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Magnetohydrodynamics (MHD) Kuvshinski Fluid Flow through a Porous Plate with Injection, Variable Pressure and Soret Effects

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ABSTRACT

This paper investigates the combined effect of injection/suction, variable pressure, heat absorption and Soret on magnetohydrodynamics (MHD) Kuvshinski fluid flow through a porous plate. The plate is assumed to be embedded in a porous media and a transverse magnetic field is applied to the stream. The equations governing is modelled as partial differential equations (PDEs). The PDEs are dimensionalised using appropriate variables and then solved analytically by regular perturbation technique to obtain the expressions for the velocity, temperature and concentration of the fluid. Skin-friction, rate of heat and mass transfer are also derived. Computations were carried out using MATLAB to examine the effect of physical parameters associated with the fluid flow and presented graphically and discussed. The findings from this study are found to be in good agreement with literature when compared.

Keywords: Suction/injection, porous medium, convective flow, MHD, Perturbation

Nomenclatures

g	acceleration due to gravity
T'	fluid temperature
C'	species concentration
R_m	Chemical molecular diffusivity
K_c	Chemical reaction parameter
C_p	Specific heat at constant pressure
k	Thermal conductivity
G_r	Grashof number
$\mathrm{P_r}$	Pradtl number
M	Magnetic field parameter
$\mathrm{T'_\infty}$	Temperature of the fluid at infinity (K)
$\mathrm{T'_w}$	Temperature of the fluid far away of the fluid from the plate (K)
$*$	Dimensionless properties
∞	Free stream conditions

Greek symbols

β	Volumetric Coefficient
β_1	Volumetric coefficient of thermal expansion
β_2	Volumetric coefficient of concentration
ρ	Fluid Density
υ	Kinematic Viscosity
φ	Heat Absorption Parameter
σ	Electric Conductivity of the Fluid (ms^{-1})
ε	Activation energy parameter
χ	Dimensionless coordinate perpendicular to the plate
λ	Dimensionless concentration of the fluid
Ψ	Dimensionless temperature of the fluid

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Subscripts

0 Condition in the free stream
P Plate
w Wall condition

Superscript

* Dimensional

1.0 INTRODUCTION

Suction/injection method was first introduced one of the means for preventing or delaying boundary layer separation. Suction/injection is one of the methods of boundary layer control, which have the aim of reducing losses of energy in channels. The study of injection/suction on the boundary layer control played an important role in the field of aerodynamics and space sciences. By controlling the flow as such, fuel consumption might be decreased by 30%; a considerable reduction in pollutant emission is achieved. In mass transfer cooling, suction/injection of a fluid through the bounding significantly change the flow field and as a result, affect the heat transfer rate from the plate.

Injection is defined as the administering a fluid in to a system as in the case of blood transfusion while in the case of suction is defined as the exclusion of fluid from a system. If the two runs at the same time, then the opposite sides of the plates are porous which allow the fluid to move in and out. Suction/injection of fluid channels has gained a special concerned due to its paramount applications of different field such as Science, engineering, petroleum drilling industries and food processing industries etc (Usman *et al.,* 2023).

The effect of heat source on mixed convection flow of a viscous incompressible and electrically conducting fluid along an infinite vertical plate with magnetic field has been studied by Investigated the influence of variable thermal conductivity and heat (Zayyanu *et al.,* 2022).

A porous medium is a substance that contains pores, or spaces between solid materials through which liquid or gas can pass. Yale and Uwanta (2019) studied Soret effect on magnetohydrodynamics flow of a viscous, incompressible, electrically conducting fluid past an infinite vertical plate with heat and mass transfer has been studied. The governing equations are solved analytically using perturbation technique.

Convection is the process of heat transfer by the bulk movement of molecules within fluids such as gases and liquids. The initial heat transfer between the object and the fluid takes place through conduction, but the bulk heat transfer happens due to the motion of the fluid (Takhar, 2007). Suction This is a production of partial vacuum by the removal of air in order to force fluid into a vacant space procedure adhesion (Chamkha, 2004). Injection is used to control the fluid flow in the channel, and an exothermic chemical reaction of Arrhenius kinetic is considered (Mitra and Das, 2009).

Heat and mass transfer in porous medium are known to have applications in industrial, chemical engineering, nuclear reactors, geophysical and in petroleum industries. Recent development in binary flow of mixtures and the determination of molecular weights separation of isotopes, food processing and filtration process lead to increased investigations understanding such flow (Dangana and Amos, 2020).

