

The Impact of Heat Source/Sink on Non-Linear Free Convection Fluid Flow with Chemical Reaction

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ABSTRACT

This research investigates how heat sources and sinks influence non-linear free convection fluid flow when a chemical reaction is present. The model underlying this study integrates non-linear density variations based on both concentration and temperature, providing a detailed framework for analyzing complex fluid behaviors. To solve the governing equations for non-dimensional temperature, concentration, and velocity, the method of undetermined coefficients is employed, allowing precise calculation of these variables under various conditions. The effects of numerous physical parameters on heat and mass transfer rates and the velocity field are illustrated through a series of graphs and tables. The findings reveal that an increase in the Prandtl number, as well as higher suction parameters, leads to a reduction in temperature within the fluid. Furthermore, the velocity of the fluid increases with higher values of the Grashof number (Gr) and modified Grashof number (Gc), which represent the relative influences of buoyancy forces due to temperature and concentration gradients. However, the velocity decreases when the chemical reaction parameter is elevated, indicating the complex interaction between reaction rates and flow dynamics. Additionally, the study examines non-dimensional distributions of velocity, temperature, and concentration to demonstrate the impact of influential parameters, offering insights into how fluid properties adjust under different thermal and chemical conditions. The skin friction coefficient, representing resistance to fluid motion, and the local Nusselt number, indicating heat transfer efficiency, are also analyzed. A key observation is that drag forces, which oppose fluid movement, tend to decrease as the Prandtl number and heat source/sink levels increase, highlighting the moderating effects of these parameters. Overall, this research has practical implications, particularly in the efficient design of heating and cooling systems for electronic devices. By advancing the understanding of heat and mass transfer dynamics in non-linear convection flows, the study builds on previous research, offering enhanced methodologies and insights that contribute to improving thermal management in advanced engineering applications.

Keywords: Heat source/sink, chemical reaction, non-linear free convection

NOMENCLATURE

λ_1 co-efficient of non-linear change in density with respect to temperature parameter
 λ_2 co-efficient of non-linear change in density with respect to concentration parameter
 C non-dimension concentration
 C dimension concentration
 C'_w concentration of the fluids close to porous plate
 C'_∞ concentration of the fluids at a distance from the porous plate
 g acceleration
 Gc mass Grashof number
 Gr thermal Grashof number
 K chemical reaction in non-dimension parameter
 k_e chemical reaction in dimension form
 k fluids thermal conductivity

Nu Nusselt number
 Pr non-dimension Prandtl number
 Sc non-dimension Schmidt number
 T non-dimension temperature
 T' dimension temperature
 T'_w temperature of the fluids close to the porous plate
 T'_∞ temperature of the fluids at a distance from the porous plate
 U non-dimension velocity
 u_w velocity of the plate
 V_∞ injection/suction parameter
 x vertical porous plate along the x
 y vertical porous plate normal the y
 Y non-dimension porous plate normal to Y
 d heat source/sink parameter

GREEK SYMBOLS

α thermal diffusivity
 β_0, β_1 thermal expansion coefficient
 β_0^*, β_1^* concentration expansion coefficient

τ non-dimension skin friction
 ν kinematic viscosity

1.0 INTRODUCTION

Because fluid flow involving chemical reactions has important applications in engineering, science, and industry, such as cooling mechanisms in nuclear plants, electronics, microchips, petroleum refining, atomic processes, and refrigeration, researchers have studied it in great detail. In fluid flows, chemical reactions can be either generative, increasing the concentration of fluid species, or destructive, decreasing the concentration of fluid species.

(Ganesan and Rani, 2000) and Rani et al. (2013) found that generative chemical reactions decrease velocity and concentration while raising the temperature. Deka and Chaliha (2012) observed that chemical reactions slow down fluid velocity and increase concentration, while Paul and Deka (2013) reported that chemical reactions, conversely, increase velocity. Studies by (Kumar and Bansal, 2019), and Kumar and Rizvi (2021) revealed that chemical reactions reduce velocity in fluid flow, whereas Chitra and Kavitha (2020) found that chemical reactions enhance concentration levels. Arifuzzaman et al. (2019) demonstrated that destructive reactions lower concentration, while Rana et al. (2021) highlighted that exothermic reactions release heat in Williamson fluids, whereas endothermic reactions absorb heat.

