. An increment in the value of Couple stress parameter declined the velocity profile at the wall of the plate and increased speedily far from the wall, while temperature and concentration are enhancement.
iv. An increase in Schmidt number was observed to reduce the concentration.
v. Increase in Eckert number and Dufour number reduced Nusselt number and enhance Sherwood number, while increase in heat generation /absorption increased Nusselt number and reduced Sherwood number.

AUTHORS' CONTRIBUTION

OBI conceptualized the study. AF designed the study. SLO performed the mathematical computations. FO discussed the computational results. IMO prepared the first draft of the manuscript, reviewed by RMT and ABU. All authors contributed to the development of the final manuscript and approved its submission.

CONFLICT OF INTEREST

None.

ETHICS APPROVAL AND INFORMED CONSENT

This study did not involve human or animal subjects. Therefore, ethical consideration was not applicable.

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