Diffusion thermo effect on an unsteady MHD free convective mass transfer flow past an accelerated vertical plate with chemical reaction and heat sink

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Abstract
The objective of this paper is to analyze the Diffusion thermo effect on an unsteady MHD free convective mass transfer flow of a viscous incompressible electrically conducting fluid past an accelerated vertical plate embedded in a porous medium in presence of heat sink and chemical reaction. The resulting partial differential equations governing the flow have been solved by adopting Laplace-Transform technique in closed form. The expression for the velocity field, the temperature field, the concentration field are obtained. The forms of wall shear stress, Nusselt number and Sherwood number are derived. The results are shown in figures and tables followed by quantitative discussion.

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Keywords—Dufour number, Unsteady flow, Electrically conducting fluid, Laplace-Transformation technique.

INTRODUCTION
With many engineering situations such as humidifiers, dehumidifiers, cooling towers, web bulb thermometer, absorbers, evaporative condensers, combustors and many others are examples that shows the combined heat and mass transfer process taking place simultaneously.

The effect of chemical reaction depends on whether the reaction is heterogeneous or homogeneous. Das et al.

studied the effect of first order reaction on the flow past an impulsively started infinite vertical plate with uniform heat flux and mass transfer. Muthucumaraswamy and Ganesan
studied the effect of chemical reaction on unsteady flow past an impulsively started infinite vertical plate. Rapits and Perdiks
studied numerically the steady two-dimensional flow in the presence of chemical reaction over a non-linearly semi-infinite stretching sheet. Some other scholar also studied chemical reaction effects on heat and mass transfer laminar boundary layer flow e.g. Chamikha,
Kandasamy et al.
Afity,
Takhar et al.
and Reddy et al.

In the general areas of fluid dynamics and heat transfer, the subject of convective flow in porous media has attached considerable attention in the last several decades. Study of flow through porous media heavily based on Darcy’s experimental law,
Wooding
and Brinkman
have modified Darcy’s law which is used by many authors on study of convective flow in porous media. Free convection effect on a flow past a moving vertical plate embedded in porous in porous medium was analyzed by Chaudhary and Jain.

Israel-Cookey et al.
have made an analysis on MHD natural convention oscillatory Couette flow of a radiating viscous fluid in a porous medium with periodic wall temperature.

The heat and mass transfer simultaneously affecting each other that will cause the cross-diffusion effect. It has been found that an energy flux can be generated not only by temperature gradients but by concentration gradients as well. The energy flux caused by a concentration gradient is called the Dufour or diffusion-thermo effect. Diffusion-thermo (Dufour) effect was found to be a considerable magnitude such that it can’t be ignored.

Chapman and Cowling
have studied the effects of thermal diffusion and diffusion thermo on the transport of heat and mass transfer which was developed from the kinetic theory of gasses. The effect of diffusion thermo in stagnation-point flow of air with injection of gasses of various molecular weights in to boundary layer was studied experimentally by Sparrow et al.

In the present work, we have proposed to study Dufour effect on magneto hydrodynamic heat and mass transfer flow past an accelerated infinite vertical plate embedded in a porous medium in presence of chemical reaction and heat sink.

MATHEMATICAL ANALYSIS
The Dufour effect on an unsteady two-dimensional magnetohydrodynamic free convective mass transfer flow of a viscous incompressible and electrically conducting fluid past an accelerated infinite vertical plate in a porous medium in presence of chemical reaction and heat sink is considered.

We made the following assumptions

- The \( x' \)-axis is taken to be the infinite plate and the \( y' \)-axis normal to it.
- Let the components of velocity along \( x' \) axes and \( y' \) axes be \( u' \) and \( v' \) which are chosen in the upward direction along the plate and normal to the plate respectively.
Initially the plate and the fluid at the same
temperature $T_e$ with concentration level $C_e$ at all
pts. At time $t' > 0$, the plate temperature is suddenly
raised to $T_u$ and concentration level at the plate gets
raised to $C_u$ and are maintained constant thereafter.

A magnetic field of uniform strength applied
perpendicular to the plate.

It is assume that the plate is accelerated with velocity
$u' = U t'$ in its own plane at time $t' > 0$.

