Journal of Basics and Applied Sciences Research (JOBASR)
ISSN (print): 3026-9091, ISSN (online): 1597-9962
Volume 2(2) June 2024
DOI: https://doi.org/10.33003/jobasr-2024-v2i2-53

Influence of Thermal Diffusion (Soret Term) on Heat and Mass Transfer Flow over a Vertical Channel with Magnetic Field Intensity

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Keywords:
Soret term, Heat and Mass Transfer, Magnetic Field, Thermal Radiation.

ABSTRACT
The influence of thermal diffusion (Soret term) on heat and mass transfer flow over a vertical channel with magnetic field intensity was studied. The non-linear partial differential equations governing the flow are non-dimensionalised, transformed to a steady state and solved semi-analytically using perturbation method. Graphical results for velocity, temperature, concentration, skin friction, Nusselt number and Sherwood number have been obtained, to show the effects of different parameters entering into the problem. Results from these study shows that velocity and concentration increase with the increase in the thermal diffusion (Soret term). It is fascinating to note thatthe solution of the present work aligns with that of the anchor paper by silencing the thermal diffusion (Soret term) in the present work.

INTRODUCTION

The study of magnetohydrodynamic flows through porous media is of considerable interest because of its abundant applications in several branches of science and technology; such as in astrophysical, geo-physical problem and in developing magnetic generator for obtaining electrical energy at minimum cost. The theory developed by viscous flow through porous media is useful in analyzing the influence of temperature and pressure on flow of soil water. The unsteady free convection flows over a semi-infinite vertical plate was studied by Takhar *et al*. (1997). Takhar and Ram (1994) also studied the MHD free porous convection heat transfer of water 400C through a porous medium. Raju and Varma (2011) considered the unsteady MHD free convection oscillatory Couette flow through a porous medium with periodic wall temperature. In the context of space technology in process involving high temperatures, the effects of radiation are vital importance. Recent developments in hypersonic flights, missile, rocket combustion chambers, power plants for inter planetary flight and gas cooled nuclear reactors, have focused attention on thermal radiation as a mode of energy transfer, and emphasize the need for improved understanding of radiative transfer in these processes. Several authors (Raju et al., (2012); Nath *et al.*, (1991); Raptis and Perdikis, (1999); Bakier, (2001); Kim, (2000); Chamkha and Khaled, (2001) have studied thermal radiating MHD boundary layer flows with applications in astrophysical fluid dynamics. Combined the heat and mass transfer problems with chemical reaction are of importance in many processors and have there fore received a considerable amount of attention in recent years. Das *et al.* (1994) have studied the effect of homogeneous first order chemical reaction on the flow past an impulsively started infinite vertical porous plate was studied by Raju *et al.* (2013). Chamkha (2000) studied the MHD flow past a uniformly stretched vertical permeable surface in the presence of heat generation/absorption. As per, Mahdy and Ah-med (2015), the Soret effect, for instance, has been utilized for isotope separation, and in mixture between gases with very light molecular weight (H2, He). Raju *et al.* (2008) analyzed the Soret effects due to natural convection between heated inclined plates with magnetic field. Recently, Ablel-Rahman (2008) studied the thermal diffusion effect on MHD combined free forced convection and mass transfer flow of a viscous fluid through a porous medium with heat generation. Thermo diffusion and chemical effects with simultaneous thermal and mass diffusion in MHD mixed convection flow with Ohmic heating was considered by Reddy.*et al*. (2009). Recently, Sarma *et al.* (2014) studied MHD free convection and mass transfer flow past an accelerated vertical plate with chemical reaction in presence of radiation. Ahmed and Batin (2014) considered magnetohydrodynamic heat and mass transfer flow with induced magnetic field and viscous dissipative effects. Mutuku-Njane and Makinde (2014) investigated on hydromagnetic boundary layer flow of nanofluids over a permeable

How to cite this article: Ibrahim, Y., Adamu, I., Ibrahim, U. T., and Sa'adu, A. (2024). Influence of Thermal Diffusion (Soret Term) on Heat and Mass Transfer Flow over a Vertical Channel with Magnetic Field Intensity. *Journal of Basics and Applied Sciences Research*, *2*(2), 60-70. https://doi.org/10.33003/jobasr-2024-v2i2--53

moving surface with Newtonian heating. The study of thermal conductivity and magnetic field intensity effects on heat and mass transfer flow over a vertical channel both numerically and analytically was investigated by Uwanta and Usman (2014). A numerical investigation on the study of the effect of thermal conductivity on MHD flow past an infinite vertical plate with Soret and Dufour effects has been carried out by Usman and Uwanta (2013).

Motivated by the above studies, in this paper we have considered thermal diffusion (Soret effect) on heat and mass transfer flow with magnetic field intensity. The novelty of this study is the consideration of thermal diffusion (Soret effect). In spite of that many authors contributed similar works, still there are many interesting aspects to be considered. Hence authors are encouraged to carry on with the further investigation.

