Dufour Effects on Unsteady MHD Free Convective Flow of Two Immiscible Fluid in a Horizontal Channel Under Chemical Reaction and Heat Source

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Abstract. The effect of Dufour on Unsteady MHD convective immiscible fluid flow passing through a horizontal channel in the presence of Heat, mass transfer, chemical reaction and Heat source consumption are studied here. The non-linear equations are solved with the appropriate boundary conditions. The governing equations of the flow are solved by a regular Perturbation technique. Then the effects of various flow parameters like Grashof numbers for heat and mass transfer, Prandtl number, Viscosity ratio, conductivity ratio, Radiative parameter, Schmidt number, Dufour effect etc. on the velocity field have been solved graphically and analyzed quantitatively.

Introduction
MHD is the mathematical framework which concerns the magnetic fields in electrically conducting fluids. e.x. in plasmas and liquid metals. The presence of magnetic fields leads to forces that in turn act on the fluid (typically a plasma), thereby potentially altering the geometry (or topology) and strength of the magnetic fields themselves. The study of MHD was first initiated by the Swedish electrical engineer Hannes Alfvén (1942).

The Soret effect, for instance, has been utilized for isotope separation, and in mixtures between gases with very light molecular weight (H2, He). For medium molecular weight (N2, air), the Dufour effect was found to be of a considerable magnitude such that it cannot be neglected (Eckert and Drake [1]). Bejan and Khair [2] studied the buoyancy induced heat and mass transfer from a vertical plate embedded in a saturated porous medium. RamiVempati et al. [3] studied numerically the effects of Dufour and Soret numbers on an unsteady MHD flow past an infinite vertical porous plate with thermal radiation.

Soret and dufour effects on transient MHD flow past a semi-infinite vertical porous plate with chemical reaction was investigated by Shivaiah and Anand [4]. Sarada and Shanker [5] studied the effects of soret and dufour on an unsteady MHD free convection flow past a vertical porous plate in the presence of suction or injection. Also Vempati and Laxmi-Narayana-Gari [3] investigated the effects of soret and dufour on unsteady MHD flow past an infinite vertical porous plate with thermal radiation. Raptis et al. [6] in 2004 analyzed the steady MHD asymmetric flow of an electrically conducting fluid past a semi-infinite stationary plate in the presence of radiation.
Pal D, Talukdar B[7] analysed the unsteady magnetohydrodynamic convective heat and mass transfer in a boundary layer slip flow past a vertical permeable plate with thermal radiation and chemical reaction. Joseph et al [9] then studied the slip effect on MHD oscillatory flow of fluid in a porous medium with heat and mass transfer and chemical reaction. Also he studied about the Unsteady MHD Free Convective Two Immiscible Fluid Flows in a Horizontal Channel with Heat and Mass Transfer.

Kumar and Jain (2013) investigated the influence of mass transfer and thermal radiation on unsteady free convective flow through porous media sandwiched between viscous fluids. Hence among other scholars and Authors, Chamkha (2000) considered the flow of two-immiscible fluids in porous and nonporous channels. Simon and Shaga [8]iya (2013) studied the convective flow of two immiscible fluids and heat transfer with porous along an inclined channel with pressure gradient. Sivakami, L. [11]et al studied the soret Effect on Unsteady MHD Free Convective Two Immiscible Fluid Flow through a Horizontal Channel with Heat and Mass Transfer under the influence of magnetic field and chemical reaction.

The aim of this paper is to find out the effect of soret on unsteady MHD free convective immiscible fluids flow in a horizontal channel with heat and mass transfer under the chemical reaction with heat source. The equations of continuity, linear momentum, energy and diffusion, which govern the flow field, are solved by a regular perturbation method. Numerical results and discussion are presented graphically.

Formulation of the Problem
The geometry considered here consists of two immiscible fluids having heat at constant pressure $C_p$ with porous upper channel and non-porous lower channel bounded by two infinite horizontal parallel plates extending in the $X$ and $Z$ directions with the $Y$-direction normal to the plates. The regions $0 \leq y \leq h$ and $-h \leq y \leq 0$ are denoted as Region-I and Region-II respectively. The fluid flowing through Region-I is having density $\rho_1$, dynamic viscosity $\mu_1$, thermal conductivity $k_1$, thermal diffusivity $D_1$. Similarly the fluid flowing through Region-II is having density $\rho_2$, dynamic viscosity $\mu_2$, thermal conductivity $k_2$, thermal diffusivity $D_2$.