With the above assumption and under usual boundary layer
and boussinesq’s approximation, the governing equations reduce to

The continuity “eq.”
$$ \frac{\partial u}{\partial x} = 0 $$

The momentum “eq.”
$$ \frac{\partial u'}{\partial t'} = g \beta (T' - T_e) + g \beta' (C' - C_e) + \nu \frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_i^2 u'}{\rho} u' - \frac{u'}{K} $$

The energy “eq.”
$$ \frac{\partial T}{\partial t'} = \frac{k}{\rho C_p} \frac{\partial^2 T}{\partial y'^2} + \frac{D_{Bu} K_p}{C_p C_r} \frac{\partial^r C'}{\partial y'^2} - Q^* (T' - T_u) $$

The species diffusion “eq.”
$$ \frac{\partial C'}{\partial t'} = \frac{D_c}{\rho C_p} \frac{\partial^2 C'}{\partial y'^2} - \frac{K_p (C' - C_{u_e})}{2} $$

where $U$: acceleration of the plate, $C_p$: specific heat at
constant pressure, $C'$: species concentration, $C_e$: species
concentration in free stream, $C_{u_e}$: species concentration at the
plate, $C_r$: concentration susceptibility, $D$: chemical molecular
diffusivity, $D_M$: mass diffusivity, $g$: acceleration due to
gravity, $k$: thermal conductivity, $K'$: permeability of porous
medium, $K_r$: thermal diffusion ratio, $K_p$: chemical reaction
parameter, $Q^*$: rate of absorption, $T'$: temperature, $T_u$, $T_e$:temperature at the plate, $T_{x_e}$:temperature at the free
stream,$\beta$: coefficient of volume expansion for heat transfer, $\beta'$:
coefficient of volume expansion for mass transfer, $\mu$: coefficient of
viscosity, $\nu$: kinematic viscosity, $\rho$: fluid
density, $\theta$: non-dimensional temperature, $C$: non
dimensional concentration $\sigma$: electrical conductivity, $u'$: dimensionless
velocity component in $x'$-direction.

And the corresponding boundary conditions are
$t' \leq 0$, $u' = 0$, $T' = T_{x_e}$, $C' = C_{x_e}$ for all $y'$
$t' > 0$,
$$ u' = U t', \quad T' = T_{x_e}, \quad C' = C_{x_e} \text{ at } y' = 0
$$
$$ u' \rightarrow 0, \quad T' \rightarrow T_{x_e}, \quad C' \rightarrow C_{x_e} \text{ as } y' \rightarrow \infty $$

In order to write the governing equations and the boundary
conditions in dimensionless form, the following non-
dimensional quantities are introduced.

$$ u = \frac{u'}{u_{x_e}}, \quad t' = \frac{t' u_{x_e}^2}{u}, \quad y = \frac{y u_{x_e}}{u}, \quad T' = \frac{T' - T_{x_e}}{T_{u} - T_{x_e}}, \quad C' = \frac{C' - C_{x_e}}{C_{u_e} - C_{x_e}}, \quad C_{\infty} = \frac{C_{\infty}}{C_{u_e} - C_{x_e}} $$

The Grashof number is
$$ Gr = \frac{g \beta u (C_{x_e} - C_{u_e})}{u_{x_e}^3} $$

The Schmidt number is
$$ Sc = \frac{\nu}{\rho C_p} $$

The species diffusion number is
$$ Sc_s = \frac{D_s C_p}{\rho C_p} $$

The M mixture parameter is
$$ M = \frac{\sigma B_i^2 u}{\rho u_{x_e}^2} $$

The thermal diffusion number is
$$ Pr = \frac{\mu C_p}{k} $$

The thermal diffusion number is
$$ Pr_{T} = \frac{\sigma C_r}{\rho u_{x_e}^2} $$

The Schmidt number is
$$ Sc = \frac{\nu}{\rho C_p} $$

The Dufour number is
$$ Du = \frac{M D M K_p (C_{u_e} - C_{x_e})}{u C_p C_r (T_u - T_{x_e})} $$

The heat sink parameter is
$$ Q = \frac{Q u}{\rho C_p u_{x_e}^2} $$

where $u_{x_e}$ is characteristic velocity = $(U u)^{\frac{1}{3}}$

Hence by using the above non-dimensional quantities, the
Equations (2) to (4) in the non-
dimensional form can be written as

$$ \frac{\partial u}{\partial t} = Gr \theta + Ge C + \frac{\partial^2 u}{\partial y'^2} \left( M + \frac{1}{u} \right) u $$

$$ \frac{\partial \theta}{\partial t} = \frac{1}{Pr} \frac{\partial^2 \theta}{\partial y'^2} - Q \theta $$

$$ \frac{\partial C'}{\partial t'} = \frac{1}{Sc} \frac{\partial^2 C'}{\partial y'^2} - K C $$

And the corresponding boundary conditions are
$t' \leq 0$ : $u = 0, \theta = 0, C = 0 \forall y'$
$t' > 0$
$$ u = U t', \theta = 1, C = 1, y' = 0$$
$$ u \rightarrow 0, \quad T \rightarrow T_{x_e}, \quad C \rightarrow C_{x_e} \text{ as } y' \rightarrow \infty $$