MATERIALS AND METHODS

Consider an unsteady flow of a viscous incompressible fluid past a vertical channel with variable thermal conductivity and magnetic field intensity. A magnetic field B_0 of uniform strength is applied transversely to the direction of the flow. The $x'-$axis is taken along the plate in the vertically upward direction and the $y'-$axis is normal to the plate in the direction of the applied uniform magnetic field. The fluid been electrically conducting, the magnetic Reynolds number is assumed to be very small and hence the induced magnetic field can be neglected in comparison with the applied magnetic field in the absence of any input electric field. It is also assumed that the effect of viscous dissipation is negligible in the energy equation. Under the above assumptions as well as Boussinesq's approximation, the equations of conservation of mass, momentum, energy and species governing the free convection boundary layer flow past a vertical channel can be expressed as:

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

$$\frac{\partial u'}{\partial t'}=v\frac{\partial^2 u'}{\partial y'^2}-\frac{\sigma B_0^2}{\rho}u'-\frac{v}{k^*}u'+g\beta\left(T'-T'_0\right)+g\beta^*\left(C'-C'_0\right) \tag{2}$$

$$\frac{\partial T'}{\partial t'}=\frac{k_0}{\rho C_P}\frac{\partial}{\partial y'}\left[1+\alpha\left(T'-T'_0\right)\frac{\partial T'}{\partial y'}\right]-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y'} \tag{3}$$

$$\frac{\partial C'}{\partial t'}=D\frac{\partial^2 C'}{\partial y'^2}-R^*\left(C'-C'_0\right)+\frac{D_m K_T T_0^2}{c_s c_p D C_0^2}\frac{\partial^2\theta}{\partial y^2} \tag{4}$$

With the following initial and boundary conditions as follows:

$$\begin{aligned}&t\le 0,\ u'=0,\ T'\to T'_w,\ C'\to C'_w\ \ for\ all\ y'\\&t>0,\ u'=0,\ T'=T'_w,\ C'=C'_w\ \ at\ y'=0\\&\qquad u'=0,\ T'=T'_0,\ C'=C_0\ \ at\ \ y'=H\end{aligned} \tag{5}$$

The thermal radiation is assumed to be present in the form of a unidirectional flux in the y- direction that is transverse to the vertical surface. Using the Roseland approximation, the radiative heat flux q_r is given by:

$$q_r=-\frac{4\sigma_0'}{3k'}\frac{\partial T'^4}{\partial y'} \tag{6}$$

Where u' and v' are the Darcian velocity components in the x and y directions respectively, t is the time, v is the kinematic viscosity, g acceleration due to gravity, β is the coefficient of volume expansion with temperature, ρ is the density of the fluid, σ is the scalar electrical conductivity, β^* is the volumetric coefficient of expansion with concentration, C_p is the specific heat capacity at constant pressure, k^* is the dimensionless permeability of the porous medium, k_0 is the dimensionless thermal conductivity of the ambient fluid, α is the constant depending on the nature of the fluid, R^* is the dimensionless chemical reaction, D is the coefficient of molecular diffusivity, B_0 is the magnetic induction of constant strength, q_r is the radiative heat flux in the $y-$direction, σ'_0 is the Stefan-Boltzmann constant, k' is the mean absorption coefficient, $T'\ and\ T'_0$ are the temperatures of the fluid inside the thermal boundary layer and the fluid temperature in the free stream respectively, while $C'\ and\ C'_0$ are the corresponding concentrations.

To obtain the solutions of equations (2), (3) and (4) subject to the conditions (5) in non-dimensional forms, we introduce the following non-dimensional quantities:

$$\begin{aligned}&u=\frac{u'}{u_0},\ t=\frac{t'u_0}{H^2},\ y=\frac{y'}{H},\ \theta=\frac{T'-T'_0}{T'_w-T'_0},\\&C=\frac{C'-C'_0}{C'_w-C'_0},\ \Pr=\frac{u_0\rho C_p}{k_0},\ M=\frac{\sigma B_0^2H^2}{\rho u_0},\\&Sc=\frac{u_0}{D},\ k=\frac{k^*u_0}{vH^2},\ K_r=\frac{R^*H^2}{\rho u_0^2},\ \lambda=\alpha\left(T'-T'_0\right),\\&R=\frac{16a\sigma'_0HT'^3_0}{k'u_0^2},\ Gr=\frac{H^2g\beta\left(T'_w-T'_0\right)}{u_0^2},\\&Gc=\frac{H^2g\beta^*\left(C'_w-C'_0\right)}{u_0^2},\ Sr=\frac{D_mK_TT_0^2}{c_sc_pDC_0^2}\end{aligned} \tag{7}$$

Applying these non-dimensionless quantities (7), the set of equations (2), (3), (4) and (5) reduces to the following:

$$\frac{\partial u}{\partial t}=\frac{\partial^2 u}{\partial y^2}-Mu-\frac{1}{k}u+Gr\theta+GcC \tag{8}$$

$$\Pr\frac{\partial \theta}{\partial t}=(1+\lambda\theta)\frac{\partial^2 \theta}{\partial y^2}+\lambda\left(\frac{\partial \theta}{\partial y}\right)^2-R\theta \tag{9}$$

$$\frac{\partial C}{\partial t}=\frac{1}{Sc}\frac{\partial^2 C}{\partial y^2}-ScKrC+Sr\frac{\partial^2 \theta}{\partial y^2} \tag{10}$$

The initial and boundary conditions in non-dimensional quantities are:

$$\begin{aligned} &t\le 0,\ u=0,\ \theta=0,\ C=0\ \ for\ all\ y\\ &t>0,\ u=0,\ \theta=1,\ C=1\ at\ y=0\\ &\quad u=0,\ \theta=0,\ C=0\ at\ y=1\end{aligned} \tag{11}$$

Where M is the magnetic field parameter, k is the porous material, Gr is the thermal Grashof number, Gc is the solutal Grashof number, $\Pr$ is the Prandtl number, λ is the variable thermal conductivity parameter, R is the radiation parameter, Kr is the chemical reaction parameter, Sc is the Schmidt number, Sr is the Soret term, t is the dimensionless time, while $u\ and\ v$ are the dimensionless velocity components in $x-and\ y-$ directions respectively.

