Thermal Diffusion (Soret Effect) on an Unsteady MHD Mixed Convective Heat and Mass Transfer Flow through Vertical Porous Medium with Chemical Reaction

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Abstract—A parametric study to investigate the effect of thermal diffusion (Soret effect) on an MHD mixed convective heat and mass transfer flow of an incompressible viscous electrically conducting fluid past a vertical porous plate. The magnetic Reynolds number is assumed to be so small that the induced magnetic field can be neglected as compared with the applied magnetic field. The resultant set of the non-dimensional governing equations are solved analytically by adopting perturbation technique. The profiles of the velocity, temperature, concentration, skin friction, Nusselt number and Sherwood number at the plate are demonstrated graphically for various values of the parameters involved in the problem and the results are physically interpreted. It is found in our discussion that thermal diffusion effect raises the fluid flow.

Keywords: Thermal-Diffusion, MHD, Dimensional, Perturbation Technique, Heat and Mass Transfer

INTRODUCTION

MHD is the science of movement in which all the characteristics of fluid with the magnetic benefits under the conduction of electric current. There are lots of applications of MHD principles in Engineering, Plasma Physics, in area of Biotechnology and Bio medical science. The effects of MHD in various heat and mass transfer problems with mixed convection are applied by several authors such as Elbashbeshy (2003), Singh *et al.* (2000) and Ahmed (2010).

Soret effect which is also known as thermal-diffusion effect concerns with the methods of separating heavier gas molecules from lighter ones by maintaining temperature gradient over a volume of a gas containing particles of different masses. The mass flux created by temperature gradient is termed as Soret or thermal –diffusion effect. In view of the importance of Soret effect, several authors have carried out their research works to investigate the problems

related to thermal-diffusion effect. Some of them are Anghel *et al.* (2000), Postenlnicu (2004), Alam *et al.* (2004) and Ahmed (2010).

Several investigators have studied the impact of reaction in several convective heat and mass transfer flows of whom Apelblat (1982) and Anderson *et.al* (1994) are price mentioning. Chambre and Young (1958) have conferred a primary order reaction within the neighbourhood of a horizontal plate. Muthucumaraswamy (2002) conferred heat and mass transfer effects on an endlessly moving isothermal surface with uniform suction by taking in to account the homogenous reaction of 1st order.

The main aim of present study is to investigate the effect of thermal-diffusion (Soret effect) on a mixed convective heat and mass transfer flow through vertical porous plate with MHD. The work is an extension to the work done by Allan and Derbery (2018).

MATHEMATICAL FORMULATION OF THE PROBLEM

In the present study, an MHD conducting heat and mass transfer flow of a viscous incompressible electrically conducting fluid past an infinite vertical porous plate with constant suction is considered as well as a uniform transverse magnetic field. This investigation is considered with the following assumptions:

- The polarization effects are assumed to be negligible and so electric field is also negligible.
- The suction velocity is constant.
- The variations of all fluid properties other than the variation of fluid density are completely ignored.
- When the plates are infinite, all the physical variables are functions of y' and t' only.
- It is assumed that the variation of expansion coefficient is negligibly small and assumed pressure and influence of the pressure on the density is negligible.
- The free stream oscillates about a steady mean.

Here, it is assumed $U'(t) = U_0(1 + \varepsilon e^{i\omega t})$, where U_0 is the mean stream velocity, ε is the amplitude of the free stream variation and U' is velocity along the plate.

We introduce a co-ordinate system, where X-axis vertically upwards along the plate, Y-axis remains perpendicular to the plate and directed to the fluid region and Z-axis remains along the width of the plate as shown in **Figure 1**

Fig. 1: Physical Model of the Problem

Let the components of velocity along the X-axis be u' and components of velocity along the Y-axis be v' . So u' is chosen in the upward direction along the plate and v' are chosen normal to the plate.