I. SOLUTION OF THE PROBLEM

On Taking Laplace-Transforms of the equations (8) to (10) the
following differential equations are obtained

$$ d^2 \tilde{\sigma} \left( s + a \right) \tilde{u} = - Gr \tilde{\theta} - Gc \tilde{C} $$

$$ d^2 \tilde{\theta} \left( s + Q \right) \tilde{Pr} \tilde{\theta} = - Du \tilde{Pr} \frac{Sc (s + K) e^{-\sqrt{(s + K) Sc} y}}{s} $$

$$ d^2 \tilde{C} \left( s + K \right) \tilde{C} = 0 $$

subject to boundary conditions:
$$ \tilde{u} = \frac{1}{s}, \quad \tilde{\theta} = \frac{1}{s}, \quad \tilde{C} = \frac{1}{s} \text{ at } y' = 0$$
$$ \tilde{u} = 0, \quad \tilde{\theta} = 0, \quad \tilde{C} = 0 \text{ at } y' = \infty $$

where,$$ a = M + \frac{1}{\alpha}, \quad \tilde{u} = \mathcal{L} \{ u (y,t) \}$$
$$ \tilde{C} = \mathcal{L} \{ C (y,t) \}, \quad \tilde{\theta} = \mathcal{L} \{ \theta (y,t) \}$$

394
The solutions of the eqs (12) to (14) subject to boundary condition (15) are as follows:

\[ \bar{C}(y, s) = \frac{e^{\sqrt{(s+K)s}y}}{s} \]  

(16)

\[ \bar{u}(y, s) = \frac{1}{s^2} + \frac{1}{s} \left[ \frac{\text{Gr}}{s (s+K) + \alpha} \right] e^{-\sqrt{(s+K)s}y} \]  

(17)

Taking inverse Laplace-Transforms of the eqs (16) to (18) the respective concentration, temperature and velocity field are derived as furnished below:

\[ C(y, t) = \psi_{1} \]

(19)

\[ \theta(y, t) = \frac{a_3}{a_2} \phi_1 + \left( 1 - \frac{a_3}{a_2} \right) \phi_2 + \left( \frac{a_1 + a_3}{a_2} \right) e^{s \cdot \gamma} \phi_3 \]

(20)

\[ u(y, t) = \frac{y}{4\sqrt{x}} \phi_0 + \left( \frac{a_8 + \frac{a_3 a_6}{a_2 a_7}}{a_2} \right) \phi_1 + \left( \frac{a_2 a_4}{a_5} \right) \phi_2 + \left( \frac{a_3 a_4}{a_2 - a_5} \right) e^{s \cdot \gamma} \phi_3 + \left( \frac{a_1 a_6 + a_3 a_6}{a_2 - a_7} \right) e^{s \cdot \gamma} \phi_4 + \left( \frac{1 + a_4 a_4 + a_3 a_6}{a_2 - a_5} \right) e^{s \cdot \gamma} \phi_5 + \left( \frac{a_4 a_6 + a_3 a_6}{a_2 - a_5} \right) e^{s \cdot \gamma} \phi_6 + \left( \frac{a_1 a_6 + a_3 a_6}{a_2 - a_5} \right) e^{s \cdot \gamma} \phi_7 + \left( \frac{a_3 a_6 + a_3 a_6}{a_2 (a_2 - a_5)} - \frac{a_1 a_4}{a_2 (a_2 - a_5)} \right) e^{s \cdot \gamma} \phi_8 + \left( \frac{a_3 a_6 + a_3 a_6}{a_2 - a_7} + \frac{a_1 a_4}{a_2 (a_2 - a_7)} \right) e^{s \cdot \gamma} \phi_9 + \left( \frac{a_3 a_6 + a_3 a_6}{a_2 - a_7} + \frac{a_1 a_4}{a_2 (a_2 - a_7)} \right) e^{s \cdot \gamma} \phi_{10} \]