All the variables are functions of $y'$ and $t'$ only, due to the bounding surface being infinitely long along the $x'$ axis. The flow is assumed to be fully developed and that all fluid properties are constants. The magnetic field Reynolds number is assumed very small. Hence the governing equations of the fluid flow for the different regions are

**REGION I: Porous Region**

$$\frac{\partial y'_1}{\partial y'} = 0$$

$$\left(\frac{\partial u'_1}{\partial t'} + V'_1 \frac{\partial u'_1}{\partial y'}\right) = \mu_1 \frac{\partial^2 u'_1}{\partial y'^2} - \frac{\partial p'}{\partial x'} - \sigma B_0^2 u'_1 + \rho_1 g \beta_1 (T'_1 - T'_w) + \rho_1 g \beta'_1 (C'_1 - C'_w)$$

$$\rho_1 c_p \left(\frac{\partial T'_1}{\partial t'} + V'_1 \frac{\partial T'_1}{\partial y'}\right) = k_1 \frac{\partial^2 T'_1}{\partial y'^2} + \frac{\partial q'}{\partial y'} + Q'_0 + \frac{\partial k_t}{\partial y'} \frac{\partial^2 C'_1}{\partial y'^2}$$
\[
\frac{\partial c'_1}{\partial t} + V'_1 \frac{\partial c'_1}{\partial y'} = D_1 \frac{\partial^2 c'_1}{\partial y'^2} - K'_1 (C'_1 - C_{w1}') \tag{4}
\]

**REGION II: Clear Region**

\[
\frac{\partial v'_1}{\partial y'} = 0 \tag{5}
\]

\[
\rho_2 \left( \frac{\partial u'_1}{\partial t} + V'_1 \frac{\partial u'_1}{\partial y'} \right) = \mu_2 \frac{\partial^2 u'_1}{\partial y'^2} - \frac{\partial P_r}{\partial x'} - \sigma B'_0 U'_2 + \frac{\mu_2}{k_1} U'_2 + \rho_2 g \beta f_2 (T'_2 - T'_{w2}) + \rho_2 g \beta c'_2 (C'_2 - C'_{w2}) \tag{6}
\]

\[
\rho_2 c_p \left( \frac{\partial T'_1}{\partial t} + V'_1 \frac{\partial T'_1}{\partial y'} \right) = k_2 \frac{\partial^2 T'_1}{\partial y'^2} - \frac{\partial q_r}{\partial y'} + Q'_1 + \frac{\rho K_t}{c_s} \frac{\partial^2 c'_1}{\partial y'^2} \tag{7}
\]

\[
\frac{\partial c'_1}{\partial t} + V'_2 \frac{\partial c'_1}{\partial y'} = D_2 \frac{\partial^2 c'_1}{\partial y'^2} - K'_2 (C'_2 - C_{w2}') \tag{8}
\]

Assuming that the boundary and interface conditions on velocity are no slip, given that at the boundary and interface, the fluid particles are at rest, \( x \) component of the velocity vanish at the wall.

The boundary and interface conditions on the temperature for both fluids are:

\[
T'_1(h) = T'_{w1}, T'_2(h) = T'_{w2}, T'_1(0) = T'_2(0), k_1 \frac{\partial T'_1}{\partial y'} = k_2 \frac{\partial T'_2}{\partial y'} at y' = 0 \tag{9}
\]

The boundary and interface conditions on the concentration for both fluids are:

\[
C'_1(h) = C'_{w1}, C'_2(h) = C'_{w2}, C'_1(0) = C'_2(0), D_1 \frac{\partial c'_1}{\partial y'} = D_2 \frac{\partial c'_1}{\partial y'} when y' = 0 \tag{10}
\]

The equations (1) and (5) implies that \( V'_1 \) and \( V'_2 \) are independent of \( y' \), they are refunction of time alone.

Hence \( V' = V_0 (1 + \varepsilon A e^{i \omega t}) \).

Assuming that \( V'_1 = V'_2 = V' \). Where \( \varepsilon A \leq 1 \). By assuming the following dimensionless quantities:

\[
U_i = \frac{U_i}{u}, \quad y = \frac{y}{h}, \quad t = \frac{t}{h^2}, \quad V = \frac{V}{h}, \quad V_i = \frac{V_i}{V_0}, \quad P_r = \frac{\mu_1 c_p}{k_1}, \quad \alpha_1 = \frac{\mu_2}{\mu_1}, \quad \beta_1 = \frac{k_2}{k_1}, \quad \tau_1 = \frac{\rho_2}{\rho_1}, \quad \gamma_1 = \frac{\tau_1}{\alpha_1}, \quad m_1 = \frac{\beta y}{\tau_1}, \quad n_1 = \frac{\beta c}{\tau_1}, \quad k_2 = \frac{h^2}{K_1}, \quad \sigma_c = \frac{\tau_1}{\mu_1}, \quad M_2 = \frac{g H^2}{\mu_1}, \quad F = \frac{4}{\alpha_1}, \quad \frac{d q_r}{d y} = 4(T'_{1} - T'_{w1}) \},
\]