ANALYTICAL SOLUTIONS

The governing equations presented in this problem are highly coupled and non-linear and exhibit no closed-form solutions. It is, therefore, of interest to reduce the governing equations of the present problem to a form that can be solved in closed form. At steady state, the physical parameters do not have any effect, hence the steady state equations and boundary conditions for the problem can be written as:

$$\frac{d^2u}{dy^2}-\left(M+\frac{1}{k}\right)u+Gr\theta+Gc=0 \tag{12}$$

$$\frac{d^2\theta}{dy^2}-R\theta=0 \tag{13}$$

$$\frac{d^2C}{dy^2}-ScKrC+Sr\frac{d^2\theta}{dy^2}=0 \tag{14}$$

The boundary conditions are:

$$\begin{aligned} &u=0,\ \theta=1,\ C=1\quad at\quad y=0\\ &u=0,\ \theta=0,\ C=0\quad at\quad y=1\end{aligned} \tag{15}$$

To find the approximate solution to equations (12) -(14) subject to equation (15), we use perturbation method, which is a method that is used to approximate the solution to a differential equation analytically. Therefore, the physical variables $u,\theta\ and\ C$ can be expressed in the power of $(R<<1)$. This can be possible physically as R for the flow is always less than unity. Hence, we can assume the solution of the form

$$\begin{aligned} u&=u_0(y)+Ru_1(y)+0(R^2)\\ \theta&=\theta_0(y)+R\theta_1(y)+0(R^2)\\ C&=C_0(y)+RC_1(y)+0(R^2)\end{aligned} \tag{16}$$

Using equation (16) in equations (12)-(14) and equating the coefficient of like powers of R we have:

$$u_0''-\left(M+\frac{1}{k}\right)u_0=-Gr\theta_0+GcC_0 \tag{17}$$

$$\theta_0''=0 \tag{18}$$

$$C_0''-ScKrC_0+Sr\theta_0''=0 \tag{19}$$

$$u_1''-\left(M+\frac{1}{k}\right)u_1=-Gr\theta_1-GcC_1 \tag{20}$$

$$\theta_1''=\theta_0 \tag{21}$$

$$C_1''-ScKrC_1+Sr\theta_1''=0 \tag{22}$$

The corresponding boundary conditions are:

$$\begin{aligned} &u_0=0,\ \theta_0=1,\ C_0=1\\ &u_1=0,\ \theta_1=0,\ C_1=0\qquad at\qquad y=0\\ &u_0=0,\ \theta_0=0,\ C_0=0\\ &u_1=0,\ \theta_1=0,\ C_1=0\qquad at\qquad y=1\end{aligned} \tag{23}$$

Solving equation (17)-(22) with the help of equation (23), we get:

$$\begin{aligned} u_0&=H_1e^{y\sqrt{\alpha}}+H_2e^{-y\sqrt{\alpha}}+E_1+E_2y+\\ &E_3e^{y\sqrt{ScKr}}+E_4e^{-y\sqrt{ScKr}}\end{aligned} \tag{24}$$

$$\theta_0=1-y \tag{25}$$

$$C_0=A_1e^{y\sqrt{ScKr}}+A_2e^{-y\sqrt{ScKr}} \tag{26}$$

$$\begin{aligned} u_1&=H_3e^{y\sqrt{\alpha}}+H_4e^{-y\sqrt{\alpha}}+E_5+E_6y+E_7y^2+\\ &E_8y^3+E_9e^{y\sqrt{ScKr}}+E_{10}e^{-y\sqrt{ScKr}}\end{aligned} \tag{27}$$

$$\theta_1=-\frac{1}{3}y+\frac{1}{2}y^2-\frac{1}{6}y^3 \tag{28}$$

$$C_1=B_1e^{y\sqrt{ScKr}}+B_2e^{-y\sqrt{ScKr}}+B_3+B_4y \tag{29}$$

In view of the above equations, the solutions are:

$$\begin{aligned} u(y)&=H_1e^{y\sqrt{\alpha}}+H_2e^{-y\sqrt{\alpha}}+E_1+E_2y+E_3e^{y\sqrt{ScKr}}+\\ &E_4e^{-y\sqrt{ScKr}}+R\begin{pmatrix}H_3e^{y\sqrt{\alpha}}+H_4e^{-y\sqrt{\alpha}}+E_5+\\ E_6y+E_7y^2+E_8y^3+\\ E_9e^{y\sqrt{ScKr}}+E_{10}e^{-y\sqrt{ScKr}}\end{pmatrix}\end{aligned} \tag{30}$$

$$\theta(y)=1-y+R\left(-\frac{1}{3}y+\frac{1}{2}y^2-\frac{1}{6}y^3\right) \tag{31}$$

$$C(y)=A_1e^{y\sqrt{ScKr}}+A_2e^{-y\sqrt{ScKr}}+R\begin{pmatrix}B_1e^{y\sqrt{ScKr}}+\\ B_2e^{-y\sqrt{ScKr}}+\\ B_3+B_4y\end{pmatrix} \tag{32}$$

The skin friction, Nusselt number and Sherwood number are the important physical parameters for this type of boundary layer flow, which in non-dimensional form respectively are given by:

$$\left.\frac{du}{dy}\right|_{y=0} = H_1\sqrt{\alpha} - H_2\sqrt{\alpha} + E_2 + E_3\sqrt{ScKr} - E_4\sqrt{ScKr} + R\begin{pmatrix} H_3\sqrt{\alpha} - H_4\sqrt{\alpha} + \\ E_6 + E_9\sqrt{ScKr} - \\ E_{10}\sqrt{ScKr} \end{pmatrix} \quad (33)$$

$$\left.\frac{d\theta}{dy}\right|_{y=0} = -1 + R\left(-\frac{1}{3}\right) \quad (34)$$

$$\left.\frac{dC}{dy}\right|_{y=0} = A_1\sqrt{ScKr} - A_2\sqrt{ScKr} + R\begin{pmatrix} B_1\sqrt{ScKr} - \\ B_2\sqrt{ScKr} + B_4 \end{pmatrix} \quad (35)$$

RESULTS AND DISCUSSIONS

Results

In order to report on the analysis of the fluid flow, analytical computations are carried out for various values of magnetic parameter (M), thermal Grashof number (Gr), solutal Grashof number (Gc), permeability parameter (k), radiation parameter (R), Schmidt number (Sc), chemical reaction parameter (Kr), and thermal diffusion term $(Sr,\ Soret\ term)$.