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Several researches have been conducted on the Kuvshinski flow in various phenomena. Ibrahim and Suneetha (2015) examined the influence of chemical reaction and heat source on MHD free convection boundary layer flow if radiation absorbing Kuvshinshiki fluid in a porous medium. Buggaramulu and Krishna (2017) extended their work by considering an infinite vertical porous plate with radiation and chemical reaction effects. Rama Prasad *et al.* (2021) studied aligned magnetic field effect on unsteady MHD double diffusive free convection flow of Kuvshinki fluid past an inclined moving plate. Mohana *et al.* (2022) extended it to investigate chemical reaction with aligned magnetic field effects on unsteady MHD Kuvshinski flow past an inclined porous plate in the presence of radiation and Soret effects. Furthermore, effects of injection and heat sink/source on convective Kuvshinki fluid through a porous medium was investigated by Disu and Omokhuale (2022). Kodi and Ravuri (2022) analysed Soret and chemical reaction effects on heat and mass transfer in MHD flow of a Kuvshinski fluid through porous medium with aligned magnetic field and radiation. Janga and Gajjala (2023) in their extension of this flow considered heat mass transfer on unsteady MHD Kuvshinski fluid flow past an inclined porous plate with multiple slip effect. Shaik *et al.* (2023) examined radiation absorption and diffusion thermos effects on unsteady MHD Kuvshinski fluid flow past an inclined porous plate in the presence of thermal radiation and chemical reaction. Recently, Khayer and Chakraborty (2024) researched on unsteady MHD viscous dissipative Kuvshinski fluid past an infinite vertical porous plate with radiation, Soret, and joule heating effect analytically using perturbation technique.

2.0 MATHEMATICAL FORMULATION

We considered an unsteady flow of an incompressible, viscous, electrically conducting and heat-absorbing fluid through a semi-infinite vertical plate. A uniform transverse magnetic field of magnitude B_0 is applied in the presence of temperature and concentration buoyancy effects in the direction of the y'− axis. The transversely applied magnetic field and magnetic Reynolds number is assumed to be very small so that the induced magnetic field is negligible. We assumed that there is no applied voltage which implies the absence of an electric field. The physical variables are independent of the x'−axis. We further assume that there exist a homogeneous first order chemical reaction between the diffusing species and the fluid. The presence of variable injection/suction is considered. The effect of injection, variable pressure and Soret are taken into account.

The governing equations under the usual Boussinesq's and boundary layer approximations are:

Continuity Equation

$$\frac{\partial \mathrm{v}'}{\partial \mathrm{y}'} = 0 \tag{1}$$

Momentum Equation

$$\left(1+\lambda'\frac{\partial}{\partial \mathrm{t}'}\right)\frac{\partial \mathrm{u}'}{\partial \mathrm{t}'} + \mathrm{v}'\frac{\partial \mathrm{u}'}{\partial \mathrm{y}'} = -\frac{\partial \mathrm{P}}{\partial \mathrm{y}} + \nu\frac{\partial^2 \mathrm{u}'}{\partial \mathrm{y}'^2} + \mathrm{g}\beta^{\mathrm{T}}(\mathrm{T}'-\mathrm{T}'_\infty) + \mathrm{g}\beta^{\mathrm{c}}(\mathrm{C}'-\mathrm{C}'_\infty)$$

$$-\left(1+\lambda'\frac{\partial}{\partial \mathrm{t}'}\right)\left(\frac{\sigma \mathrm{B}_0^2}{\rho}+\frac{\nu}{\mathrm{K}'}\right)\mathrm{u}' \tag{2}$$

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Energy Equation

$$\left(1+\lambda'\frac{\partial}{\partial t'}\right)\frac{\partial T'}{\partial t'}+v'\frac{\partial T'}{\partial y'}=\frac{k}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2}+\frac{1}{\rho C_p}Q_T(T'-T'_\infty) \quad (3)$$

Mass Equation

$$\left(1+\lambda'\frac{\partial}{\partial t'}\right)\frac{\partial C'}{\partial t'}+v'\frac{\partial C'}{\partial y'}=D_m\frac{\partial^2 C'}{\partial y'^2}-K_m(C'-C'_\infty)+\frac{D_m k_T}{T_m}\frac{\partial^2 T'}{\partial y'^2} \quad (4)$$

Subject to the boundary conditions:

$$t'\le 0: u'=0, T'=T'_\infty, C'=C'_\infty \text{ for all } y'$$

$$t'>0\begin{cases}u'=u_p, T'=T'_\infty+(T'_w-T'_\infty)\epsilon e^{wt}, C'=C'_\infty+(C'_w-C'_\infty)\epsilon e^{wt} \text{ at } y'=0\\ u'\to 0, T'\to T'^{I}_\infty, C'\to C'^{I}_\infty \quad \text{as } y'\to\infty\end{cases} \quad (5)$$

$$\text{Here } v'=v_0, -\frac{\partial P}{\partial x}=\lambda_1\varepsilon e^{wt} \quad (6)$$

We define the following dimensionless quantities:

$$u=\frac{u'}{U_0}, y=\frac{U_0}{\nu}y', t=\frac{U_0}{\nu}t', \theta=\frac{(T'-T'_\infty)}{(T'_w-T'_\infty)}, \chi=\frac{(C'-C'_\infty)}{(C'_w-C'_\infty)} \quad (7)$$