Cheng and Minkowczyk (2023) examined linear density change concerning temperature in their analysis of free convection close to a vertical plate in porosity to mimic heat transfer from a dyke. Using an implicit finite difference scheme, Usman et al. (2023) solved the effects of injection and suction on free convection through a vertical porous channel with constant heat and simultaneous thermal radiation and chemical reactions. They discovered that non-dimensional velocity and concentration decrease with destructive reactions and increase with generative reactions.

Kumar and Singh (2016) explored heat sources and sinks in natural convection, showing that an increase in heat sources raises velocity, while heat sinks reduce it. Muthucumaraswamy (2002) studied chemical reactions near a moving vertical surface under heat and mass transfer conditions with suction injection, and Anwar et al. (2024) examined the influence of heat source/sink and radiation on the flux of unstable nanofluids driven by MHD buoyancy over a moving vertical porous plate.

Additionally, Jha et al. (2015), highlight that the intensity of a heat source is pivotal in determining

temperature, flow velocity, and substance concentration within a vertical tube. They found higher heat source intensities increase temperature and flow velocity while reducing concentration. Kumar et al. (2018) show that the heat source size and Rayleigh number significantly impact natural convection, with larger heat sources and higher Rayleigh numbers enhancing heat transfer and volumetric flow rates. Van den Berg et al. (2001) revealed that variable thermal conductivity can slow the cooling rate in a constant viscosity mantle model.

According to Sharma (2023), heat conduction rises when the Prandtl number falls. Taking temperature, concentration gradients, and chemical reactions into account, Muthucumaraswamy and Ganesan (2013) examined unsteady free convection flow via a vertical plate and concluded that increasing the chemical reaction parameter decreases velocity. Similar studies were conducted by Nabwey et al. (2022), who consider chemical processes when examining combined heat and mass transfer in free and forced convection flow with uniform wall temperature and concentration.

Chamkha (2011) examined fully developed and developing natural convection flows in vertical flat plates with asymmetric heating. Idowu et al. (2020) analyzed heat generation and absorption effects in MHD Casson fluid natural convection flow, finding that these parameters increase velocity. Shah et al. (2022) observed that electron movement actively deteriorates composite oxide materials. Ganga et al. (2015) used a partially heated circular wavy enclosure to study the behavior of Casson fluid flow.

Heat creation or absorption in fluid flows is essential in many physical processes, such as cooling applications, combustion, nuclear waste storage, and food storage. In their study, Swain et al. (2019) examined how heat-generating chemical processes affected natural convection MHD flow over a moving vertical plate. They discovered that the flow velocity was unaffected by the heat source. The effects of a heat source/sink on magnetized Williamson fluid flow were examined by Rehman et al. (2023), who found that higher heat generation results in higher temperatures.

Agrawal et al. (2023) examined the thermal performance of nanofluid flow past a vertical surface. Slimani et al. (2020) analyzed energy transfer in an

Al_2O_3 nanofluid within a conical enclosure. Kumar and Singh (2016) investigated the role of heat sources and sinks in free convective flow, concluding that velocity increases with heat source intensity, while the opposite occurs with a heat sink. A related study by (Jha and Sarki, 2018), (Jha and Sarki, 2019) investigated nonlinear density variation in the presence of Soret and Dufour effects.

Chen and Weng (2009) studied velocity-slip and temperature-jump effects on natural convection flow, concluding that the temperature jump, influenced by rarefaction and fluid-wall interaction, is vital in slip-flow natural convection. Fluid injection and suction in flow formations are also essential in aircraft design and spacecraft stability.

This study builds upon the work of Muthucumaraswamy (2002) by introducing additional factors, specifically the effects of non-linear density variation about both concentration and temperature parameters, along with the influence of heat sources and sinks. By incorporating these elements, the research seeks to provide a more comprehensive understanding of fluid dynamics, particularly focusing on how non-linear density variations affect heat and mass transfer

processes in convection flows. The expanded model aims to enhance accuracy in predicting fluid behavior under complex conditions, with applications in fields where precise control of temperature and concentration is essential, such as advanced cooling systems and chemical processing.

2.0 MATHEMATICAL ANALYSIS

This study takes into account some important variables, including the presence of a heat source or sink, non-linear change in density, concentration, and temperature parameters, and chemical reaction. The study examines the steady, fully developed free convection and mass transfer flow close to an infinitely extending, vertically moving porous plate. The convective and mass transfer processes are facilitated by the analysis's assumption of a sizable concentration and temperature differential between the fluid distant from the porous plate and the plate itself. The coordinate system is defined for the mathematical formulation with the y -direction perpendicular to the vertically moving porous plate and the x -direction aligned along it. Figure 1 shows a schematic illustration of this flow configuration, emphasizing the fluid velocity, plate setup, and pertinent parameters.

