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Heat Generation, Thermal Radiation and Chemical Reaction Effects on Unsteady MHD Casson Fluid Flow on an Inclined Vertical Porous Plate

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Abstract

The effects of 'heat generation', 'thermal radiation', and 'chemical reaction' on the unsteady free convective magnetohydrodynamic (MHD) flow of Casson fluid over an inclined vertical plate with porosity have been examined. The governing equations are transformed into a dimensionless form through similarity transformations to provide a range of options. The identified issue is examined using MATLAB Software. The concepts of 'skin friction' and 'rate of heat and mass transfer' are further elaborated upon. The influence of different measurable physical variables on the terms 'velocity', 'temperature', and 'concentration' is analyzed, with numerical results presented through the corresponding curves. The findings indicate that both the inclination angle and magnetic fields are likely to impede the flow's motion. The parameters related to heat generation and thermal radiation contribute positively to the heat transfer process.

Keywords:- MHD; Casson Fluid; Inclined angle; Heat generation, Thermal radiation; Chemical reaction.

Terminology:

u	x component of fluid Velocity $(m\,s^{-1})$
T	Heating profile (k)
C	Mass density $(Kg\,m^{-3})$
g	Gravitational Acceleration $(m\,s^{-1})$
c_p	Pressure Specific heat of the fluid $(JKg^{-1}k)$
D_M	Mass diffusivity $(\,m^2s^{-1})$
Pr	'Prandtl number'
Gm	'Grashof number' of mass transfer
Gr	'Grashof number' of heat transfer
Kr	Reaction of chemical
Sc	'Schmidt number'
γ	'Casson parameter'
σ	Fluid's electric conductivity $(m^{-1}s)$

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ρ	Density (Kg m^{-3})
k	Thermal conductivity ($W\ m^{-1}k^{-1}$)
ν	Kinematic viscosity $(m^2 s^{-1})$
$\beta_T{}'$	The volumetric coefficient for thermal expansion (k^{-1})
$\beta_C{}'$	The volumetric coefficient for concentration expansion $(m^3 Kg^{-1})$
K'	Porosity of the fluid
$\mu\beta$	Plastic dynamic viscosity $(m^2 s^{-1})$
M	Magnetic field
K	Permeability Parameter
A	Non-zero positive constant
ε	Small quantity
ν_0	Scale for measuring suction velocity.
α	Angle of inclination
λ	Aligned magnetic field
H	Heat generation Parameter

1. Introduction

MHD fluid flow has numerous applications across various industries and technological fields, including MHD generators, nuclear reactor design, and flow measurement devices. Magnetohydrodynamics (MHD) examines the behavior of electrically conducting fluids in the presence of magnetic fields. Recent and promising research on conventional electrically conductive fluid flows indicates that magnetic influences play a crucial role in their heat and mass transfer characteristics. The exploration of MHD encompasses several practical applications, such as induction manometers and the use of liquid sodium for cooling in nuclear power plants, where fluid potential differences perpendicular to both the motion and magnetic field are fundamental.

The significance of non-Newtonian fluids in engineering applications is increasingly recognized. Among these, the Casson fluid is characterized by its time-invariant properties and non-Newtonian behavior. This fluid is distinguished by its unique characteristics. The Casson fluid model, introduced by Casson in 1957, provided a framework for estimating the flow characteristics of mixtures containing pigments and oils. A study conducted by B. Shankar et al. in 2020 examined the effects of a heat source on the inhomogeneous magnetohydrodynamic (MHD) free convection flow of an oscillating vertical plate within a porous medium, utilizing finite element analysis, which yielded varied results. The transmission of thermal radiation, chemical reactions, and the Hall and ion slip effects in the rotating flow of a micropolar liquid were investigated by Krishna et al. in 2021. Additionally, Obalalu et al. (2021) employed the optimal homotopy analysis method to analyze heat transfer and nonuniform flow in a dissipative Casson fluid under solar radiation. Riaz Khan et al. (2021) explored how a porous stretching or shrinking sheet can enhance heat transfer and improve the thermal properties of Casson fluid. The influence of thermal radiation and wall temperature on the flow of MHD boundary layer fluid with gyrotactic microorganisms was developed by Sankad et al. in 2021. A notable study by Bejawada et al. in 2022 reported significant findings regarding a nonlinear surface chemical reaction occurring along an inclined surface in a Forchheimer porous medium, which affects the radiation on MHD Casson flow. Khatun and Islam (2022) investigated the effects of magnetic fields and heat generation/absorption on non-uniform MHD convection flow along a penetrating or shrinking wedge, considering thermophoresis and variable fluid properties. Furthermore, Gautam et al. (2022) conducted an analysis of two non-Newtonian fluids exhibiting bioconvection-induced MHD flow in the presence of multiple slippers, heat sources, and nonlinear heat radiation. The study conducted by Nabila Hameed et al. (2022) involved the assessment of Casson Hybrid Nanofluid in conjunction with a nonlinear tensile surface to investigate the effects of the magnetic field, as well as heat generation and absorption.