Substituting v', (6) and (7) into equation (2), (3) and (4), then, we have the following non – dimensional form of equations:

$$\left(1+\lambda_1\frac{\partial}{\partial t'}\right)\frac{\partial u'}{\partial t'}+\frac{\partial u'}{\partial y}=\lambda\varepsilon e^{wt'}\frac{\partial P}{\partial t}+\frac{\partial^2 u'}{\partial y^2}+G_r\phi+G_m\psi-(M+\frac{1}{K})(1+\lambda_1\frac{\partial}{\partial t'})u' \quad (8)$$

$$\left(1+\lambda_1\frac{\partial}{\partial t}\right)\frac{\partial \phi}{\partial t}+\frac{\partial \phi}{\partial y}=\frac{1}{P_r}\frac{\partial^2\phi}{\partial y^2}+\psi\phi \quad (9)$$

$$\left(1+\lambda_1\frac{\partial}{\partial t}\right)\frac{\partial \chi}{\partial t}+\frac{\partial \chi}{\partial y}=\frac{1}{S_c}\frac{\partial^2\chi}{\partial y^2}+R_m\chi+R_c\frac{\partial^2\chi}{\partial\chi^2} \quad (10)$$

where, $S_c=\frac{\upsilon}{D_m}, R_m=\frac{K_m}{V_0^2}, R_c=\frac{D_m K_T}{T_m\upsilon}, G_r=\frac{g\beta_1\upsilon(T'_w-T'_\infty)}{V_0^3}, G_m=\frac{g\beta_2\upsilon(T'_w-T'_\infty)}{V_0^3},$

$$M=\frac{\sigma B_0^2\upsilon}{\rho V_0^2}, K\frac{K'V_0^2}{\upsilon^2}, P_r=\frac{K_0}{\upsilon C_p}, \Psi=\frac{Q_0\upsilon}{\rho C_p V_0^2}$$

The corresponding initial and boundary conditions in non-dimensional form become:

$$u_0=0, \phi=1+\varepsilon e^{wt}, \chi=1+\varepsilon e^{wt}, y=0 \quad (11)$$

$$u_0=0, \phi=1, \quad \chi=1 \text{ at } y\to 0$$

$$u_0=0, \phi_0=0, \chi_0=0, y=1$$

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3.0 ANALYTICAL SOLUTIONS

To solve (8) to (10) subject to the boundary conditions (11), we assume solutions of the form:

$$u(y,t) = u_0(y) + u_1(y)\varepsilon e^{wt} \quad (12)$$

$$\chi(y,t) = \chi_0(y) + \chi_1(y)\varepsilon e^{wt} \quad (13)$$

$$\phi(y,t) = \phi_0(y) + \phi_1(y)\varepsilon e^{wt} \quad (14)$$

On substituting equations (12) to (14) into equations (8) to (10). The following are set of ordinary differential equations (ODEs) are gotten:

$$u_0 : u_0'' - u_0' - (m + \frac{1}{k})u_0 = 0 \quad (15)$$

$$u_1 : u_1'' - u_1' - (m + \frac{1}{k} + \lambda_1 mw + \frac{\lambda_1}{k}w + w + \lambda_1 w^2)u_1 = 0 \quad (16)$$

$$\phi_0 : \phi_0'' - (\phi_0' - \psi\phi_0)P_r = 0 \quad (17)$$

$$\phi_1 : \phi_1'' + P_r\phi_1' + (\psi - \lambda_1 w^2 - w))P_r\phi_1 = 0 \quad (18)$$

$$\chi_0 : \chi_0'' - S_c\chi_0' - R_m S_c\chi_0 = -S_c\psi\phi_0'' \quad (19)$$

$$\chi_1 : \chi_1'' - S_c\chi_1' - (R_m + w + \lambda_1 w^{2)S_c}\chi_0 = -S_c\psi\phi_1'' \quad (20)$$

Equation (16) to (20) will be solve subject to the following boundary condition:

$$u_0 = u_1 = u_p\,, \phi_0 = \phi_1 = 1\,, \chi_0 = \chi_1 = 1 \;\; at\; y = 0 \quad (21)$$

$$u_0 = u_1 \to 0\,,\; \phi_0 = \phi_1 \to 0, \chi_0 = \chi_1 \to 0 \; as \;\; y \to \infty$$

The exact solutions for fluid velocity $u(\chi,t)$, temperature $\phi(\chi,t)$ and species concentration $\chi(\chi,t)$ are obtained and expressed in the following form:

$$u(\chi,t) = E_{12}e^{-d10\chi} + E_{13}e^{-d2\chi} + E_{14}e^{-d6\chi} + \{E_{16}e^{-d12\chi} + E_{17}e^{-d4\chi} + E_{18}e^{-d8\chi}\}\varepsilon \quad (22)$$

$$\phi(\chi,t) = e^{-d2\chi} + (e^{-d4\chi})\varepsilon e^{wt} \quad (23)$$

$$\chi(\chi,t) = E_6e^{-d6\chi} + E_7e^{-d2\chi} + \{E_9e^{-d8\chi} + E_{10}e^{-d4\chi}\}\varepsilon e^{wt} \quad (24)$$

The expression for skin friction is

$$C_f = -d_{10}E_{12} - d_2E_{13} - d_6E_{14} - (d_{12}E_{16} + d_4E_{17} + d_8E_{18})\varepsilon e^{wt} \quad (25)$$

The expression for Nusselt number (Nu) in terms of heat transfer is

$$N_u = -d_2 - (d_4)\varepsilon e^{wt} \quad (26)$$

The expression for Sherwood number (Sh) in terms of mass transfer is

$$S_h = -d_6E_6 - d_2E_7 - (d_8E_9 + d_4E_{10})\varepsilon e^{wt} \quad (27)$$

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4.0 RESULT AND DISCUSSION

Magnetohydrodynamics (MHD) kuvshinski fluid flow through a porous plate with injection, variable pressure and soret effects has been formulated and solved analytically by regular perturbation technique. In order to understand the flow of the fluid computations are performed for different parameters such as: G_m, G_r, ϕ, Sc, Pr, M, K, λ_1, λ_2, ψ and R_m.