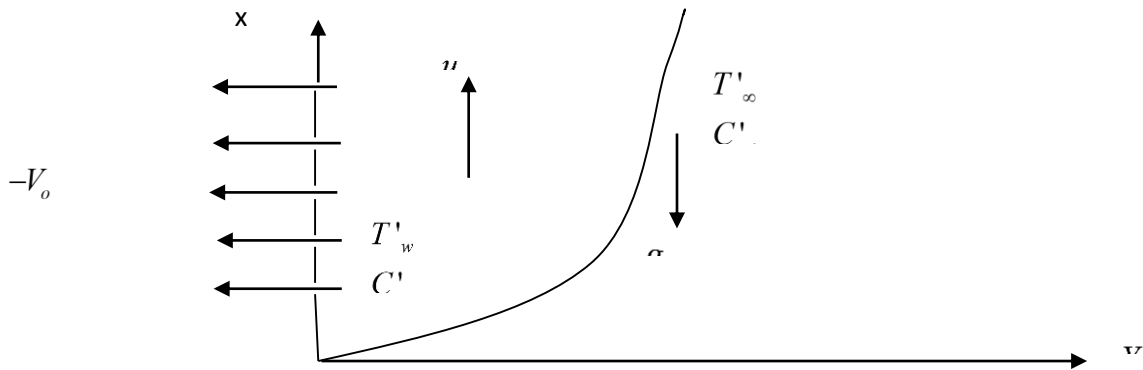


Figure 1. Flow configuration

$$-V_0 \frac{du}{dy} = g \left[\beta_0(T^I - T_\infty^I) + \beta_1(T^I - T_\infty^I)^2 + \beta_0^*(C^I - C_\infty^I) + \beta_1^*(C^I - C_\infty^I)^2 + v \frac{d^2 u}{dy^2} \right] \quad (1)$$

$$-v_0 \frac{dT^I}{dy} = \alpha \frac{d^2 T^I}{dy^2} + \frac{q_0(T^I - T_\infty^I)}{\rho C P} T^I \quad (2)$$

$$-v_0 \frac{dC^I}{dy} = \delta \frac{d^2 C^I}{dy^2} - k_e(C^I - C_\infty^I) \quad (3)$$

The dimensional boundary conditions are:

$$\left. \begin{aligned} u = u_w, T^I = T_w^I, C^I = C_w^I \text{ at } y = 0 \\ u \rightarrow 0, T^I \rightarrow T_w^I, C^I \rightarrow C_w^I \text{ as } y \rightarrow \infty \end{aligned} \right\} \quad (4)$$

Introducing the dimensionless quantities as:

$$\left. \begin{aligned} Y = \frac{yV_0}{v}, \quad Pr = \frac{v}{\alpha}, \quad Sc = \frac{v}{d}, \quad U = \frac{u}{u_w}, \quad C = \frac{C^I - C_\infty^I}{C_w^I - C_\infty^I}, \quad T = \frac{T^I - T_\infty^I}{T_w^I - T_\infty^I}, \\ K = \frac{k_e \alpha}{V_0^2}, \quad C = \frac{C^I - C_\infty^I}{C_w^I - C_\infty^I}, \quad T = \frac{T^I - T_\infty^I}{T_w^I - T_\infty^I}, \quad K = \frac{k_e \alpha}{V_0^2}, \quad \lambda_2 = \frac{\beta_1^*}{\beta_0^*} (C_w^I - C_\infty^I), \\ Gr = \frac{g\beta_0^* v (T_w^I - T_\infty^I)}{V_0^2 u_w}, \quad Gc = \frac{g\beta_0 v (C_w^I - C_\infty^I)}{V_0^2 u_w}, \quad \lambda_1 = \frac{\beta_1}{\beta_0} (T_w^I - T_\infty^I), \quad d = \frac{Q_0 (T_w^I - T_\infty^I)}{\rho CP} \end{aligned} \right\} \quad (5)$$