The Benchmark solution concerning the MHD nanofluid flow through a porous cylinder, influenced by electron dynamics and dissipating due to chemical reactions, was presented by Sina Sadighi et al. (2022). Nagaraju et al. (2023) reported findings on MHD convective flow of a second-order liquid within an absorbing medium, highlighting the effects of elevated wall temperatures and surface concentrations, which lead to Soret effects and chemical reactions. Majeed et al. (2023) determined the heat and mass transfer characteristics in MHD Casson fluid flow over a cylinder, utilizing higher-order finite element method calculations within a wavy channel. Significant contributions to the study of MHD mixed convection fluids, including heat generation and absorption in heterogeneous reactions between concentric cylinders, were made by Z. Abbas et al. (2023). Reddy et al. (2023) elucidated the effects of heat absorption and evolution on MHD heat transfer fluid flow across a porous medium. A. B. Vishalakshi et al. (2023) investigated the use of a permeable strain plate for the transfer of MHD Casson fluid through a non-Fourier heat flow model. The variations in radiation flux associated with the MHD stretching sheet, influenced by Casson nanofluid and Joule parameters, were revealed by Reddy and Maddileti (2023). Furthermore, B. Shankar Goud et al. (2023) conducted a study demonstrating the impact of thermal radiation on the flow of MHD fluid through a vertical porous plate at high velocities. Additionally, Jawad Ahmed et al. (2023) focused on the interaction of gyrostatic microorganisms and Joule heating in the context of Casson nanofluidic magneto-bioconvection flow on a rotating plate.

The aim of this study is to derive a mathematical formulation for the unsteady flow of a natural convective Casson fluid influenced by magnetohydrodynamics (MHD). This investigation encompasses the flow over a vertically accelerating plate, which experiences exponential acceleration while accounting for the effects of radiation within a porous medium. The findings of this research hold significant potential applications in the dyeing industry and the production of petroleum products.

2. Mathematical formulation

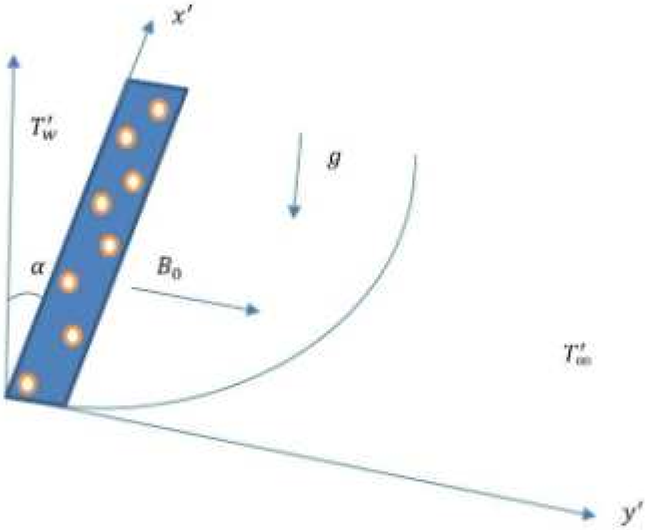

Figure 1: Physics of the problem.

An infinitely inclined vertical plate placed in a uniform porous medium with high velocity. The flow is considered as a not steady, laminar two-dimensional viscous, and not compressible. The impact of external uniform magnetic fields is considered with 'thermal radiation', 'heat generation', and 'chemical reaction' which applies in a homogenous environment. The coordinates are selected so the $x' - axis$ represents the wall in the upward direction and the $y' - axis$ is perpendicular to it. Initially, it is supposed that the speed of the free flow is exponentially increasing because of disturbances, also supposed that the plate moves at a steady velocity (u') along the fluid flow path. Additionally supposed that the temperature or concentration and suction speed at the wall increase exponentially along with time. We assume that 'rigid plate', 'incompressible flow', 'two-dimensional flow', 'non-Newtonian fluid', and 'free convection'. Also, in the energy equation, the role of the 'induced magnetic field', 'electric field', and 'viscous dissipation' are ignored. The Boussinesq's approximation is applied with the above considerations then the regulating equations are given below:

$$\frac{\partial v'}{\partial y'} = 0 \rightarrow v' = v_0 (v_0 > 0) \tag{1}$$

here $\pi = e_{ij}e_{ij}$ with $e_{ij} = (i,j)^{th}$ section as a percentage of deformation, π_c denotes the key value of π according to a format that isn't Newtonian, μB is plastic viscosity in a dynamic state and P_y denotes fluid yield stress.