Therefore, this study is focused on the effects of these governing parameters on steady velocity, temperature as well as concentration profiles. The diffusing species of most common interest in air has Schmidt number and is taken for water $(Sc = 0.60)$, carbon dioxide $(Sc = 0.94)$, Methanol $(Sc = 1.0)$, and Propyl benzene $(Sc = 2.62)$. The value of thermal Grashof number is taken to be positive which corresponds to the cooling of the plate.

The default values of the thermo physical parameters are specified as follows:

$$Gr = 5.0, Gc = 5.0, M = 2.0, k = 0.5$$
$$R = 5.0, Kr = 1.0, Sc = 0.60, Sr = 2.0$$

All graphs are therefore, correspond to these values unless otherwise indicated.

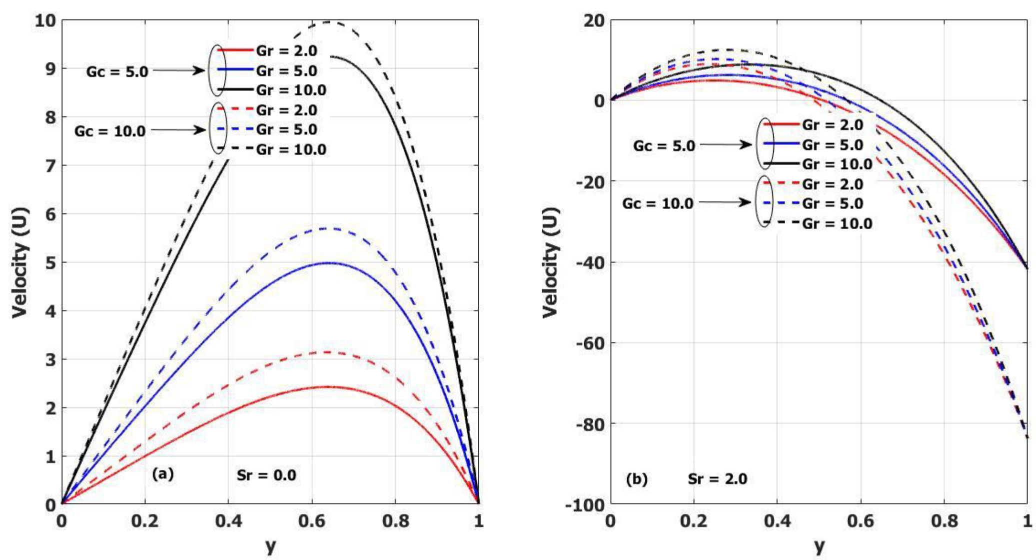

Figure 1: Comparison between the work of Uwanta and Usman (2014) and the present work.

Figure 1 illustrate the comparison between the velocity profile analysis conducted by Uwanta and Usman (2014) and the current study. Figure 1(a) portray the relationship between (Gr) and various values of (Gc) in the absent of (Sr), while Figure 1(b) represent the role of (Gr) with respect to different values of (Gc) under the action of (Sr). It is noticed that an increase in (Gr) and (Gc) results in an increase in the velocity profile, due to the fact that increase in the values of (Gr) and (Gc) has the tendency to increase the thermal and mass buoyancy effect. It is pertinent to also note that the inclusion of (Sr) in Figure 1(b) leads to the suppression of the velocity distribution.

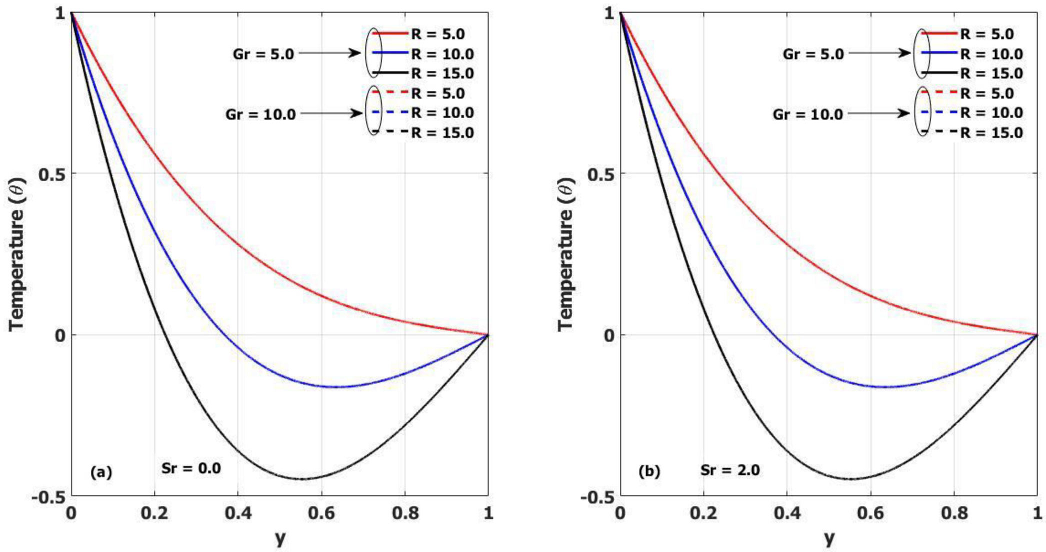

Figure 2: Comparison between the work of Uwanta and Usman (2014) and the present work.