Equations (1) –(4) are reduced to the following non-dimensional form:

$$\frac{d^2 U}{dY^2} + \frac{dU}{dY} + Gr[T + \lambda_1 T^2] + Gc[C + \lambda_2 C^2] = 0 \quad (6)$$

$$\frac{d^2 T}{dY^2} + Pr \frac{dT}{dY} - dT = 0 \quad (7)$$

$$\frac{d^2 C}{dY^2} + Sc \frac{dC}{dY} - KScC = 0 \quad (8)$$

The non-dimensional boundary condition is given as:

$$\left. \begin{aligned} U = 1, \quad T = 1, \quad C = 1 \text{ at } Y = 0 \\ U \rightarrow 0, \quad T \rightarrow 0, \quad C \rightarrow 0 \text{ as } Y \rightarrow \infty \end{aligned} \right\} \quad (9)$$

To find the solution of equations (6), (7) and (8) concerning boundary conditions (9), we obtain:

$$T(Y) = \exp[-(Pr - \sqrt{\delta})Y] \quad (10)$$

$$C(Y) = \exp[-(Sc - \sqrt{KSc})Y] \quad (11)$$

$$U(Y) = -Gr \left\{ \frac{[e^{-m_1 Y} + \lambda_1 e^{-2m_1 Y}] - [e^{-Y} + \lambda_1 e^{-Y}]}{[m_1(m_1-1)2m_1(2m_1-1)]} \right\} - Gc \left\{ \frac{[e^{-m_2 Y} + \lambda_2 e^{-2m_2 Y}] - [e^{-Y} + \lambda_2 e^{-Y}]}{[m_2(m_2-1)2m_2(2m_2-1)]} \right\} + e^{-Y} \quad (12)$$

It is worth noting that when $\lambda_1 = 0$, $\lambda_2 = 0$, the mathematical equation represents linear free convection and mass transfer flow, indicating a linear relationship between density variation and both temperature and concentration. Conversely, when $\lambda_1 = 1$, $\lambda_2 = 1$, it describes non-linear natural convection and mass transfer flow, accounting for the coefficient of non-linear change in density concerning temperature and concentration parameters.

Nusselt number represents the ratio of heat transfer by fluid when heat changes through fluids by convection. The rate of heat transfer is given by

$$Nu = \left(\frac{dT}{dY} \right)_{Y=0} = -m_1 \quad (13)$$

Where $m_1 = - (Pr - \sqrt{\delta})$,

Therefore, fluid flowing against the boundary surface would experience viscous forces called skin friction. It is the fluid forces against the direction of the wall surface and is given by

$$\tau = \left(\frac{dU}{dY} \right)_{Y=0} = \frac{Gr[m_1(1-2m_1)\lambda_1 - (-1-\lambda_1)]}{m_1(m_1-1)2m_1(-2m_1-1)} - \frac{Gc[(-m_2-2m_2)\lambda_2(-1-\lambda_2)]}{m_2(m_2-1)2m_2(2m_2-1)} - 1 \quad (14)$$

where $m_1 = - (Pr - \sqrt{\delta})$, $m_2 = - (Sc - \sqrt{KSc})$.

3.0 RESULTS AND DISCUSSION

This study examines the effects of a heat source or sink on non-linear free convection fluid flow in the presence of a chemical reaction. Additionally, a MATLAB program was developed to generate line graphs illustrating velocity, temperature, and concentration profiles, providing a clear visualization of the problem and showcasing the influence of various key parameters. These parameters include the non-dimensional chemical reaction parameter (K), Prandtl number (Pr), Schmidt number (Sc), Grashof number for heat transfer (Gr), Grashof number for mass transfer (Gc), and the suction parameter (δ). The default values chosen for analysis are: $Pr = 0.71$, $Sc = 0.78$, $K = 2.0$, and $\lambda_1 = \lambda_2 = Gr = Gc = d = 1.0$. The results were compared with Muthucumaraswamy's findings (2002), confirming excellent agreement.