Assuming 'solid surface', 'flow is not compressible', 'single dimensional flow', 'fluid isn't Newtonian', 'naturally dissipation, 'magnetization elicitation', 'electric region' and 'phrase for variable viscosity' for energy equation are ignored. With the presumption stated above also applying the approximation of Boussinesq, below are the regulating formulas (Bejawada (2022))

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = v\left(1+\frac{1}{\gamma}\right)\frac{\partial^2 u'}{\partial y^2} + g\beta_T Cos\,\alpha + g\beta_C Cos\,\alpha - \left(\frac{\sigma B_0{}^2}{\rho}sin^2\lambda - \frac{v}{K'}\right)u' \tag{2}$$

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{k}{\rho c_p}\frac{\partial^2 T'}{\partial y'^2} - \frac{1}{\rho c_\rho}\frac{\partial q_r}{\partial y'} + \frac{Q_0}{\rho c_p}(T' - T'_\infty) \tag{3}$$

$$\frac{\partial C'}{\partial t'} = D_M\frac{\partial^2 C'}{\partial y'^2} - k_2'(C' - C'_\infty) \tag{4}$$

having the beginning and termination constraints:

$$u' = u_p', \quad T' - T'_w = \varepsilon(T'_w - T'_\infty)e^{n't'}, C' - C'_w = \varepsilon(C'_w - C'_\infty)e^{n't'}\ at\ \ y' = 0$$

$$u' = u'_\infty, \quad T' \rightarrow T'_\infty,\ C' \rightarrow C'_\infty\ at\ \ y' \rightarrow \infty \tag{5}$$

Here, $v' = -V_0\left(1 + A\varepsilon e^{n't'}\right)\ here\ A > 0.$

Using the Rosseland approximation, the expression for radiative heat flux is given by:

$$q_r{}' = -\frac{4\sigma^*}{3k^*}\frac{\partial T'^4}{\partial y'} \tag{6}$$

Applying Taylor's series Formula:

$$T'^4 \cong 4T'^3_\infty T' - 3T'^4_\infty \tag{7}$$

Thus, we have:

$$q_r = -\frac{4\sigma^*}{3k^*}\frac{\partial(4T'^3_\infty T' - 3T'^4_\infty)}{\partial y'} \tag{8}$$

Using equations (8) in equation (3), we get

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{k}{\rho c_p}\frac{\partial^2 T'}{\partial y'^2} - \frac{1}{(\rho c_p)_{nf}}\frac{16\sigma^* T'^3_\infty}{3k^*}\frac{\partial^2 T'}{\partial y'^2} + \frac{Q_0}{\rho c_p}(T' - T'_\infty) \tag{9}$$

Defining the following dimensionless terms:

$$y = \frac{U_0 y'}{v}, u = \frac{u'}{U_0}, t = \frac{t' U_0{}^2}{4v},\ \theta = \frac{(T' - T'_w)}{(T'_w - T'_\infty)},\ C = \frac{(C' - C'_w)}{(C'_w - C'_\infty)}$$

If we remove " ′ " sign (for simplicity) from the equations (1-4), we get

$$\frac{\partial u}{\partial t} - (1 + A\varepsilon e^{nt})\frac{\partial u}{\partial y} = \left(1 + \frac{1}{\gamma}\right)\frac{\partial^2 u}{\partial y^2} - (M^2 sin^2\lambda + \frac{1}{K})u + G_r\theta\ Cos\ \alpha\ + G_m\ C\ Cos\ \alpha \tag{10}$$

$$\frac{\partial \theta}{\partial t} - (1 + A\varepsilon e^{nt})\frac{\partial \theta}{\partial y} = \frac{1+Nr}{Pr}\frac{\partial^2 \theta}{\partial y^2} + H\theta \tag{11}$$

$$\frac{\partial C}{\partial t} - (1 + A\varepsilon e^{nt})\frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} - Kr\ C \tag{12}$$

Subject to the the beginning and the end constraints:

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

$$u \rightarrow 0, \theta \rightarrow 0, C \rightarrow 0, \qquad y \rightarrow \infty, \tag{13}$$

3. Solution:

MATLAB software is employed as a powerful tool to tackle the identified problem effectively. By leveraging its extensive computational capabilities and built-in functions, MATLAB allows for the analysis and modeling of complex data sets. The software facilitates the implementation of various algorithms and mathematical techniques that are essential for solving the specified issue. In addition to problem-solving, MATLAB excels in data visualization, enabling users to create a wide range of graphs and plots. These visual representations are crucial for interpreting results, identifying trends, and communicating findings clearly. By generating corresponding graphs, MATLAB not only enhances the understanding of the underlying data but also aids in presenting the results in a visually appealing and informative manner. Overall, the integration of MATLAB in this context serves to streamline the analytical process, providing both the computational power needed to address the issue and the graphical tools necessary for effective data presentation.

4. Observations with Discussion:

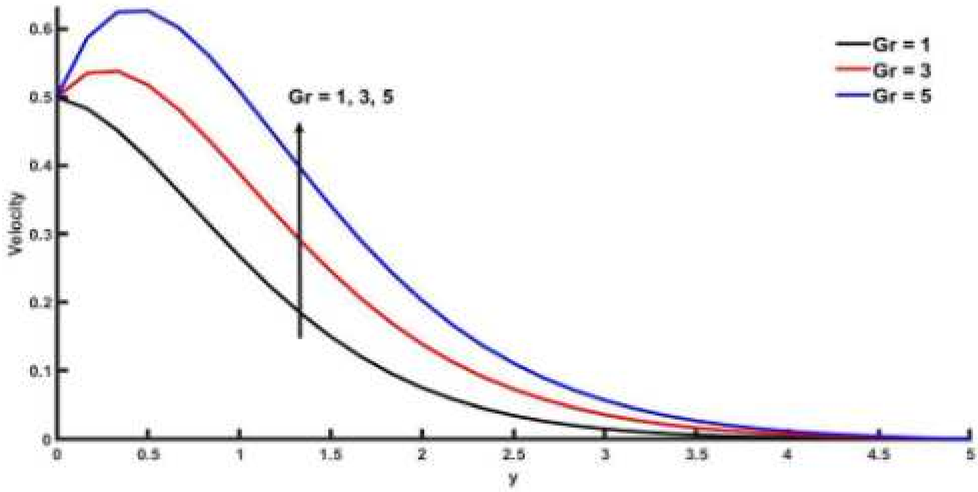

Figure 2: Effects of Gr (Grashof number of Heat Transfer) on Velocity.