Figure 2 represent the comparison between the temperature profile analysis conducted by Uwanta and Usman (2014) and the current study. Figures 2(a) and 2(b) portray the relationship between (R) and various values of (Gr). However, it is observed that in Figure 2(b), there is very insignificant influence of (Sr) on the flow that significantly boost fluid temperature profile at both the cold plate and the hot plate respectively.

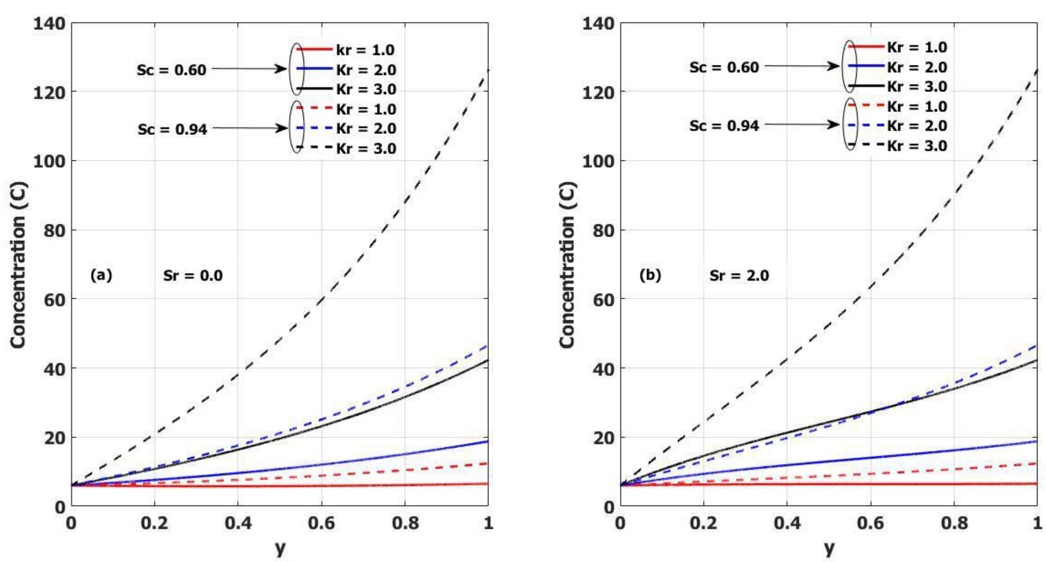

Figure 3: Comparison between the work of Uwanta and Usman (2014) and the present work.

Figure 3 represent the comparison between the concentration profile conducted by Uwanta and Usman (2014) and the current study. Figure 3(a) portray the relationship between (Kr) and various values of (Sc) in the absent of (Sr), while Figure 3(b) represent the role of (Kr) and various values of (Sc) in the present of (Sr). However, it is observed that in Figure 3(b), there is significant increase in concentration profile due to the presence of (Sr).

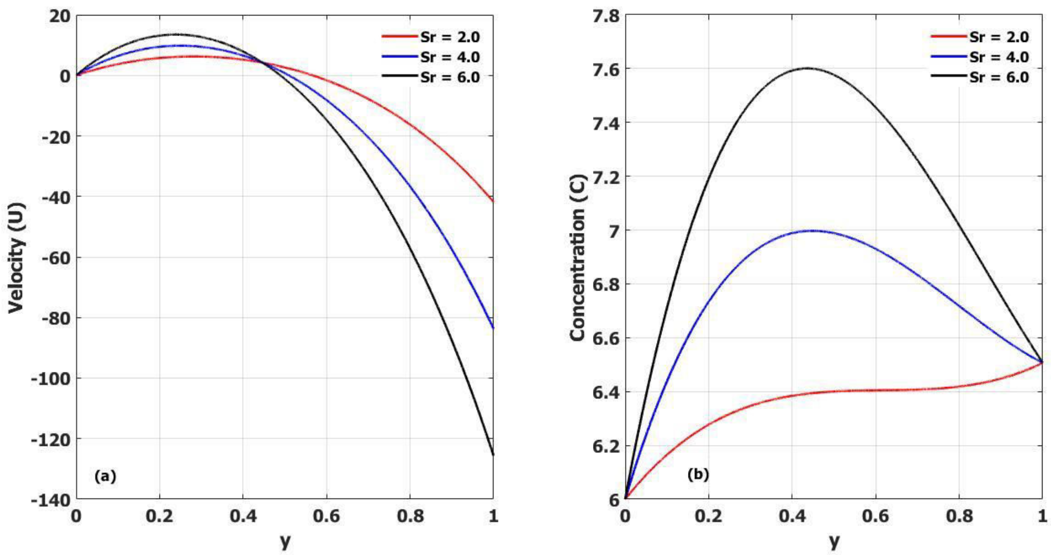

Figure 4: Velocity and Concentration profiles for different values of thermal diffusion (Sr)

Figure 4 represent the velocity and concentration profiles for different values of (Sr). It is observed in Figure 4(a) that an increase in (Sr) leads to the increase of the velocity profile at the upper plate, while the reverse is observed at the buttom plate where the velocity profile decreases. It is pertinent to report that in Figure 4(a), there exist a point of intersection at the upper part of the plate. However, in Figure 4(b), it is observed that an increase in (Sr), leads to the enhancement of the concentration profile.