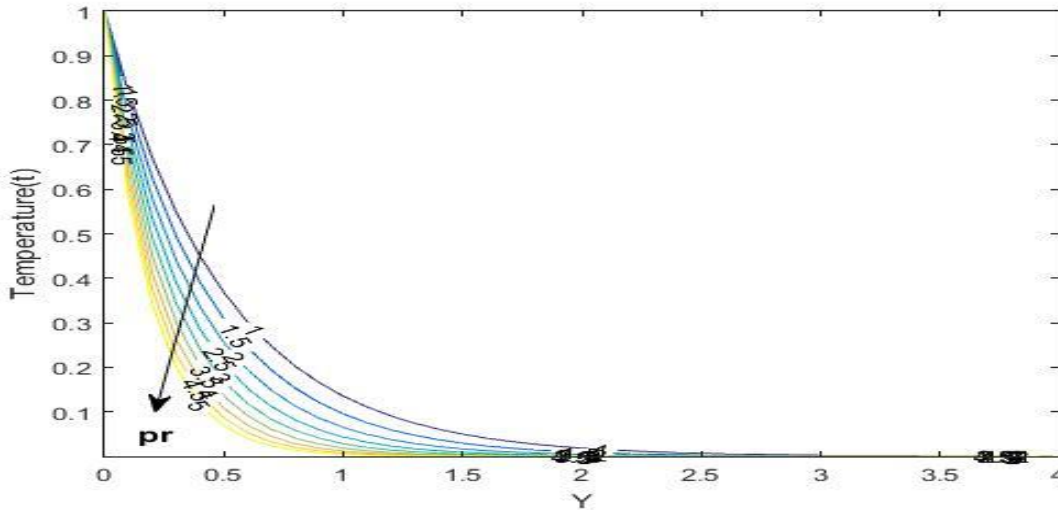


Figure 2. Profile of temperature indicating values of Prandtl number (Pr) on the flow

An increase in the Prandtl number reduces the temperature, as shown in Figure 2, which is due to a reduction in thermal boundary layer thickness with increasing Prandtl number. It is illustrated that increases in the Prandtl number decrease the temperature. This is because heat sink lowers the fluid's thermal conductivity which leads to a fall in temperature. Conversely, a decrease in Prandtl number increases the temperature, showing that heat vanishes more quickly.

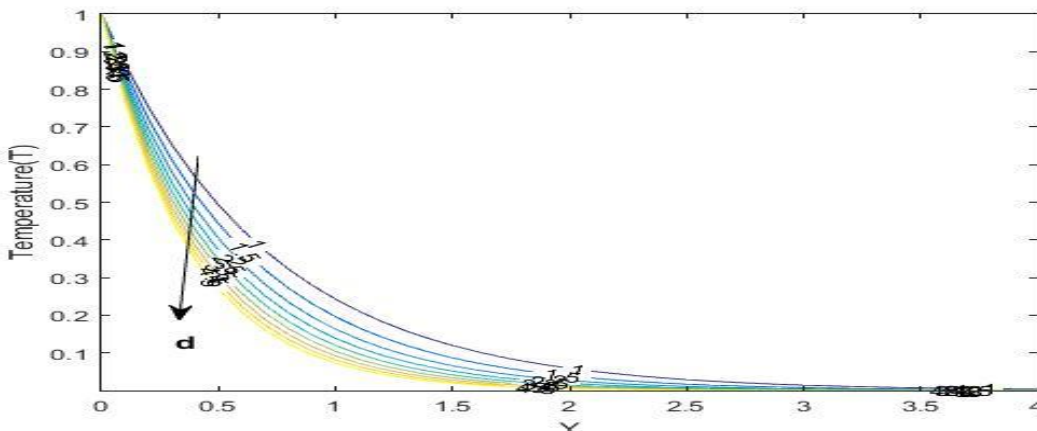


Figure 3: Profile of temperature indicating the values of Heat Sink parameter on the flow

Figure 3 demonstrates that temperature decreases as the number of heat source/sink parameters increases. Because the thermal conductivity of the fluid falls, which results to a drop in temperature. Conversely, a heat source raises thermal conductivity, thereby enhancing the fluid's temperature. Moreover, a decrease in the heat source/sink

parameter increases the temperature, showing that the heat dissipates more quickly in this situation as depicted in figure 3 above.