As the Grashof Number of heat transfer increases, the velocity profile of fluid flow is enhanced due to stronger buoyancy forces, increased velocity gradients, improved heat transfer efficiency, potential transitions to turbulent flow, and the development of non-uniform velocity distributions.

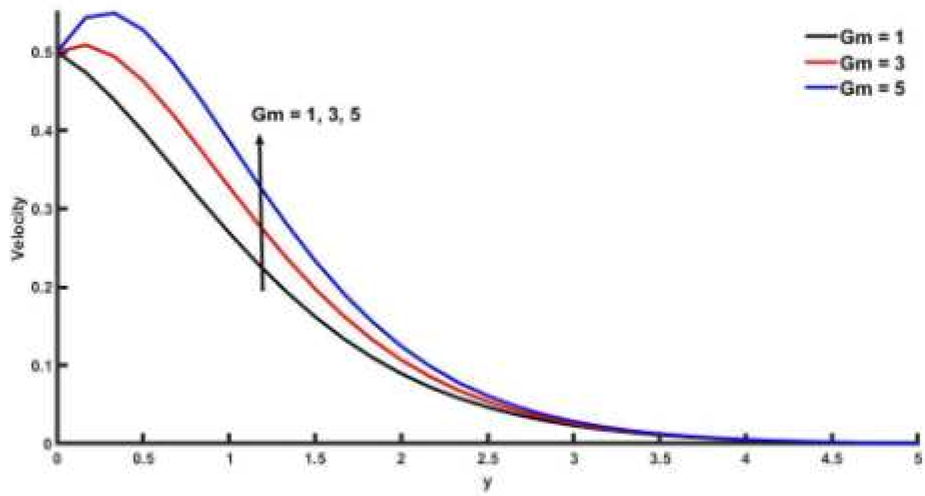

Figure 3: Impact of Gm ('Grashof number' of Mass Transfer) on Velocity.

As the Grashof Number increases, it indicates a greater influence of buoyancy forces relative to viscous forces, which enhances the natural convection within the fluid. This results in a more pronounced movement of the fluid, leading to an increase in the velocity of the flow.

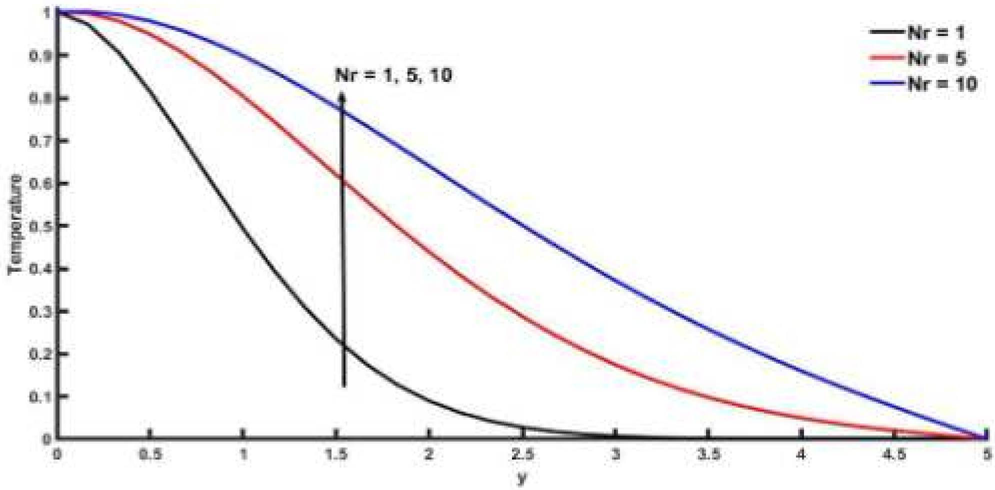

Figure 4: Impact of Nr ('Thermal Radiation Parameter') on Temperature.

The heating profile of the fluid flow is positively correlated with the thermal radiation parameter, indicating that as the thermal radiation parameter increases, the temperature distribution within the fluid flow also tends to rise. This relationship suggests that enhanced thermal radiation contributes to more effective heat transfer within the fluid, leading to a higher overall temperature.