(21)

where, \( a_1 = \frac{\text{Gr} Pr Sc - K Sc}{s (s+K) s} \), \( a_2 = \frac{\text{Pr Q - K Sc}}{s (s+K) s} \), \( a_3 = K a_1 \), \( a_4 = \frac{\text{Gr} - a_5 = a - Q Pr}{s (s+K) s} \), \( a_5 = \frac{\text{Gr}}{s (s+K) s} \), \( a_6 = \frac{K a_1 + a_5}{s (s+K) s} \), \( a_7 = a - K Sc - a_5 = K a_1 \), \( a_8 = \frac{\text{Ge}}{s (s+K) s} \), \( \alpha_1 = \frac{\text{Gr} a_1 + a_5}{s (s+K) s} \), \( \alpha_2 = \frac{\text{Gr}}{s (s+K) s} \), \( \alpha_3 = K a_1 \), \( \phi_1 = \phi(K, y, Sc, t) \), \( \phi_2 = \phi(Q, y, Pr, t) \), \( \psi_3 = \phi(a_1 + Q, y, Pr, t) \), \( \phi_4 = \phi(a_2 + K, y, Sc, t) \), \( \phi_5 = \phi(a, y, 1, t) \), \( \phi_6 = \phi(a_2 + a, y, 1, t) \), \( \phi_7 = \phi(a_2 + a, y, 1, t) \), \( \phi_8 = \phi(a_2 + a, y, 1, t) \), \( \phi_9 = \phi(a_2 + a, y, 1, t) \), \( \phi_10 = \phi(a, y, 1, t) \), \( \psi_1 = \phi(K, y, Sc, t) \).

Skin-friction: The non dimensional skin friction at the plate in the direction of flow is given by:

\[ C_f = \frac{\sigma u}{\rho y} \]  

(22)
The rate of heat transfer coefficient in terms of the Nusselt number \( \text{Nu} \) at the plate is given by:

\[
\text{Nu} = - \left( \frac{\partial \theta}{\partial y} \right)_{y=0} = \psi_1
\]

Sherwood number: The rate of mass transfer coefficient in terms of the Sherwood number \( Sh \) at the plate is given by:

\[
Sh = \left( \frac{\partial C}{\partial y} \right)_{y=0} = \frac{a_3}{a_2} \psi_1 + \left( 1 - \frac{a_3}{a_2} \right) \psi_2 + \frac{a_4}{a_2} \psi_3 - \frac{a_3}{a_2} \psi_4
\]

where,

\[
\psi_1 = \psi(Sc, K, t), \quad \psi_2 = \psi(Pr, Q, t), \quad \psi_3 = \psi(Pr, a_3 + Q, t),
\]

\[
\psi_4 = \psi(Sc, a_2 + K, t), \quad \psi_5 = \psi(1, a, t), \quad \psi_6 = \psi(1, a + a_4, t),
\]

\[
\psi_7 = \psi(1, a + a_2, t), \quad \psi_8 = \psi(1, a + a_3, t), \quad \psi_9 = \psi(Pr, a_3 + Q, t),
\]

\[
\psi_{10} = \psi(Sc, a_2 + K, t), \quad \psi(x, z, t) = \frac{e^{-x/a} + \sqrt{xz} \text{erf} \left( \sqrt{zt} \right)}{\sqrt{\pi t}}
\]

RESULTS AND DISCUSSION

In order to have a physical view of the problem, non-dimensional velocity field, temperature field, concentration field, skin-friction, Nusselt number and Sherwood number are computed at the plate for different parameters involved and these values have been demonstrated in graphs and tables. The values of the Prandtl number \( Pr \) are chosen as 0.71 and 7.0 to represent air and water respectively. The values of Schmidt number \( Sc \) are chosen to represent the presence of various species such as Carbon dioxide \( (Sc = .94) \), Water vapour \( (Sc = .60) \), Helium \( (Sc = .22) \) and hydrogen \( (Sc = .30) \). The values of other parameters are chosen arbitrary.

Figure 1 to 8 demonstrate the variation of velocity field under the effect of thermal Grashof number \( Gr \), solutal Grashof number \( Gc \), Hartmann number \( M \), Schmidt number \( Sc \), Dufour number \( Du \), Prandtl number \( Pr \), Chemical reaction parameter \( K \) and Heat sink parameter \( Q \).

The change in velocity profile due to various values of solutal Grashof number \( Gc \) are displayed in Figure 2. It is found that the fluid velocity increases for increasing values of Grashof number of mass transfer.

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Figure 3 shows the behavior velocity for different values Prandtl number \( Pr \). The numerical result shows that the effect of increasing values of Prandtl number results in a decreasing velocity. It is observed that an increase in the Prandtl number results a decrease of the thermal boundary layer thickness within the boundary layer.

Figure 4 shows that the fluid velocity decreases for increasing Schmidt number. An increase in Schmidt number means a fall in mass diffusion which is followed the physical definition of Schmidt number. That is mass diffusion accelerates the fluid motion.

From Figure 5 it is found that velocity of the fluid decreases with increase of the Hartmann number values, because the Lorentz force that appears due interact of the magnetic field and fluid velocity resist the fluid motion.