Under the given assumptions, the equations that describe the physical situation are given by:

1. Equation of Continuity:

$$\frac{\partial v'}{\partial y'} = 0 \Rightarrow v' = -v_0 \quad (1)$$

2. Momentum Equation:

$$\frac{\partial u'}{\partial t'} + v' \frac{\partial u'}{\partial y'} = -\frac{1}{\rho} \frac{\partial p'}{\partial x'} + \nu \frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma \beta_o^2}{\rho} u' \quad (2)$$

3. Energy Equation:

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

4. Concentration Equation:

$$\frac{\partial c'}{\partial t'} + v' \frac{\partial c'}{\partial y'} = D \frac{\partial^2 c'}{\partial y'^2} - \gamma (c' - c'_\infty) + D_T \frac{\partial^2 T'}{\partial y'^2} \quad (4)$$

The boundary conditions for the velocity, temperature and concentration fields are:

$$u' = 0, \quad T' = T'_w + \varepsilon (T'_w - T'_\infty) e^{i\omega t}, \quad c' = c'_w + \varepsilon (c'_w - c'_\infty) e^{i\omega t} \quad \text{at } y' = 0 \quad (5)$$

$$u' \rightarrow U' = U_0(1 + \varepsilon e^{i\omega t}), \quad T' \rightarrow T'_\infty, \quad c' \rightarrow c'_\infty \quad \text{at } y' \rightarrow \infty \quad (6)$$

Radiative heat flux term is given by

$$\frac{\partial q_r}{\partial y'} = 4\alpha^2 (T'_\infty - T') \quad (7)$$

Outside the boundary layer we consider

$$-\frac{1}{\rho} \frac{\partial p'}{\partial x'} = \frac{dU'}{dt'} + \frac{\nu}{K'} U' + \frac{\sigma}{\rho} B_0^2 U' \quad (8)$$

We now consider the following dimensionless variables as follows:

$$\begin{aligned} u &= \frac{u'}{U_0}, \quad y = \frac{V_0 y'}{v}, \quad \omega = \frac{v \omega'}{v_0^2}, \quad U = \frac{U'}{U_0} \\ t &= \frac{t' V_0^2}{v}, \quad \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty}, \quad \phi = \frac{C' - C'_\infty}{C'_w - C'_\infty} \\ N &= \frac{4\alpha^2 v}{\rho c_p v_0^2}, \quad K = \frac{K' V_0^2}{v^2}, \quad Pr = \frac{\rho v c_p}{k} \\ M &= \frac{\sigma B_0^2 v}{\rho V_0^2}, \quad Sc = \frac{v}{D}, \quad Sr = \frac{D_T (T'_w - T'_\infty)}{v (C'_w - C'_\infty)} \\ Kr &= \frac{v \gamma}{v_0^2}, \quad Gr = \frac{v \beta g (T'_w - T'_\infty)}{U_0 V_0^2}, \quad Gm = \frac{v \beta_c g (C'_w - C'_\infty)}{U_0 V_0^2} \end{aligned} \quad (9)$$

From the equation (7)–(9), the governing equations (2)–(4) are reduced to the non-dimensional form as follows:

$$\frac{\partial u}{\partial t} - \frac{\partial u}{\partial y} = \frac{\partial U}{\partial t} + \frac{\partial^2 u}{\partial y^2} + Gr\theta + Gm\phi + M_1 (U - u) \quad (10)$$

$$\frac{\partial \theta}{\partial t} - \frac{\partial \theta}{\partial y} = \frac{1}{Pr} \frac{\partial^2 \theta}{\partial y^2} + N\theta \quad (11)$$

$$\frac{\partial \phi}{\partial t} - \frac{\partial \phi}{\partial y} = \frac{1}{Sc} \frac{\partial^2 \phi}{\partial y^2} - Kr\phi + Sr \frac{\partial^2 \theta}{\partial y^2} \quad (12)$$

Where

$$M_1 = M + \frac{1}{K}$$

Applying non-dimensional variables given in equation (9), the boundary conditions (5) and (6) are reduced to the following dimensionless form as follows:

$$\begin{aligned} u &= 0, \quad \theta = 1 + \varepsilon e^{i\omega t}, \quad \phi = 1 + \varepsilon e^{i\omega t} \quad \text{at } y = 0 \\ u &\rightarrow 1 + \varepsilon e^{i\omega t}, \quad \theta \rightarrow 0, \quad \phi \rightarrow 0 \quad \text{as } y \rightarrow \infty \end{aligned} \quad (13)$$