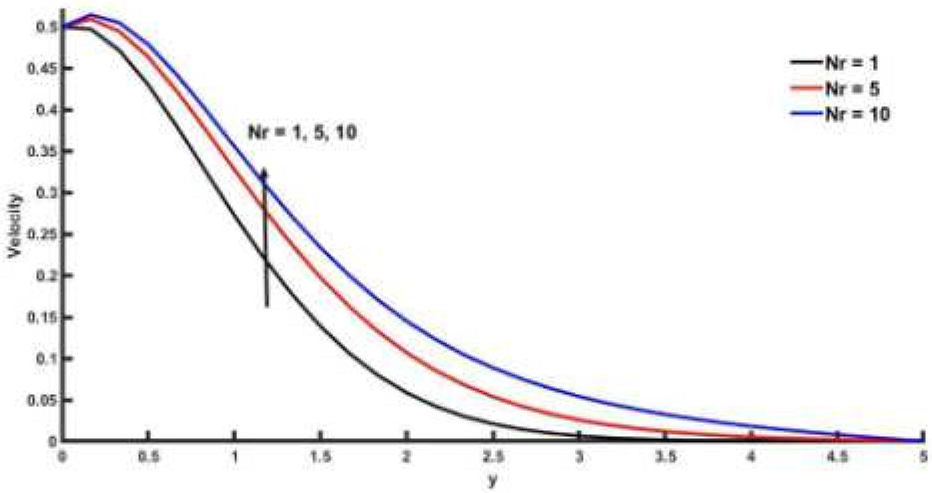

Figure 5: Impact of Nr ('Thermal Radiation Parameter') on Velocity.

The momentum of fluid flow and the thermal radiation parameter demonstrate a positive correlation, indicating that as one of these factors increases, the other tends to increase as well.

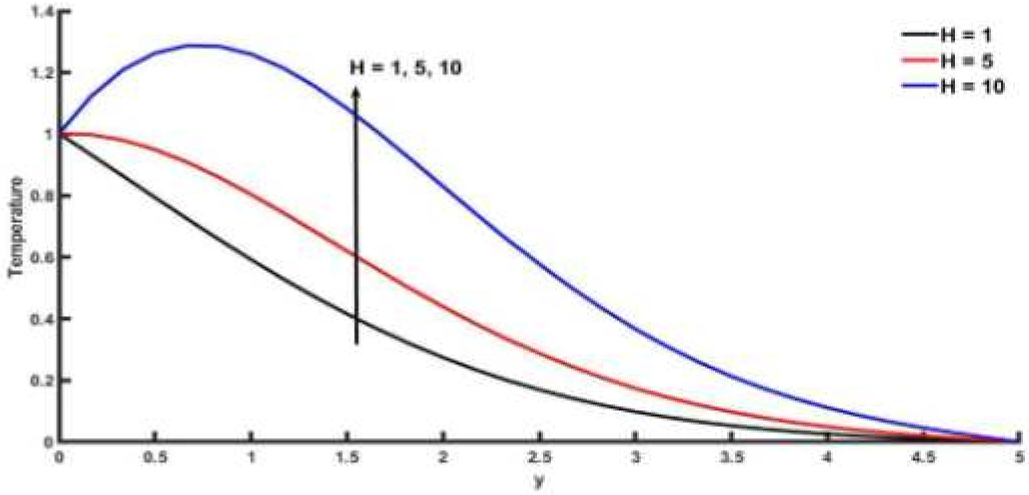

Figure 6: Effects of H ('Heat Generation Parameter') on Temperature.

The enhancement of the Heat Generation Parameter plays a crucial role in optimizing the heating profile of fluid flow within a given system. By increasing the Heat Generation Parameter, we effectively boost the amount of thermal energy produced within the fluid, which leads to a more uniform and efficient distribution of heat throughout the flow.

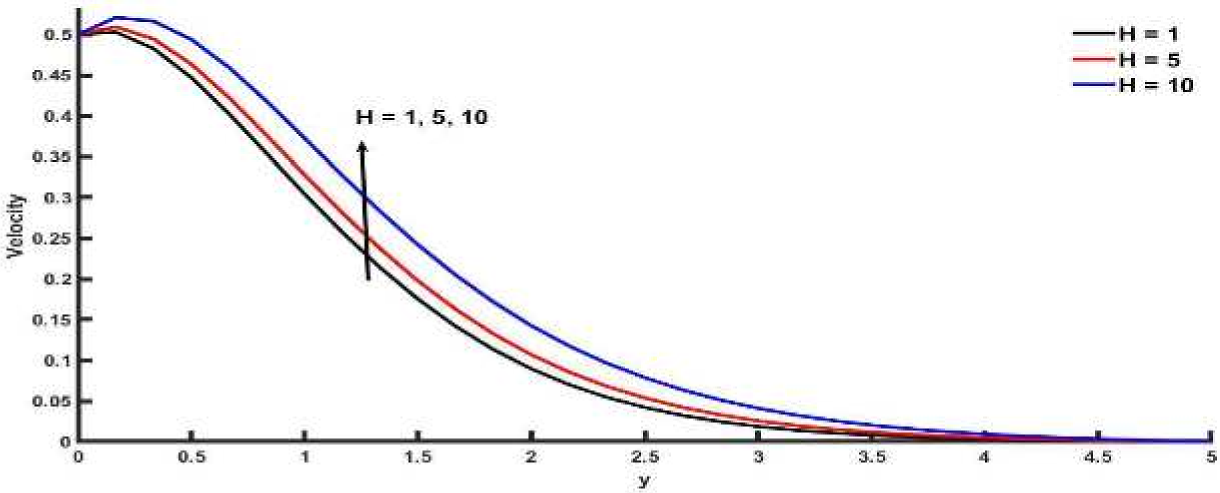

Figure 7: Effects of H ('Heat Generation Parameter') on Velocity.