It is observed from Figure 6 that the velocity is increases with increasing values of Dufour number \( Du \).

Further from Figure 7 and Figure 8 it is seen that fluid velocity decreases due to effect of chemical reaction and heat sink parameter.

The temperature of the flow with the variation of the flow parameters such as Prandtl number \( Pr \), Dufour number \( Du \), heat sink parameter \( Q \) are shown in Figure 9 to 11.

Figure 9 indicate the fact that there is a steady fall in temperature field for increasing Prandtl number.

Figure 10 shows how the fluid temperature is affected by the variations in the values of heat sink parameter \( Q \). It is seen that there is a steady fall in temperature for increasing heat sink parameter. The temperature drops as \( Q \) rises is consistent with the physical fact that when heat is absorbed by sink, there is a natural tendency to fall in temperature.

Figure 11. display the effect of Dufour number in temperature field and it is found that temperature of the flow field increases with increasing Dufour number.

How the concentration field is influenced by the flow parameters Schmidt number \( Sc \), chemical reaction parameter \( K \) are shown in Figure 12 and Figure 13.

Figure 12 shows how the concentration level of the fluid drops due to increasing Schmidt number indicating the fact that the mass diffusivity rises the concentration level . Further it is depicted from Figure 13 that concentration falls under the effect of chemical reaction parameter \( K \).

The numerical values of skin friction for various values of parameters \( Gr, Gc, Sc, Du, K \) and \( Q \) are presented in Table-1.

We observed that, an increase in the Schmidt number decrease in the values of coefficient of skin-friction while an increase in the Hartmann number, thermal Grashof number, solutal Grashof number, Heat sink parameter,
Chemical reaction parameter and Dufour number increase in the values of coefficient of skin friction. Table-2 shows the numerical values of heat transfer coefficient for different values of Prandtl number, Dufour number, heat sink parameter and chemical reaction parameter. It is observed that an increase in the Prandtl number and heat sink parameter increase in the value of heat transfer coefficient. Moreover an increase in the Dufour number and chemical reaction parameter decrease the values of coefficient of heat transfer.

Table-2 shows the numerical values of mass transfer coefficient for various values of Schmidt number and chemical reaction parameter. It is found that an increase in Sc and K increases in the values of coefficient of mass transfer.

CONCLUSION

The following are the significant outcomes of the preceding analysis:

1. The fluid flow is retarded due to imposition of the transverse magnetic field.
2. The fluid velocity decelerated in the region adjacent to the plate due to the effect of Schmidt number.
3. Acceleration in the flow and an increase in magnitude in skin-friction are observed with an increase in chemical reaction parameter.
4. Velocity and viscous drag at the plate are increases with the increase of Diffusion thermo effect.
5. The temperature decreases and Nusselt number increases with the effect of heat sink. However, Diffusion thermo effect has opposite effect on Nusselt number and temperature profile.
6. The rate of mass transfer increases and concentration decreases for chemical reaction and diffusion thermo effect.

Table-1: Skin-friction results for the values of Sc, Q, K, M, Du, Gr, Gc and α for Pr = .71

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<th>K</th>
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Table-2: Rate of heat transfer (Nu) for different values of Q, Pr, Du and K for Sc = .60 and Rate of mass transfer (Sh) values for different values of Sc and K for Pr = .71
REFERENCES


Fig-4. Velocity versus y for $M = 1, Gr = 4, Gc = 4, K = 1, \ Q = 1, \ Pr = .71, \ Du = 1, \ \alpha = 1$

Fig-5. Velocity versus y for $Sc = .6, Gr = 4, Gc = 4, K = 1, Q = 1, \ Pr = .71, \ Du = 1, \ \alpha = 1$

Fig-6. Velocity versus y for $Sc = .6, M = 1, Gr = 4, Gc = 4, K = 1, Q = 1, \ Pr = .71, \ \alpha = 1$

Fig-7. Velocity versus y for $Sc = .6, M = 1, Gr = 4, Gc = 4, Du = 1, Q = 1, \ Pr = .71, \ \alpha = 1$

Fig-8. Velocity versus y for $Sc = .6, M = 1, Gr = 4, Gc = 4, Du = 1, \ Pr = .71, \ \alpha = 1$

Fig-9. Temperature versus y for $Sc = 6, K = 1, Du = 1, Q = 1$

Fig-10. Temperature versus y for $Sc = .6, K = 1, \ Pr = .71, Q = 1$

Fig-11. Temperature versus y for $Sc = .6, K = 1, Du = 1, \ Pr = .71$

Fig-12. Concentration versus y for $K = 1$

Fig-13. Concentration versus y for $Sc = .6$