4.1 Velocity Profiles

Error! Reference source not found. and **Error! Reference source not found.** display the velocity profiles for different thermal Grashof number (G_r) and Mass Grashof number (G_m). The Grashof number for heat transfer signifies the relative effect of the thermal buoyancy force to the viscous hydrodynamic force in the boundary layer. As expected, it is observed that there is an enhancement in the velocity due to the rising of thermal buoyancy force. Also, as G_r increases, the peak values of the velocity increase rapidly near the porous plate and then decays smoothly to the free stream velocity. The modified Grashof number defines the ratio of the species buoyancy force to the viscous hydrodynamic force. As expected, the fluid velocity increases and the peak value is more distinctive due to increase in the species buoyancy force. The velocity distribution attains a distinctive maximum value in the vicinity of the plate and then decreases properly to approach the free stream value. It is noticed that the velocity increases with increasing values of the Grashof number for mass transfer. In the case of different values of Magnetic parameter, the profiles of the velocity of the boundary layer is presented in **Error! Reference source not found.**. The velocity decreases with an increase in the Hartmann number. It is because that the application of transverse magnetic field will result a resistive type force (Lorentz force) similar to drag force which tends to resist the fluid flow and thus reducing its velocity. Also, the boundary layer thickness decreases with an increase in the Hartmann number. **Error! Reference source not found. Error! Reference source not found.** presents the velocity profile for different values of Permeability parameter (K). It is found that as K rises the velocity of the fluid increases. In the boundary layer, the velocity starts by increasing to a maximum, and slowly decreases. Physically, Permeability parameter indicates thermal buoyancy characteristic of a fluid flow. The greater it gets, the more the buoyant force brought about by the temperature gradient acts upon the fluid, thereby increasing its velocity rate in the vicinity of the heated surface. The peak velocity occurs in the boundary layer where the forces of buoyancy prevail over that of viscosity. **Error! Reference source not**

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found. depicts the velocity profiles for different values of heat absorption parameter (λ_1). The momentum boundary layer decreases when the intensity of the heat absorption increases. The effect of injection parameter (ψ) on the velocity profile is graphically presented, velocity increases as the velocity profile effect becomes significant. Illustrates the effect of injection parameter (ψ) on the velocity profiles. It is observed that the velocity increases as ψ becomes significant. The effect of heat absorption parameter (ϕ) on the velocity profile is presented in **Error! Reference source not found.**. It is evident that the momentum boundary layer becomes higher as (ϕ) is increased. The velocity profiles of **Error! Reference source not found.** demonstrate the velocity profiles for different values of mass absorption parameter (R_m). It is found that the velocity rises with increase in δ. **Error! Reference source not found.** displays the velocity profiles for different values of (S_c). It is noticed that the velocity increases as s_c rises. In the effect of Prandtl number on the velocity profiles is shown. It is clear that the velocity boundary layer increases when the Prandtl number is increased. **Error! Reference source not found.** connotes the velocity profile for varied values of kuvshinski parameter $(\lambda 1)$. It is seen that higher value of kuvshinski parameter leads to rise in the velocity of the fluid.

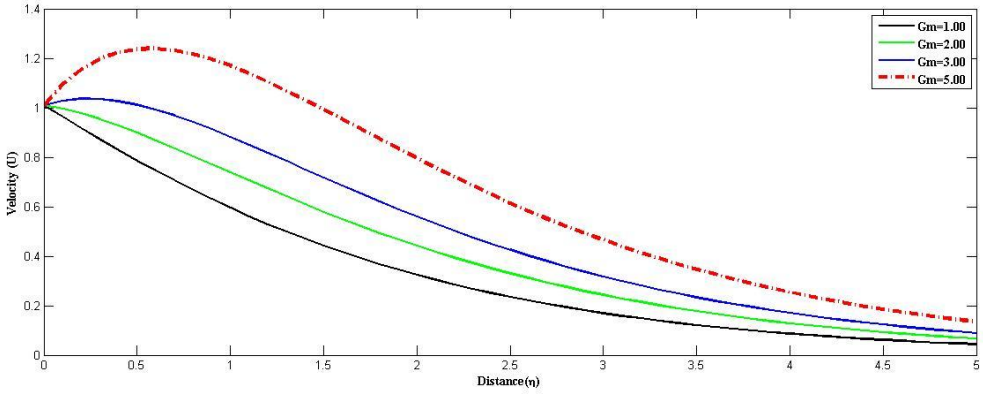

Figure 4.1.1: Velocity profile for different values of G_m.