The Heat Generation Parameter and the velocity profile of fluid flow exhibit similar characteristics, indicating a correlation between thermal behavior and fluid dynamics within a given system. Both parameters are influenced by the same underlying physical principles, such as energy conservation, momentum transfer, and the effects of viscosity.

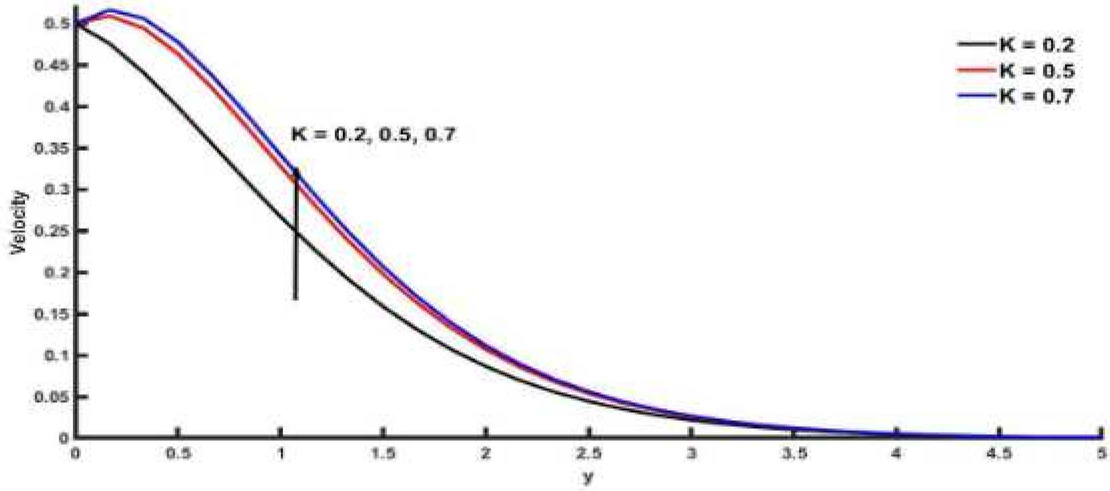

Figure 8: Effects of K (Permeability Parameter) on Velocity.

The permeability parameter, which quantifies the ability of a material to allow fluids to pass through it, demonstrates a positive correlation with fluid velocity. This means that as the permeability of a material increases, the velocity of the fluid moving through that material also tends to increase.

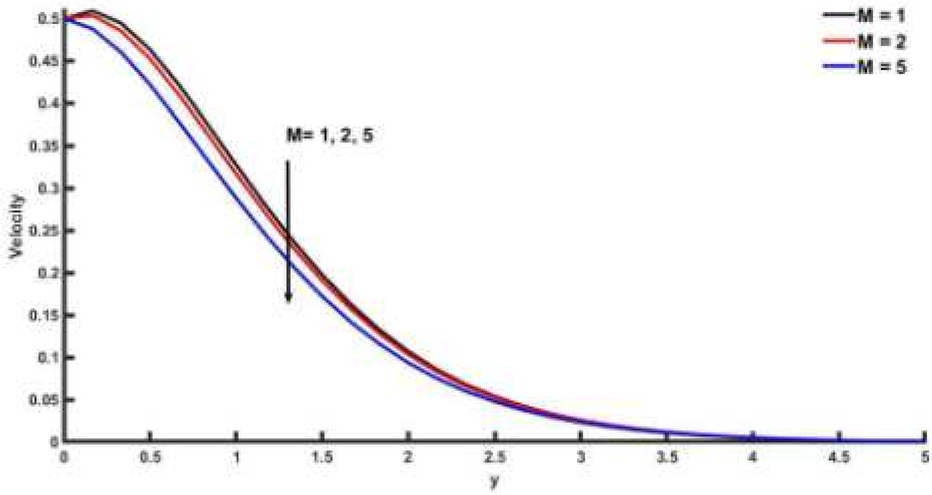

Figure 9: Effects of M (Magnetic Fields) on Velocity.

The velocity profile demonstrates a clear downward trend as the intensity of the magnetic fields increases. This observation suggests that as the strength of the magnetic fields is heightened, there is a corresponding decrease in the velocity of the particles or fluid being analyzed.