METHOD OF SOLUTION

Now we have needed to reduce the above system of partial differential equations (10)–(12) into a system of ordinary differential equations in dimensionless form, we may consider the velocity, temperature and concentration as follows:

$$u(y, t) = u_0(y) + \varepsilon e^{i\omega t} u_1(y) \quad (14)$$

$$\theta(y, t) = \theta_0(y) + \varepsilon e^{i\omega t} \theta_1(y) \quad (15)$$

$$\phi(y, t) = \phi_0(y) + \varepsilon e^{i\omega t} \phi_1(y) \quad (16)$$

Where u_0 , θ_0 , ϕ_0 are respectively the mean velocity, mean temperature and mean concentration.

Substituting the equations (14), (15) and (16) into the equation (10), (11) and (12), neglecting the higher of ε and equating the harmonic and non-harmonic terms, we get following equations as follows:

$$\left[\frac{d^2}{dy^2} + \frac{d}{dy} - M_1 \right] u_0 = -Gr\theta_0 - Gm\phi_0 - M_1 \quad (17)$$

$$\left[\frac{d^2}{dy^2} + \frac{d}{dy} - (M_1 + i\omega) \right] u_1 = -Gr\theta_1 - Gm\phi_1 - (M_1 + i\omega) \quad (18)$$

$$\left[\frac{d^2}{dy^2} + Pr \frac{d}{dy} + NP_r \right] \theta_0 = 0 \quad (19)$$

$$\left[\frac{d^2}{dy^2} + Pr \frac{d}{dy} + P_r (N - i\omega) \right] \theta_1 = 0 \quad (20)$$

$$\left[\frac{d^2}{dy^2} + Sc \frac{d}{dy} - KrSc \right] \phi_0 = -SrSc\theta_0'' \quad (21)$$

$$\left[\frac{d^2}{dy^2} + Sc \frac{d}{dy} - Sc(Kr + i\omega) \right] \phi_1 = -SrSc\theta_1'' \quad (22)$$

Applying the equations (14), (15), and (16) the boundary conditions (13) can be written as

$$u_0 = 0, \quad u_1 = 0, \quad \theta_0 = 1, \quad \theta_1 = 1, \quad \phi_0 = 1, \quad \phi_1 = 1, \quad \text{at } y = 0 \quad (23)$$

$$u_0 = 1, \quad u_1 = 1, \quad \theta_0 = 0, \quad \theta_1 = 0, \quad \phi_0 = 0, \quad \phi_1 = 0, \quad \text{at } y \rightarrow \infty \quad (24)$$

Solving the equations from (17) to (22) and applying the boundary conditions (23) and (24), getting following equations:

$$\theta_0(y) = e^{m_1 y}$$

$$\theta_1(y) = e^{m_2 y}$$

$$\phi_0(y) = (1 - A_1)e^{m_3 y} + A_1 e^{m_1 y}$$

$$\phi_1(y) = (1 - A_2)e^{m_4 y} + A_2 e^{m_2 y}$$

$$u_0(y) = (A_3 + A_4 + A_5 - 1)e^{m_5 y} + 1 - A_3 e^{m_1 y} - A_4 e^{m_3 y} - A_5 e^{m_1 y}$$

$$u_1(y) = A_8 e^{m_6 y} + 1 - A_6 e^{m_2 y} - A_7 e^{m_4 y}$$

Where

$$m_1 = \frac{-Pr - \sqrt{Pr^2 - 4NPr}}{2}$$

$$m_2 = \frac{-Pr - \sqrt{Pr^2 - 4Pr(N - i\omega)}}{2}$$

$$m_3 = \frac{-Sc - \sqrt{Sc^2 + 4KrSc}}{2}$$

$$m_4 = \frac{A_8 Sc - A_6 \sqrt{Sc^2 + 4Sc(Kr + i\omega)}}{2}$$

$$M_1 = M + \frac{1}{K}, \quad M = \frac{\sigma \beta_0^2 v}{\rho v_0^2}, \quad K = \frac{K' v_0^2}{v^2}$$