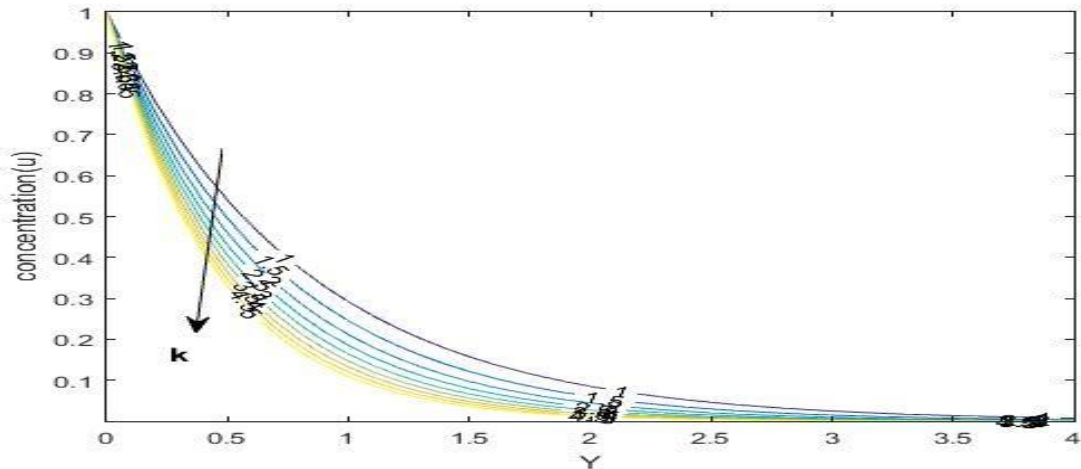


Figure 4 Concentration profile indicating the values of k on the flow

Figure 4 demonstrates that increase in number of chemical reaction parameter decreases the concentration. This is because of the higher chemical reaction rate, means that more of the reacting substance is being consumed or transformed. Chemical reaction parameter typically represents the rate of reaction, which indicates how quickly a chemical species is being consumed or produced.

Furthermore, as the chemical reaction parameter increases, the rate of consumption of the reactant also increases. This means that for a given time and position, more reactant is being converted into products, leaving a lower concentration of the reactant in the system.

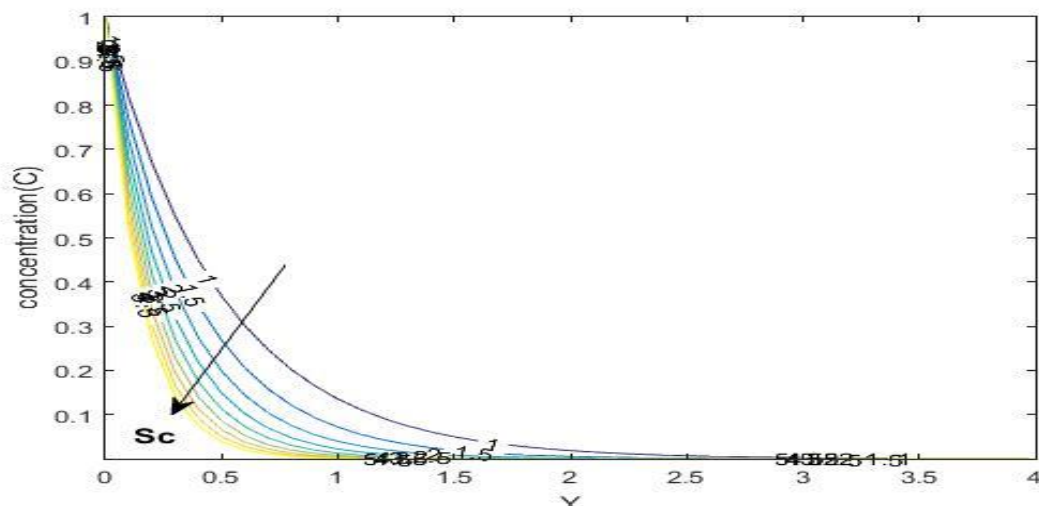


Figure 5: Concentration profile indicating the values of Sc on the flow

In Figure 5 above, when the number of Schmidt number (Sc) increases, the concentration of the species in a fluid flow generally decreases. The Schmidt number is a non-dimensional number that represents the ratio of momentum diffusivity (viscosity) to mass diffusivity. In essence, it compares how easily momentum is transformed in the fluid compared to how easily mass is diffused.

Moreover, a higher Schmidt number means that the mass diffusivity is lower relative to momentum diffusivity. This leads to slower mass transport or diffusion of chemical species within the fluid. As a result, when Sc increases, the rate at which species disperse or spread out within the fluid decreases, leading to a sharper concentration gradient and generally lower concentration throughout the flow field. The species remain more localized rather than diffusing widely.

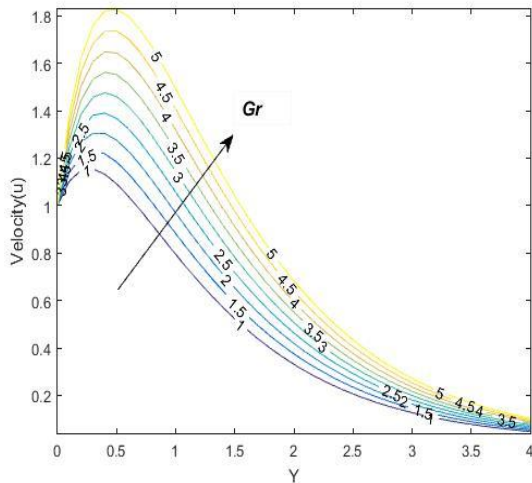


Figure 6: Velocity profile for the values of Gr

Figure 6 illustrates that when the Grashof number (Gr) increases, the velocity in the fluid flow generally increases as well. The Grashof number is a non-dimensional number that represents the ratio of the buoyant forces to the viscous forces in a fluid. A higher Grashof number signifies that buoyant forces (due to temperature or concentration differences) dominate over viscous forces. As Gr increases, the driving force behind the fluid movement becomes stronger, resulting in increased velocity of the flow