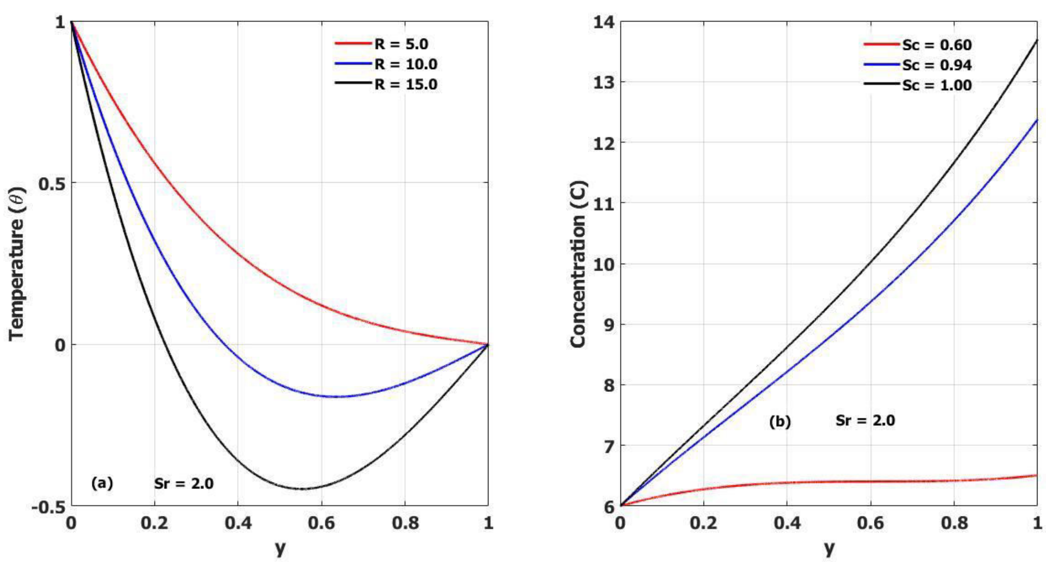

Figure 5: Temperature and Concentration profile for different values of (R) and (Sc) respectively.

Figure 5 represent the temperature and concentration profile for different values of (R) and (Sc). Figure 5(a) reveals the influence of (R) with the present of (Sr). It shows that as (R) increases, the temperature of the flow decreases. However, Figure 5(b) reveals the influence of (Sc) in the present of (Sr). It shows that as (Sc) increases, the concentration profile of the flow also increases.

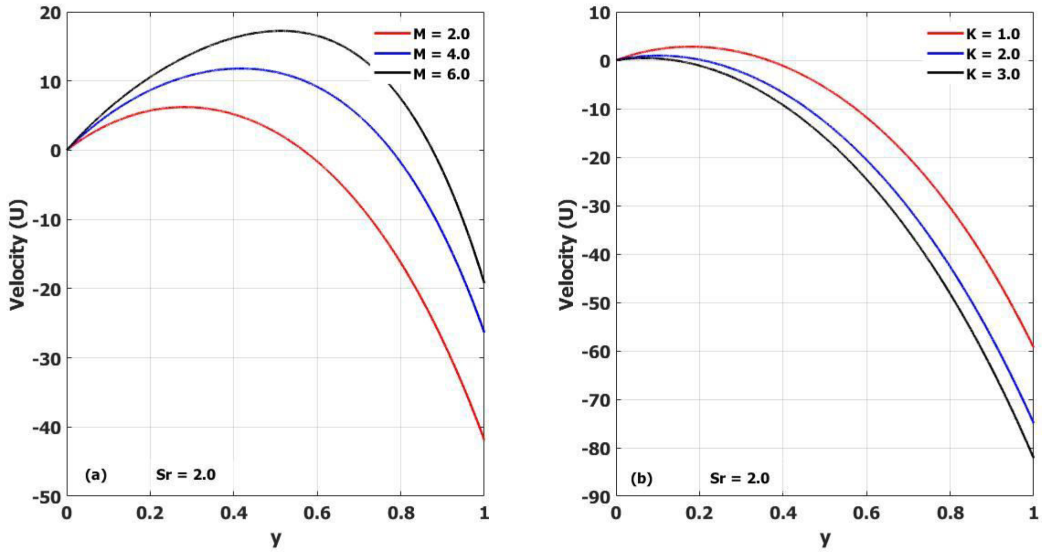

Figure 6: Velocity profile for different values of $(M) and (k)$ respectively.

Figure 6 represent the velocity profile for different values of (M) and (k). Figure 6(a) reveals the influence of (M) with the present of (Sr). It shows that as (M) increases, the velocity profile of the flow also increases. However, Figure 6(b) reveals the influence of (k) in the present of (Sr). It shows that as (k) increases, the velocity profile of the flow decreases.