$$m_5 = \frac{-1 - \sqrt{1 + 4M_1}}{2}$$

$$m_6 = \frac{-1 - \sqrt{1 + 4(M_1 + i\omega)}}{2}$$

$$A_1 = \frac{-m_1^2 Sc Sr}{m_1^2 + Sc m_1 - Kr Sc}$$

$$A_2 = \frac{-m_2^2 Sc Sr}{m_2^2 + Sc m_2 - Sc(Kr + i\omega)}$$

$$A_3 = \frac{Gr}{m_1^2 + m_1 - M_1}$$

$$(25) \quad A_4 = \frac{Gm(1 - A_1)}{m_3^2 + m_3 - M_1}, \quad A_5 = \frac{GmA_1}{m_1^2 + m_1 - M_1},$$

(26)

$$(27) \quad A_6 = \frac{Gr + GmA_2}{m_2^2 + m_2 - (M_1 + i\omega)},$$

(28)

$$A_7 = \frac{Gm(1 - A_2)}{m_4^2 + m_4 - (M_1 + i\omega)}, \quad A_8 = A_6 + A_7 - 1, \quad (31)$$

(29)

From the equations (14) to (16), we obtain velocity, temperature and concentration as follows:

(30)

$$u(y, t) = 1 + A_9 e^{m_5 y} - A_{10} e^{m_1 y} - A_4 e^{m_3 y} + \varepsilon e^{i\omega t} [A_8 e^{m_6 y} + 1 - A_6 e^{m_2 y} - A_7 e^{m_4 y}] \quad (32)$$

$$\theta(y, t) = e^{m_1 y} + \varepsilon e^{i\omega t} e^{m_2 y} \quad (33)$$

$$\phi(y, t) = (1 - A_1)e^{m_3 y} + A_1 e^{m_1 y} + \varepsilon e^{i\omega t} [(1 - A_2)e^{m_4 y} + A_2 e^{m_2 y}] \quad (34)$$

Where,

$$A_8 = A_6 + A_7 - 1, \quad A_9 = A_3 + A_4 + A_5 - 1, \quad A_{10} = A_3 + A_5 \quad (35)$$

Now we can calculate co-efficient of skin-friction at the wall of plate is given by

$$\tau_w = \left[\frac{\partial u}{\partial y} \right]_{y=0} = A_9 m_5 - m_1 A_{10} - m_3 A_4 + \varepsilon e^{i\omega t} [A_8 m_6 - A_6 m_2 - A_7 m_4] \quad (36)$$

The rate of heat transfer in terms of Nusselt number (Nu) as follows:

$$Nu = - \left[\frac{\partial \theta}{\partial y} \right]_{y=0} = -m_1 - m_2 \varepsilon e^{i\omega t} \quad (37)$$

The rate of mass transfer co-efficient in terms of Sherwood number as follows:

$$Sh = - \left[\frac{\partial \phi}{\partial y} \right]_{y=0} = -(1 - A_1) m_3 - m_1 A_1 - \varepsilon e^{i\omega t} [(1 - A_2) m_4 + A_2 m_2] \quad (38)$$

RESULTS AND DISCUSSIONS

In the present discussion, the expressions of fluid velocity, temperature, concentration viscous drag, co-efficient of rate of heat transfer and co-efficient of rate of mass transfer are piled up to get a variety of graphs with their substantial interpretations by taking some random values of different parameters implicated in the problem.

The velocity profile under the influence of Hartmann number M , Chemical reaction parameter Kr , Soret number Sr and Schmdit number Sc against the normal co-ordinate

y are exhibited in figures 2-5. It is contingent from figure 2 and 3 that, an increase in magnetic parameter M and chemical reaction parameter Kr has an inhibiting effect on fluid velocity. The fluid velocity is continuously condensed with increasing M and Kr . In other words the obligation of the transverse magnetic field and reaction tends to slow down the fluid flow. In figure 5, we observe the same trend of performance with Schmdit number Sc is concerned. But figure 4 displays the opposite behavior with respect to the above figures. i.e. the fluid motion gets accelerated under the action of mass flux.