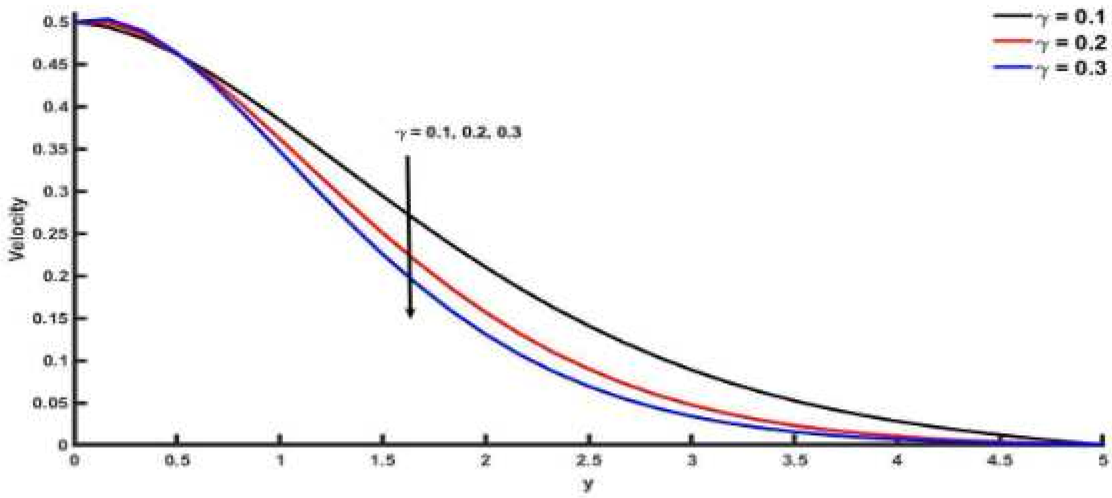

Figure 10: Effects of γ ('Casson Parameter') on Velocity.

As the Casson parameter increases, it signifies that the fluid's resistance to flow is also increasing. This is due to the fact that a higher Casson parameter implies a greater yield stress, meaning that the fluid requires a larger applied stress to initiate flow. Consequently, under the same applied conditions, the fluid will flow more slowly, resulting in a lower velocity profile.

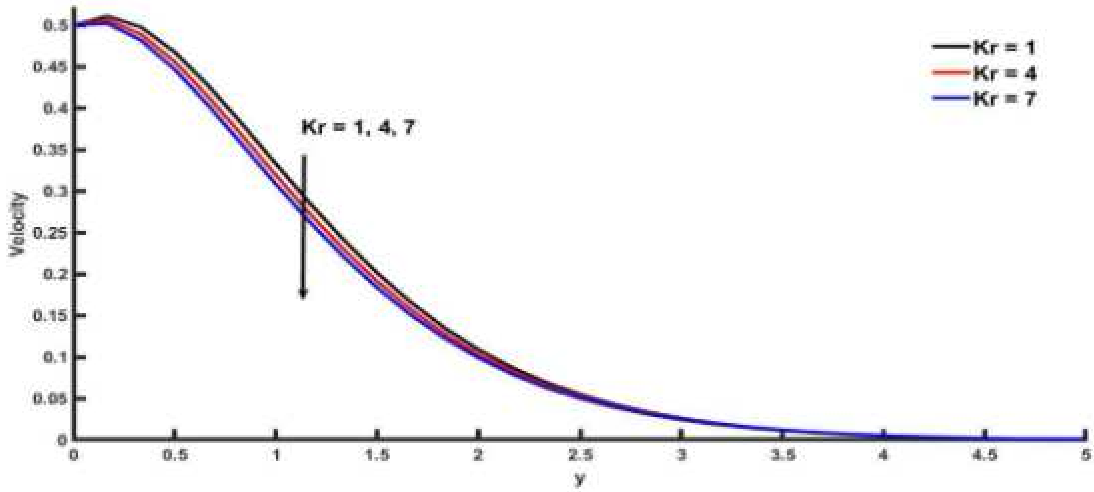

Figure 11: Effects of Kr (Chemical Reactions) on Velocity.

The relationship between chemical reactions and the velocity profile of fluid flow is inversely related, meaning that as the velocity of fluid flow increases, the rate of chemical reactions tends to decrease, and vice versa.

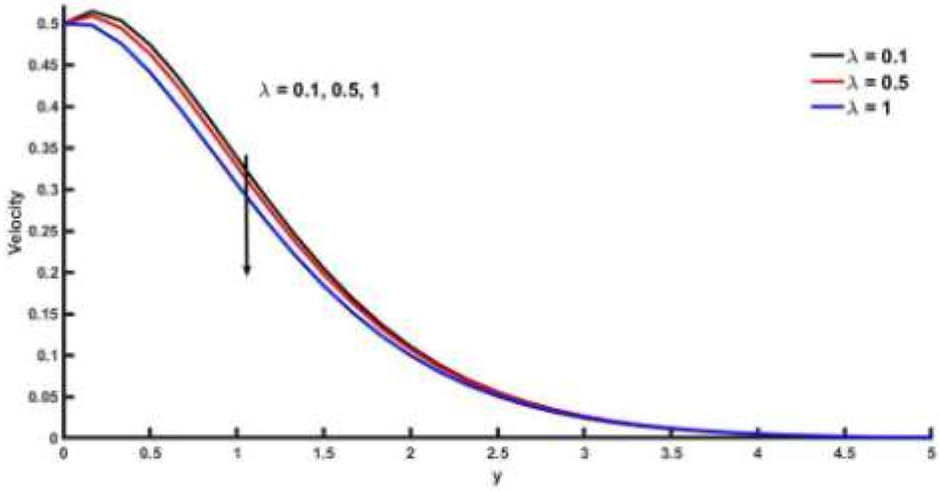

Figure 12: Impact of λ ('Aligned Magnetic Field') on Velocity.