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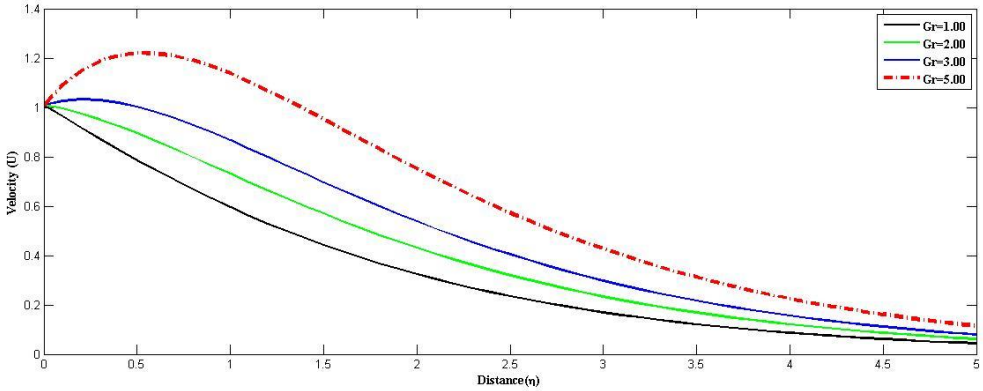

Figure 4.1.2: Velocity profile for different values of G_r.

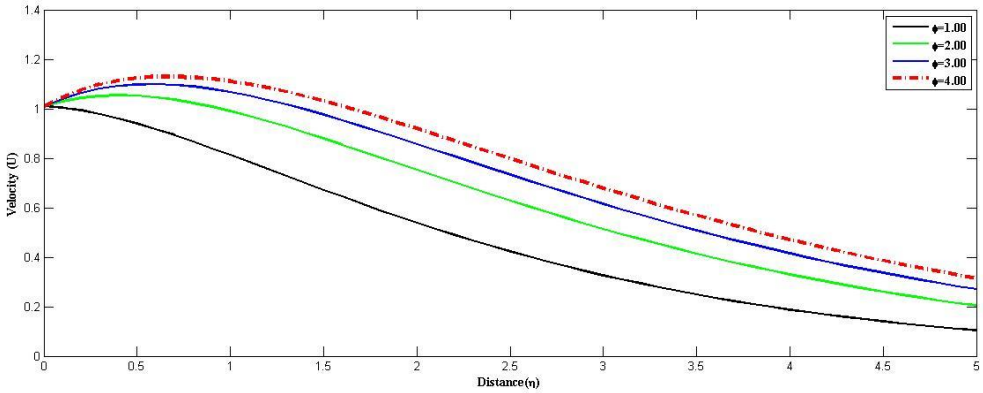

Figure 4.1.3: Velocity profile for different values of ϕ.

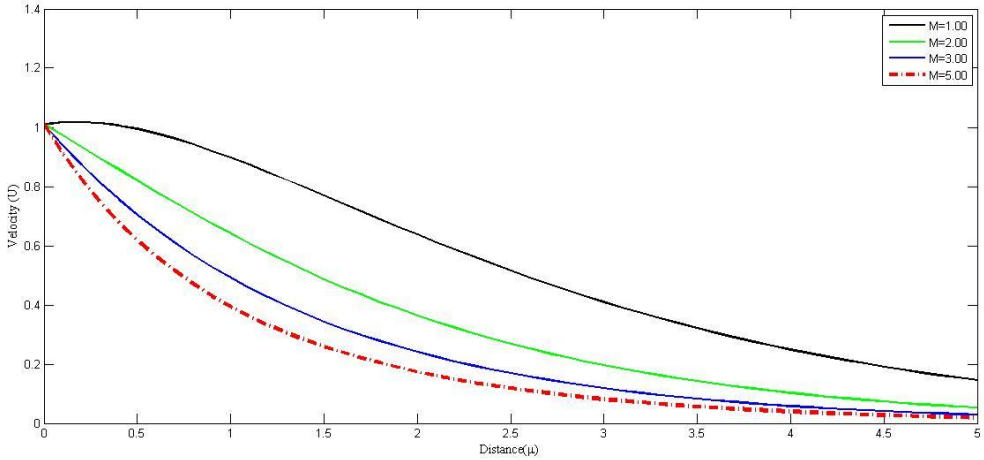

Figure 4.1.4: Velocity profile for different values of M.

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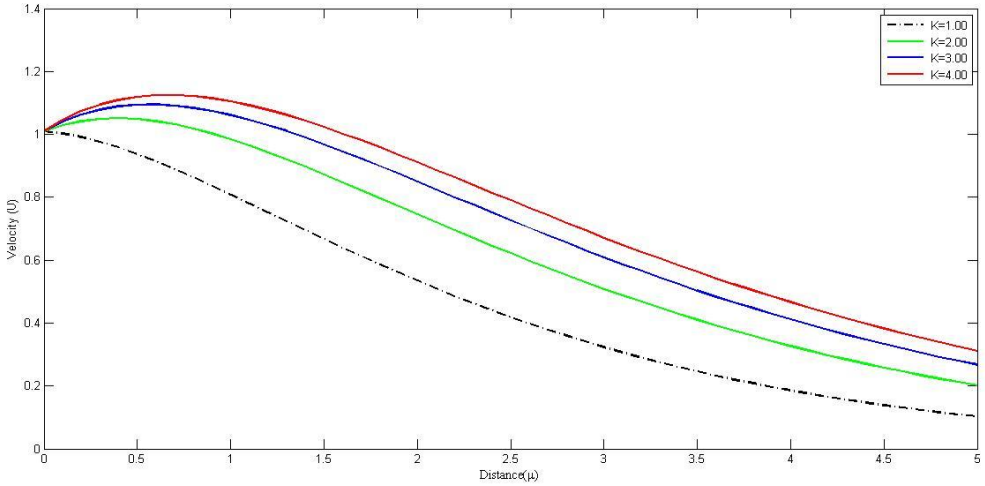