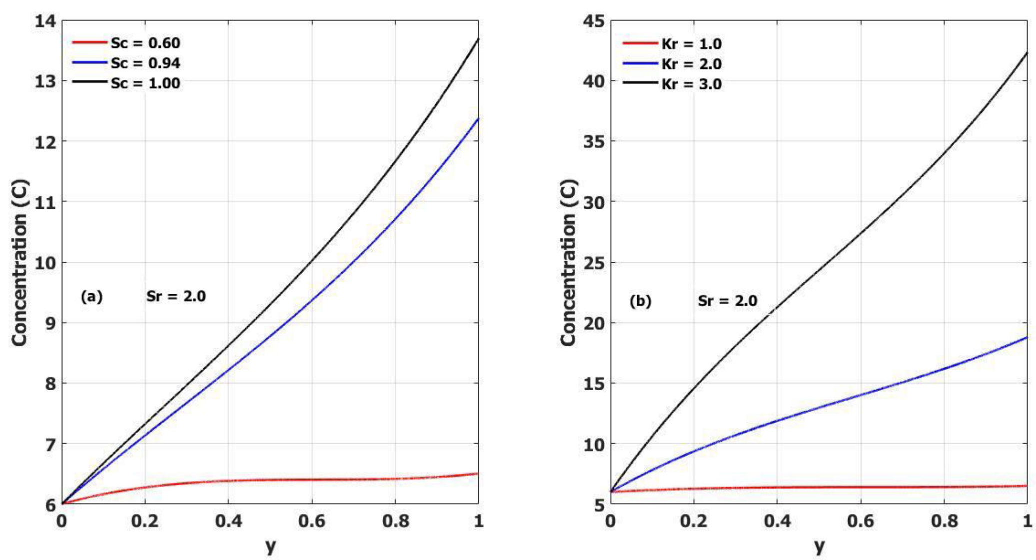

Figure 7: Concentration profile for different values of $(Sc) and (Kr)$ respectively.

Figure 7 represent the concentration profile for different values of (Sc) and (Kr). Figure 7(a) and 7(b) reveals the influence of (Sc) and (Kr) with the present of (Sr). It shows that as $(Sc) and (Kr)$ increases, the concentration profile of the flow also increases.

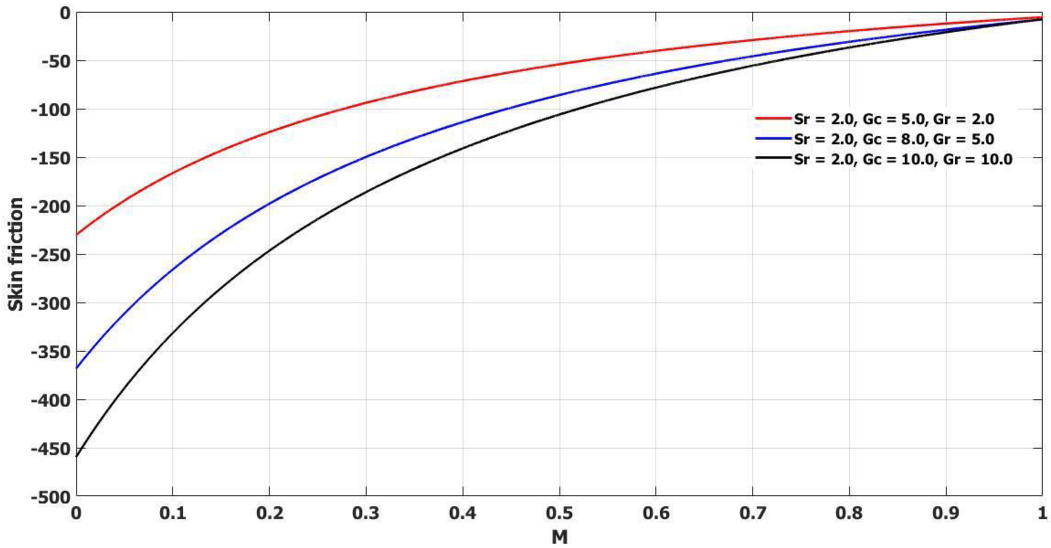

Figure 8: Skin friction for different values of $(Gc) and (Gr)$ respectively.

Figure 8 represent the skin friction for different values of $(Gc) and (Gr)$. It shows that as $(Gc) and (Gr)$ increases, the skin friction of the flow decreases.

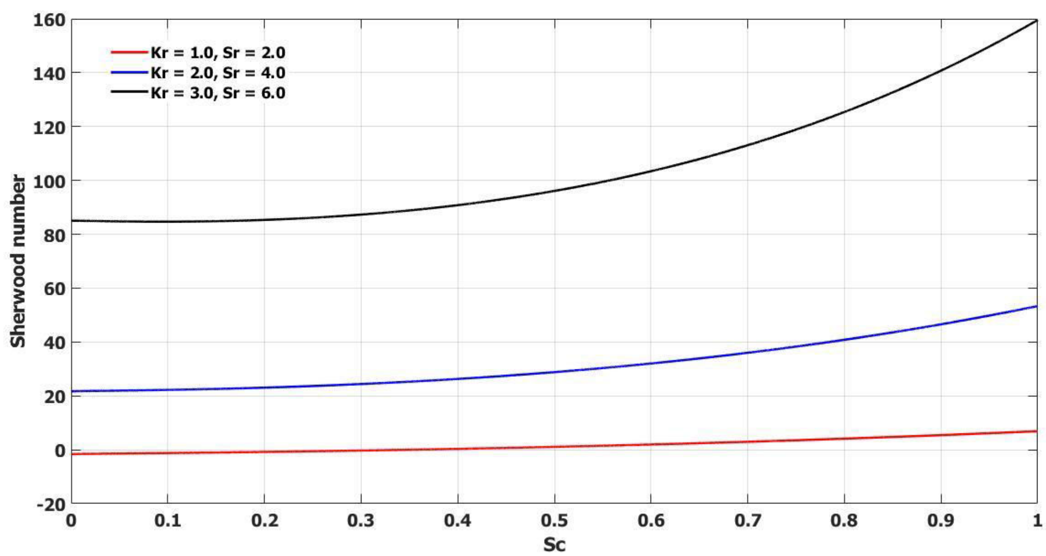

Figure 9: Sherwood number for different values of $(Kr) and (Sr)$ respectively.

Figure 9 represent the Sherwood number for different values of $(Kr) and (Sr)$. It shows that as $(Kr) and (Sr)$ increases, the Sherwood number of the flow increases.