Fig. 2: Velocity Versus y under $K=2$, $N=0.2$, $Gr=2$, $Gm=2$, $Kr=2$, $Sc=0.22$, $Pr=0.71$, $Sr=2$, $\epsilon=0.5$, $\omega=10$, $t=0.15$

Fig. 3: Velocity Versus y under $K=2$, $N=0.2$, $Gr=2$, $Gm=2$, $M=2$, $Sc=0.22$, $Pr=0.71$, $Sr=2$, $\epsilon=0.5$, $\omega=10$, $t=0.15$

Fig. 4: Velocity Versus y under $K=2$, $N=0.2$, $Gr=2$, $Gm=2$, $Kr=2$, $Sc=0.22$, $Pr=0.71$, $M=2$, $\epsilon=0.5$, $\omega=10$, $t=0.15$

Fig. 5: Velocity Versus y under $K=2$, $N=0.2$, $Gr=2$, $Gm=2$, $Kr=2$, $M=2$, $Pr=0.71$, $Sr=2$, $\epsilon=0.5$, $\omega=10$, $t=0.15$;

Fig. 6: Temperature Versus y under $N=0.2$, $\varepsilon=0.5$, $\omega=10$, $t=0.1$

Fig. 7: Temperature Versus y under $Pr=0.71$, $\varepsilon=0.5$, $\omega=10$, $t=0.15$

Figures 6 to 7 match up to the temperature distribution θ against y under the effects of the Prandtl number Pr and radiation parameter N . Rising of Pr or N shows a contrasting control on θ which indicates the fact that the fluid temperature falls down gradually for increasing values of Pr and R . It is further noticed from these figures that the fluid temperature as expected asymptotically falls from its maximum value at $y = 0$ to its minimum value at $y \rightarrow \infty$.

The effects of Soret number Sr and Schmidt number Sc on species concentration have been displayed in figures 8 and 9. It is contingent from both the figures that concentration

level of the fluid quickly rises up for increasing values of Soret number Sr and drops for increasing Schmidt number Sc . It indicates that the concentration level gets enhanced due to mass flux and high mass diffusivity.

The variations of skin friction against Ω under the influence of Hartmann number M , Chemical reaction parameter Kr , Soret number Sr and Schmidt number Sc are presented in figures 10-13. It is observed from the figures 10, 11 and 13 that an increase in magnetic intensity, chemical reaction and mass diffusivity tends to minimize the viscous drag. It is seen from figure 12 that the friction is raised by virtue of thermal diffusion effect.

Fig. 8: Concentration Versus y under $N=0.2$, $\varepsilon=0.5$, $\omega=10$, $t=0.15$, $Pr=0.71$, $Sc=0.60$, $Kr=2$

Fig. 9: Concentration Versus y under $N=0.2$, $\varepsilon=0.5$, $\omega=10$, $t=0.15$, $Pr=0.71$, $Sr=1$, $Kr=2$

Fig. 10: Skin Friction Versus ω under $K=2, N=0.2, Gr=2, Gm=2, Kr=2, Sc=0.22, Pr=0.71, Sr=2, \epsilon=0.5, t=0.15$

Fig. 11: Skin friction versus ω under $K=2, N=0.2, Gr=2, Gm=2, M=2, Sc=0.22, Pr=0.71, Sr=2, \epsilon=0.5, t=0.15$

Fig. 12: Skin Friction Versus ω under $K=2, N=0.2, Gr=2, Gm=2, Kr=2, Sc=0.22, M=2, t=0.15, Pr=0.71, \epsilon=0.5$

Fig. 13: Skin Friction Versus ω under $K=2, N=0.2, Gr=2, Gm=2, M=2, Kr=2, Pr=0.71, Sr=2, \epsilon=0.5, t=0.15$