When the intensity of the aligned magnetic fields is increased, the interaction between the magnetic fields and the charged particles within the fluid becomes more pronounced. This interaction can lead to several effects that ultimately result in a decrease in the velocity profile of the fluid flow.

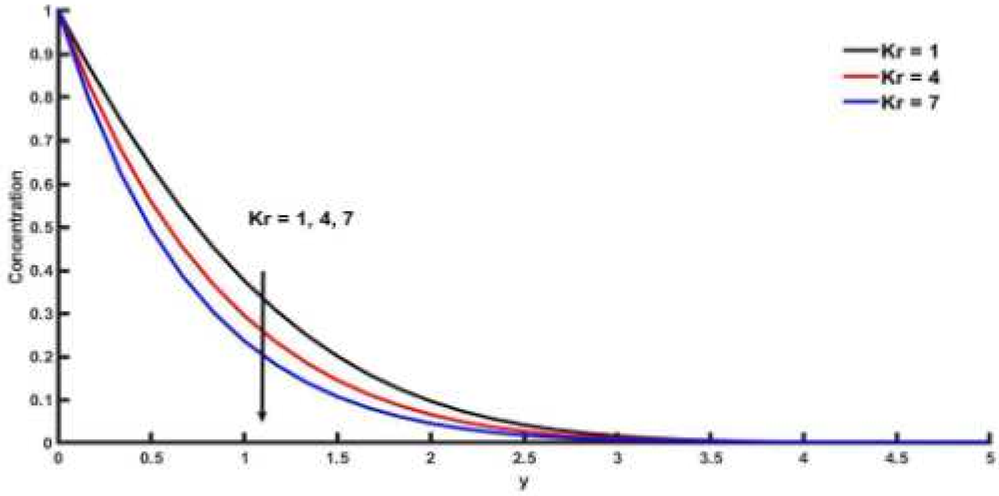

Figure 13: Impact of Kr ('Chemical Reaction') on Concentration.

As the intensity of the 'Chemical Reaction' is heightened, the concentration profile of the fluid flow experiences a decline, indicating a significant alteration in the distribution of reactants and products within the system. This decline can be attributed to several factors that interplay during the reaction process.

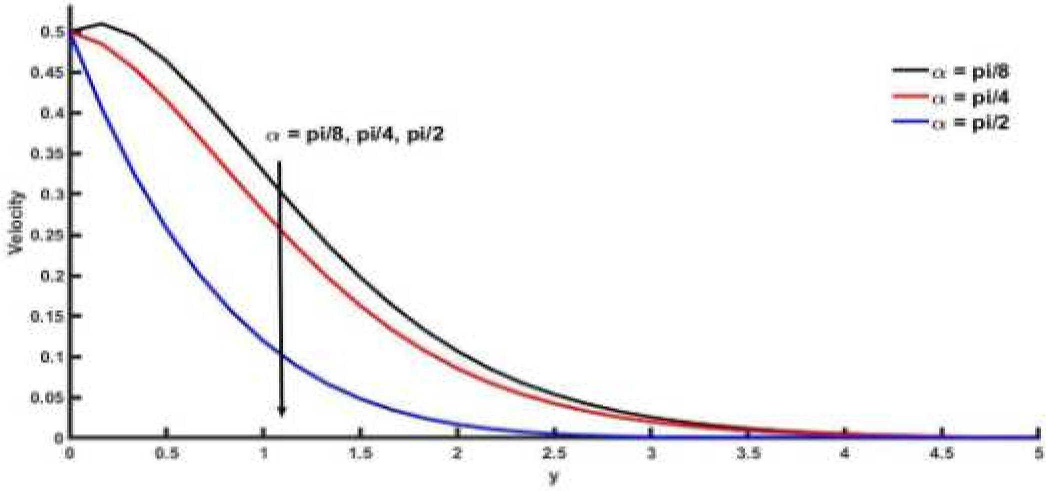

Figure 14: Impact of α (Angle of Inclination) on Velocity.

As the angle of the plate rises, the component of gravitational force acting parallel to the surface of the plate increases, while the component acting perpendicular to the surface decreases. This shift can result in a reduction in the effective driving force that propels the fluid along the plate. Consequently, the velocity of the fluid near the surface may decrease, leading to a more pronounced velocity gradient.

5. Conclusion:

- The velocity profile of the fluid flow exhibits similar characteristics in relation to various physical parameters, including the Grashof number for heat transfer (Gr), the Grashof number for mass transfer (Gm), the thermal radiation parameter (Nr), the heat generation parameter (H), and the permeability parameter (K). In contrast, it is diminished by factors such as magnetic fields (M), the Casson parameter (γ), chemical reactions (Kr), aligned magnetic fields (λ), and the angle of inclination (α).
- The Thermal Radiation Parameter (Nr) and the Heat Generation Parameter (H) exert a beneficial influence on the temperature distribution of the fluid throughout its flow.
- The concentration profile of the fluid during flow is inversely related to the chemical reaction rate (Kr).

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