CONCLUSION

In this paper, the influence of thermal diffusion (Soret term) on heat and mass transfer flow over a vertical channel with magnetic field intensity using semi-analytical method (perturbation technique) has been carried out. The expressions for the velocity, temperature and concentration fields have been constructed and the effects of the various parameters on heat and mass transfer characteristics of the fluid flow are discussed graphically. From the present analytical method, the following conclusions have been drawn:

1. The velocity of the fluid increases with an increase in thermal diffusion (Soret term) at the upper plate, thermal Grashof number, solutal Grashof number and Magnetic

parameter, while it decreases with an increase in thermal diffusion at the bottom of the plate and permeable parameter as shown in Figure 1, 4(a) and 6.

2. Increasing thermal Grashof number and thermal Radiation leads to decrease the fluid temperature. This is clearly indicated in Figure 2 and Figure 5(a).
3. An increase in concentration profile with increasing thermal diffusion (Soret term), Schmidt number and chemical reaction is observed in Figures 4(b) and 7.
4. The skin friction coefficients decrease with increasing thermal Grashof number, solutal Grashof number with the presence of thermal diffusion (Soret term) as illustrated in Figure 8.
5. It is marked in Figure 9 that the rate of concentration transfer increase with increasing value of chemical reaction and thermal diffusion (Soret term).
6. The accuracy of the present model has been verified by comparing the existing model and the present model by silencing the thermal diffusion (Soret term).

The solutions presented in this paper for various thermo physical effects would be useful for subsequent analysis in heat and mass transfer in polymer processing, metallurgical transport modeling and many geophysical processes like crude oil recovery.

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APPENDIX

$$C_1 = -1, \qquad C_2 = 1, \qquad C_3 = -\frac{1}{3},$$

$$C_4 = 0, \quad A_1 = 1 - A_2, \; A_2 = -\frac{e^{\sqrt{ScKr}}}{(e^{-\sqrt{ScKr}} - e^{\sqrt{ScKr}})},$$

$$B_1 = 1 - B_2 - B_3, \quad B_2 = \frac{B_3\left(e^{\sqrt{ScKr}} - 1\right) - e^{\sqrt{ScKr}} - B_4}{\left(e^{-\sqrt{ScKr}} - e^{\sqrt{ScKr}}\right)},$$

$$B_3 = \frac{Sr}{ScKr}, \qquad B_4 = -\frac{Sr}{ScKr},$$

$$\alpha = \left(M + \frac{1}{K}\right), \quad E_1 = \frac{Gr}{\alpha}, \qquad E_2 = -\frac{Gr}{\alpha},$$

$$E_3 = -\frac{GcA_1}{(ScKr) - \alpha}, \qquad E_4 = -\frac{GcA_2}{(ScKr) - \alpha},$$

$$E_5 = \frac{GcB_3 + 2E_7}{\alpha}, \qquad E_6 = \frac{Gr/3 - GcB_4 - 6E_8}{-\alpha},$$

$$E_7 = \frac{Gr}{2\alpha}, \qquad E_8 = -\frac{Gr}{6\alpha}, \; E_9 = -\frac{GcB_1}{(ScKr) - \alpha},$$

$$E_{10} = -\frac{GcB_3}{(ScKr) - \alpha}, \qquad H_1 = -\left(H_2 + E_1 + E_3 + E_4\right),$$

$$H_2 = \frac{E_1\left(e^{\sqrt{\alpha}} - 1\right) + E_3\left(e^{\sqrt{\alpha}} - e^{\sqrt{ScKr}}\right) + E_4\left(e^{\sqrt{\alpha}} - e^{-\sqrt{ScKr}}\right) - E_2}{\left(e^{-\sqrt{\alpha}} - e^{\sqrt{\alpha}}\right)},$$

$$H_3 = -\left(H_4 + E_5 + E_9 + E_{10}\right),$$

$$H_4 = \frac{E_5\left(e^{\sqrt{\alpha}} - 1\right) + E_9\left(e^{\sqrt{\alpha}} - e^{\sqrt{ScKr}}\right) + E_{10}\left(e^{\sqrt{\alpha}} - e^{\sqrt{ScKr}}\right) - E_6 - E_7 - E_8}{\left(e^{-\sqrt{\alpha}} - e^{\sqrt{\alpha}}\right)},$$

NOMENCLATURE

$C -$ *Concentration*
$T -$ *Temperature*
$Cp -$ *specific heat at constant pressure*
$D -$ *mass diffusivity*
$g -$ *acceleration due to gravity*
$Gr -$ *Grashof number*
$Gc -$ *solutal grashof number*
$k -$ *porous parameter*
$Nu -$ *Nusselt number*
$\Pr -$ *Prandtl number*
$Sc -$ *Schmidt number*
$R -$ *radiation parameter*
$Kr -$ *chemical reaction*
$Sr -$ *Soret term*
$C_f -$ *skin friction*
$Sh -$ *sherwood number*
$u, v -$ *velocities in the x and y direction respectively*
$x, y -$ *Cartesian coordinates along the plate and normal to it respectively*
$B_0 -$ *magnetic field of constant strength*
$M -$ *magnetic field parameter*

GREEK LETTERS

$\beta * -$ *coefficient of expansion with concentration*

$\beta -$ *coefficient of thermal expansion*

$\rho -$ *density of fluid*

$\theta -$ *dimensionless temperature*

$\nu -$ *kinematic viscosity*

$\sigma_0^{'} -$ *Stefan Boltzmann constant*

$\lambda -$ *variable thermal conductivity*

$\sigma -$ *electrical conductivity of the fluid*

SUBSCRIPT

$w -$ *condition at wall*

$\infty -$ *condition at infinity*