Figure 4.1.5: Velocity profile for different values of K

4.2 Temperature profile

Figure 4.2.1 represents the impact of Prandtl number Pr on the temperature profiles. It is found that increase in Prandtl number causes a decrease in the thermal boundary layer of the fluid, because, either increases of kinematic viscosity or decrease of thermal conductivity leads to increase in the value of Prandtl number. Hence temperature decreases with increasing of Prandtl number. The effect of the mass absorption parameter on the temperature field is displayed in Figure 4.2.2. It is depicted that the temperature of the fluid rises as mass absorption becomes significant. **Error! Reference source not found.** displays velocity profiles for different values of heat absorption parameter (ϕ). It is obvious that as ϕ increases the thermal boundary layer rises. 4.2.2 exhibits the effect of injection parameter on the temperature of the fluid. It is shown that as injection rises the temperature within the boundary layer is higher.

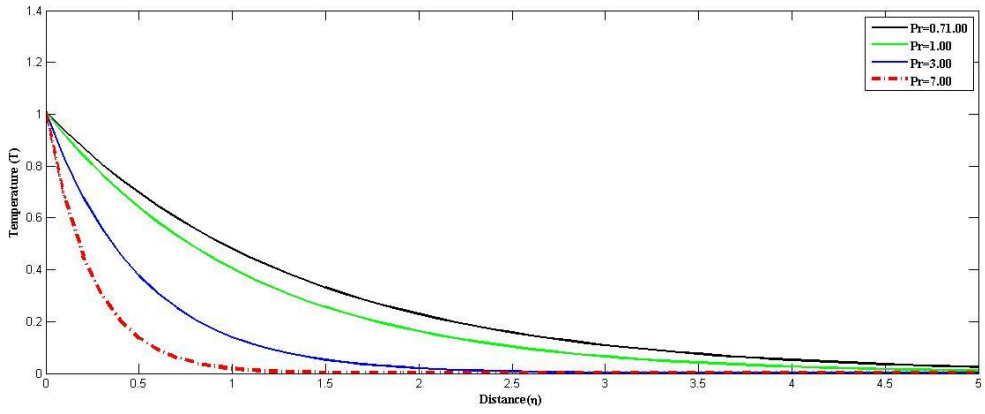

Figure 4.2.1: Temperature profile for different values of Pr

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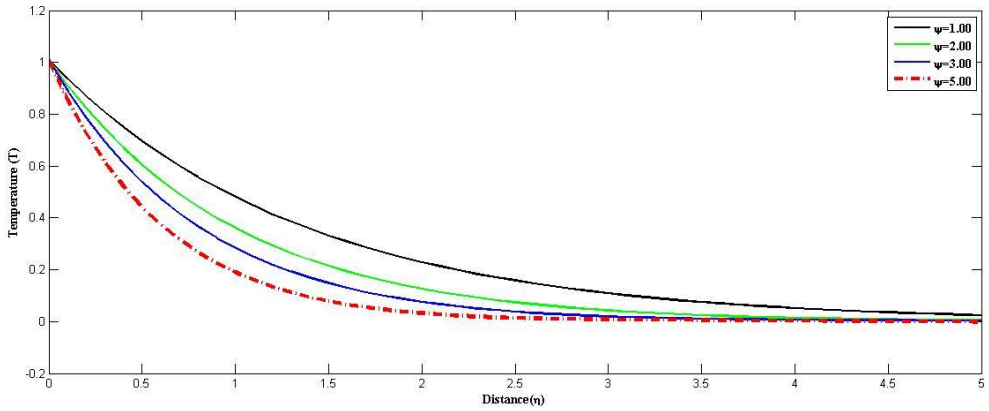

Figure 4.2.2: Temperature profile for different values of ψ.