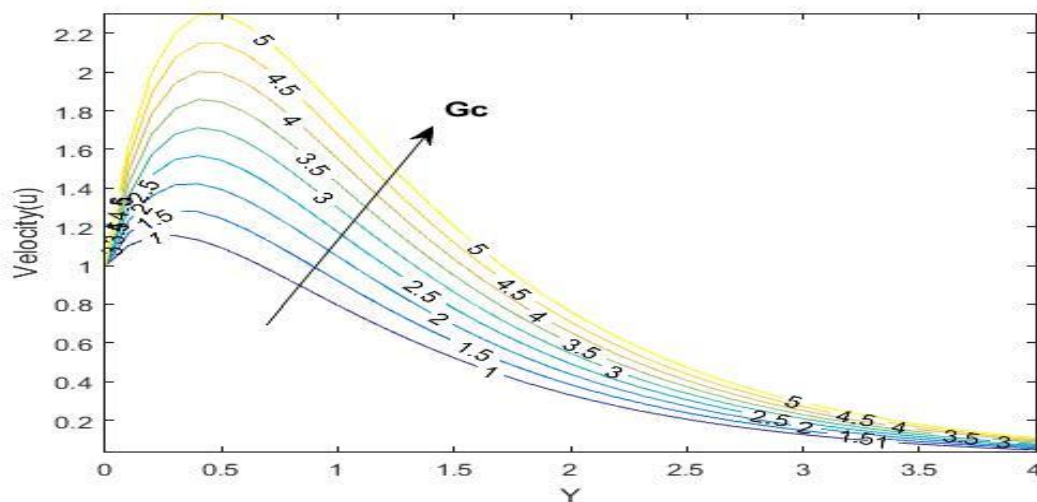


Figure 7: Velocity profile of the values of Gc on the flow

Figure 7 demonstrates the impact of Gc on velocity. When the modified Grashof number for concentration (Gc) increases, the velocity of the fluid flow also tends to increase. This is because Gc represents the ratio of buoyant

forces due to concentration gradient to viscous forces. An increase in G_c means that the buoyant forces generated by concentration differences becomes dominant, which in turn accelerates the flow of the fluid. As a result, the velocity rises with increasing G_c , similar to the effect of an increase in the thermal Grashof number (Gr) in thermally driven convection flows.

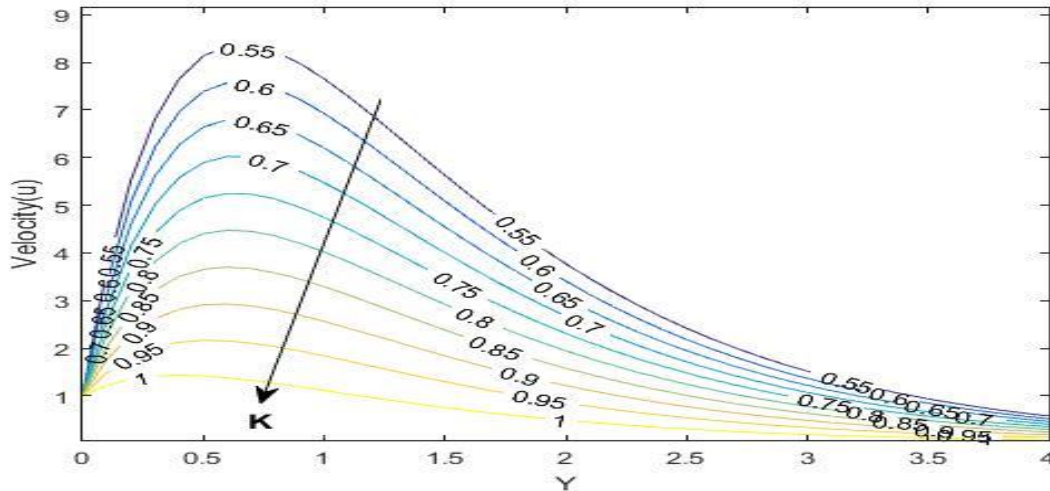


Figure 8: Velocity profile of the values of K

When the chemical reaction parameter (K) (which represents the rate of chemical reaction) increases, the velocity generally decreases. This is because a higher chemical reaction rate tends to enhance the destruction of the species being transported, reducing the concentration gradient that drives the flows.