Fig. 14: Nusselt Versus ω under $N=0.2, \epsilon=0.5, t=0.15$

Fig. 15: Nusselt Versus ω under $Pr=0.71, \epsilon=0.5, t=0.15$

**Fig. 16: Sherwood Versus ω under $N=0.2$
 $\varepsilon=0.5, t=0.15, Pr=0.71, Sc=0.60, Kr=2$**

The effects of Prandtl number Pr and radiation parameter N on the co-efficient of rate of heat transfer in terms of Nusselt number have been displayed in figures 14-15. It is found from figure 14 that the magnitude of the rate of heat transfer increases with the increase in Prandtl number Pr . This simulates that low thermal diffusivity leads the substantial rise in the heat transfer rate. Figure 15 demonstrates that the co-efficient of rate of heat transfer is reduced with the increasing values of radiation parameter N , i.e. the energy flux falls due to low thermal conductivity.

The figures 16 and 17 present the variation of the rate of mass transfer from the plate to the fluid. It is inferred from figure 16 that the Sherwood number falls down under the action of thermal diffusion effect. It is contingent from figure 17 that the co-efficient of rate of mass transfer rises under Schmidt number, i.e. the mass flux from the plate to the fluid get increased under the influence of mass diffusivity.

CONCLUSION

The following conclusions can be drawn from the present investigation of the problem:

1. The primary fluid motion is retarded under the action of transverse magnetic field and accelerated in presence of Soret number.
2. The concentration level of the fluid quickly rises up for increasing values of Soret number Sr and drops for increasing Schmidt number Sc . It indicates that the concentration level gets enhanced due to mass flux and high mass diffusivity.

**Fig. 17: Sherwood Versus ω under $N=0.2$,
 $Pr=0.71, Sr=1, Kr=2, \varepsilon=0.5, t=0.15$**

3. An increase in magnetic intensity and chemical reaction tends to minimize the viscous drag and the friction is raised by virtue of thermal diffusion effect.
4. Sherwood number falls down under the action of thermal diffusion effect and the co-efficient of rate of mass transfer rises under Schmidt number, i.e. the mass flux from the plate to the fluid get increased under the influence of mass diffusivity.

NOMENCLATURE

U	Non dimension velocity along the plate
U_0	Mean stream velocity
U'	Dimensional velocity along the plate
x, y	distances along and perpendicular to the plate, respectively
V_0	Constant suction velocity
x', y'	dimensionless distances along and perpendicular to the plate, respectively
u, v	components of dimensionless velocities along x' and y' directions respectively
u', v'	components of dimensional velocities along x' and y' directions respectively
t	non-dimensional time
t'	dimensional time
D	Diffusion co-efficient

D_T	Thermal Diffusion Ratio
K_r	Non-dimension chemical reaction parameter
K'_r	Dimensional chemical reaction parameter
K	Non-dimension porosity number
K'	Dimensional porosity number
T'	dimensional temperature of the fluid
T'_w	dimensional temperature at the plate
T'_∞	dimensional temperature in the free stream
N	Radiation parameter
K	non-dimension porosity parameter
P_r	Prandtl number
M	Magnetic parameter
Gr	Grashoff number
G_m	Grashoff number for mss transfer
S_c	Schmidt number
S_r	Soret number
C'	dimensional concentration
C'_w	dimensional concentration at the wall
C'_∞	dimensional temperature in the free stream
g	Acceleration due to gravity
p	Non dimension pressure
P'	Dimensional pressure
C_p	Specific heat at constant pressure

GREEK SYMBOLS

ρ	Density of the fluid
ν	fluid kinetic viscosity
α	Radiation absorption co-efficient
β	co-efficient of thermal expansion
β_c	Volumetric expansion co-efficient
θ	non-dimensional temperature
σ	Electrical conductivity
ϕ	non-dimensional concentration
ε	small reference parameter
ω	Frequency parameter

SUBSCRIPTS

w	Wall condition
∞	Free stream condition

SUPERSCRIPTS

$/$	Dimensional properties
$//$	Differentiation w. r. to y

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