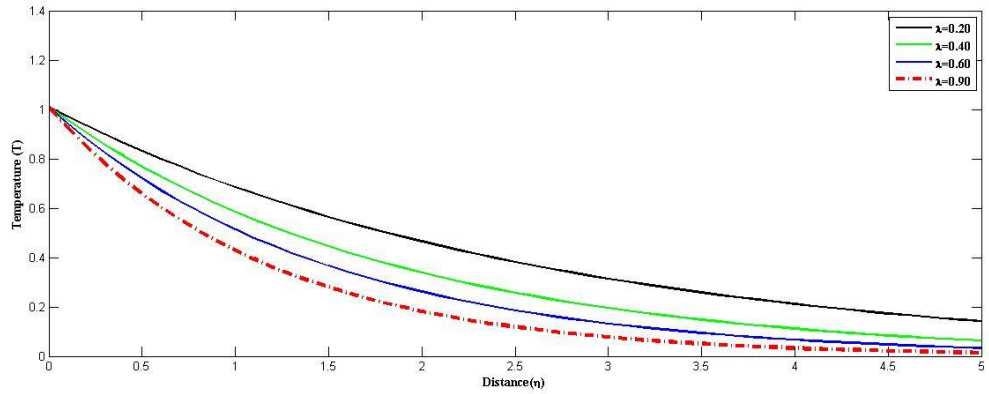

Figure 4.2.3: Temperature profile for different values of λ_1.

4.3 Concentration parameter

Figure 4.3.1 depicts the effect of suction on the concentration profiles. It is seen that the concentration of the fluid becomes lower as suction becomes significant. The concentration profiles of Figure 4.3.2 demonstrate the concentration profiles at some Schmidt values. The concentration decreases with increase in Schmidt value (Sc). The causes a narrower concentration boundary layer and reduced penetration of a solute in the fluid. Because the steeper concentration gradients are associated with slower diffusion of mass with increasing Sc. This causes a narrower concentration boundary layer and reduced penetration of a solute in the fluid. Figure 4.3.3 shows the plot of the concentration profiles for different values of Soret number. It is seen that the mass boundary layer decreases as Sc is increased. Soret effect or thermal diffusion refers to mass flow developed because of differences in temperature. The Soret effect accelerates the mass transfer between the fluid through the fluid space, hence, making the fluid to have a lowered concentration. The effect of chemical reaction on the concentration of the fluid is depicted in Figure 4.3.4. It is clear that the fluid's concentration rises and the chemical reaction parameter is increased.

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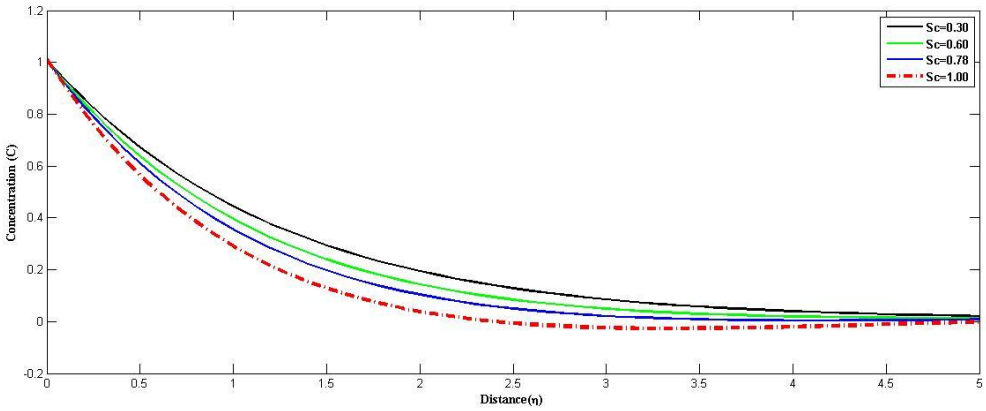

Figure 4.3.1: Concentration profile for different values of Sc.

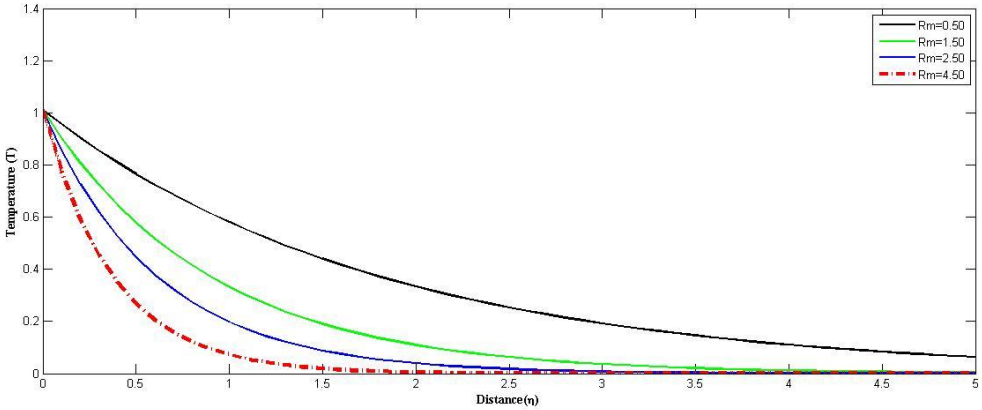

Figure 4.3.2: Concentration profile for different values of R_m.