Furthermore, in physical terms, increasing (K) leads to a more effective consumption of the solute (or reactive species), resulting in weaker buoyant forces due to concentration differences. Consequently, the reduction in buoyant forces causes the flow to slow down and thus, the velocity decreases with higher chemical reaction parameters.

Table 1: Nusselt number

d	2.0	2.5	3.0
Pr	$Nu = \left(\frac{dT}{dY}\right)_{y=0}$	$Nu = \left(\frac{dT}{dY}\right)_{y=0}$	$Nu = \left(\frac{dT}{dY}\right)_{y=0}$
0.60	0.8142	0.9811	1.1321
0.71	0.7042	0.8711	0.0221
0.85	0.5642	0.7311	0.8821

Table 1 represents the variation in the heat source/sink parameter and the Prandtl number, along with their effects on the Nusselt number. The table indicates that an increase in the Prandtl number decreases the rate of heat transfer, and increase in heat source/sink parameter simultaneously increases the Nusselt number. If heat source/sink increases, the Nusselt number would likely increase significantly due to the combination of a thinner thermal boundary layer, and a steeper temperature gradient (from the heat sink). If Pr increases while there is a heat source, the effect on the Nusselt number may be complex, as the increased heat transfer due to higher Pr could be offset by the reduced temperature gradient caused by the heat source.

Table 2: Skin friction

d	2.0	2.5	3.0
Pr	$\tau = \left(\frac{dU}{dY}\right)_{y=0}$	$\tau = \left(\frac{dU}{dY}\right)_{y=0}$	$\tau = \left(\frac{dU}{dY}\right)_{y=0}$
0.60	1.2266	0.9712	0.7996

0.71	1.4540	1.1296	0.9202
0.85	1.8589	1.3926	1.1123

Table 2 depicts the variation in the Prandtl number and heat source/sink, along with their effects on skin friction. The table indicates that the skin friction decreases as both the heat source/sink and the Prandtl number decrease. An increase in the Prandtl number implies lower thermal diffusivity, meaning heat spreads more slowly relative to momentum. This tends to thicken the thermal boundary layer. As a result, the fluid has a greater resistance to thermal gradients, which leads to a reduction in the rate of heat transfer and a possible reduction in fluid velocity near the surface, thereby lowering skin friction. Therefore the Prandtl tends to reduce skin friction, while the heat source can increase it.

Table 3: The values of velocity in the present work and the literature review for the $d=0.0$, and $(\lambda_1=\lambda_2=0.0)$

Y	Muthucumaraswamy (2002) Velocity(U(Y))	0.4	0.4000
		0.5	0.5000
		0.6	Present work 0.6000
		0.7	Velocity(U(Y)) 0.7000
		0.8	0.8000
		0.9	0.9000
0.0	0.0000		0.0000
0.1	0.1000		0.1000
0.2	0.2000		0.2000
0.3	0.3000		0.3000

Muthucumaraswamy (2002), showing that the present research is validated in the absence of a heat source/sink parameter and coefficients of nonlinear change in density and concentration. This reinforces the alignment between two sets of data and the accuracy and reliability of the results presented in this work.

4.0 CONCLUSION

The vertical porous plate's steady natural convection heat transfer in the presence of a heat source and sink was investigated and resolved analytically. Using tables and graphical representations, the behavior of several physical factors was examined. The following were the conclusions reached:

- An increase in the Prandtl number decreases the temperature. This is because heat sink lowers the fluid's thermal conductivity which tends to a fall in temperature.
- The velocity increases when there is an increase in Gr and Gc respectively.
- The velocity generally decreases when there is a rise in the chemical reaction parameter.
- It is also indicated that a heat source raises the thermal conductivity, which finally increases the temperature.
- It was observed that drag forces opposing the movement of fluids fall as the Pr number and heat source/sink rise.
- The increase in the fluid temperature enhances the thermal conductivity of the heat source while the opposite effect is observed with a heat sink.

It is observed that the velocity values obtained in the present research are in conformity with those reported by

- The velocity of the fluid decreases when the Prandtl number increases.
- And also the velocity of the fluid decreases as Sc increase

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