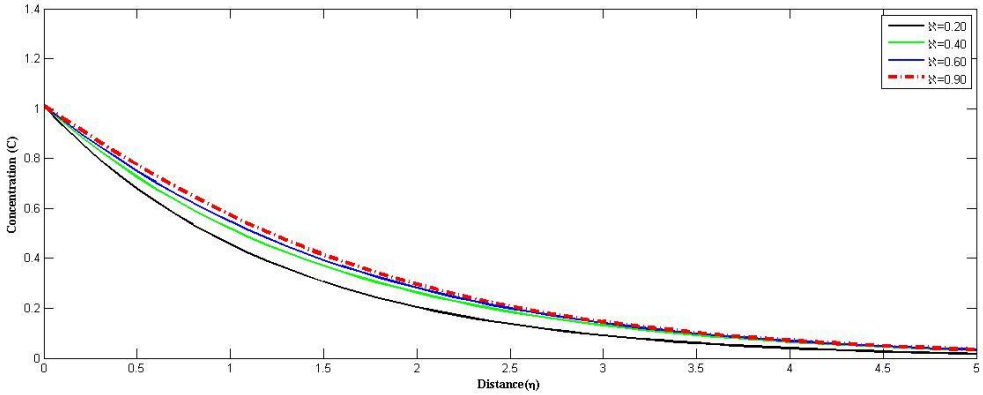

Figure 4.3.3: Concentration profile for different values of ℵ.

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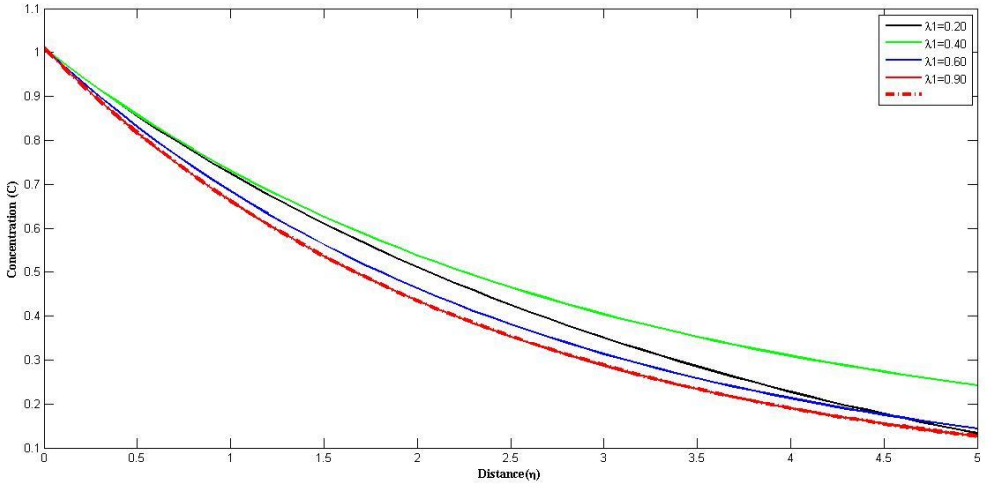

Figure 4.3.4: Concentration profile for different values of λ_1.

5.0 CONCLUSION

The current paper gives the analytical solution of injection/suction effect of heat absorption on kuvshinski fluid flow in a saturated porous medium in the presence of injection and chemical reaction mechanisms. Specifically, the governing boundary layer equations are made up with suitable boundary conditions. The boundary layer equations are simplified and non-dimensionalized. The velocity, temperature and concentration solutions are obtained by regular perturbation method. The effects of the relevant parameters on the velocity, temperature and concentration profiles are shown graphically. Our results are compared with the research conducted by Omokhuale (2023), and a very good agreement is found. The most significant conclusion are as follows:

1. An increase in the Magnetic field parameter, heat absorption improves the velocity profiles.
2. Both the thermal and mass Grashof numbers enhance the velocity profile, indicating the influence of buoyancy forces driven by temperature and concentration gradients. On the other hand, a similar trend is observed for increasing values of velocity profile and porosity parameters while a reverse pattern is seen for higher magnetic parameter.
3. Both Schmidt and Prandtl numbers lead to a fall in the momentum, mass and thermal boundary layers. An opposite trend is found as injection become significant.
4. The concentration of the fluid reduces as chemical reaction parameter rises while increase in mass absorption parameter

causes an increase in the fluid's velocity and temperature.

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BOOK OF PROCEEDINGS

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Appendix

$$a_6 = \sqrt{\frac{p_r^2 - 4\Psi p_r}{4}}, \quad a_7 = \sqrt{\frac{p_r^2 - 4(\Psi - \lambda w^2 - w)p_r}{4}}, \; d_1 = \frac{p_r^2}{2} + a_6, \; d_3 = \frac{-p_r^2}{2} + a_7$$

$$E_{16} = 1 - E_{17} - E_{18}, \; E_{17} = \frac{-G_r}{[d_4^2 - d_4 - a_2]}, \quad E_{18} = \frac{-G_m}{[d_8^2 - d_8 - a_2]}$$

$$\phi_0(\quad) = E_1 e^{d_1 \chi} + E_2 e^{-d_2 \chi}$$

$$a_1 = \left(m + \frac{1}{k}\right), \; a_2 = \left(m + \frac{1}{k} + \lambda_1 m w + \frac{\lambda_1 w}{k} + w + \lambda_1 w^2\right), \; a_3 = (\phi_0 - \Psi\phi_0, a_4 = (\Psi + w + \lambda_1 w^2)$$

$$a_5 = (R_m + w + \lambda_1 w^2)$$