\[
\xi_1 = \frac{1}{\tau_1}, \quad \rho_2, \quad \rho_2, \quad \gamma_1 = \frac{1}{\alpha_1}, \quad \rho_2, \quad \gamma_1, \quad Gr = \frac{\beta (T_{w2} - T_{w1})}{\beta_f h^2 \rho_1}, \quad G_c = \frac{g (c'_{w2} - c'_{w1}) \beta_s c_h^2}{\mu_1 \rho_1} \}, \quad P = \frac{-h^2}{\mu_1} (\frac{\partial r}{\partial x'}) \}, \quad \theta_1 = \frac{\tau_1 - T'_{w1}}{(T_{w2} - T_{w1})} \},
\]

\[
C_i = \frac{(c'_1 - c'_{w1})}{(c'_{w2} - c'_{w1})} \}, \quad D_f = \frac{\rho K_t (c'_{w2} - c'_{w1})}{c_s c_p v (T_{w2} - T_{w1})}, \quad i = 1, 2 \ldots \ldots \text{Equations (2), (3), (4), (6), (7) and (8) becomes}
\]

**REGION I:**

\[
\frac{\partial u_i}{\partial t} + (1 + \varepsilon e^{i \omega t}) \frac{\partial u_i}{\partial y} = \frac{\partial^2 u_i}{\partial y^2} + P - M^2 U_i + \text{Gr} \theta_1 + \text{Gc} C_i \tag{13}
\]

\[
\frac{\partial \theta_1}{\partial t} + (1 + \varepsilon e^{i \omega t}) \frac{\partial \theta_1}{\partial y} = \frac{1}{\rho_r} \frac{\partial^2 \theta_1}{\partial y^2} - \frac{\theta_1}{\rho_r} \frac{\partial r}{\partial y} \tag{14}
\]

\[
\frac{\partial c_i}{\partial t} + (1 + \varepsilon e^{i \omega t}) \frac{\partial c_i}{\partial y} = \frac{1}{\delta c} \frac{\partial^2 c_i}{\partial y^2} - \frac{\kappa_2}{\delta c} C_i \tag{15}
\]

**REGION II:**

\[
\frac{\partial u_2}{\partial t} + (1 + \varepsilon e^{i \omega t}) \frac{\partial u_2}{\partial y} = \alpha_1 \xi_1 \frac{\partial^2 u_2}{\partial y^2} + \xi_1 P - \xi_1 M^2 U_2 - \alpha_1 \xi_1 K^2 U_2 + \text{Grm} \theta_2 + \text{Gcn} C_2 \tag{16}
\]
\[
\frac{\partial \theta_2}{\partial t} + (1 + \epsilon e^{i \omega t}) \frac{\partial \theta_2}{\partial y} = \frac{\beta_1 \xi_1 \partial^2 \theta_2}{Pr} - \frac{F \xi_1 \theta_2}{Pr} + \frac{Df \partial^2 C_2}{Pr} \tag{17}
\]

\[
\frac{\partial C_2}{\partial t} + (1 + \epsilon e^{i \omega t}) \frac{\partial C_2}{\partial y} = \frac{\gamma_1 \partial^2 C_2}{Sc} - \frac{K_c}{Sc} C_2 \tag{18}
\]

The boundary and interface conditions in dimensionless form are given as follows

\[
U_1(1) = 0, \quad U_2(-1) = 0, \quad U_1(0) = U_2(0) \quad \frac{\partial U_1}{\partial y} = \alpha_1 \frac{\partial U_2}{\partial y} \text{ at } y = 0 \tag{19}
\]

\[
\theta_1(1) = 1, \quad \theta_2(-1) = 0, \quad \theta_1(0) = \theta_2(0) \quad \frac{\partial \theta_1}{\partial y} = \beta_1 \frac{\partial \theta_2}{\partial y} \text{ at } y = 0 \tag{20}
\]

\[
C_1(1) = 1, C_2(-1) = 0, \quad C_1(0) = C_2(0) \quad \frac{\partial C_1}{\partial y} = \gamma_1 \frac{\partial C_2}{\partial y} \text{ when } y=0 \tag{21}
\]

Solution Procedure of the Problem

To solve the governing equations (13) to (18) under the boundary and interface conditions (19) to (21), one expand\(U_1(y, t), \theta_1(y, t), C_1(y, t), U_2(y, t), \theta_2(y, t), C_2(y, t)\), as a power series on the perturbative parameter \(\epsilon\). Here, let \(\epsilon \leq 1\). Thus

\[
U_1(y, t) = U_{10}(y) + \epsilon e^{i \omega t} U_{11}(y)
\]

\[
\theta_1(y, t) = \theta_{10}(y) + \epsilon e^{i \omega t} \theta_{11}(y)
\]

\[
C_1(y, t) = C_{10}(y) + \epsilon e^{i \omega t} C_{11}(y)
\]

\[
U_2(y, t) = U_{20}(y) + \epsilon e^{i \omega t} U_{21}(y)
\]

\[
\theta_2(y, t) = \theta_{20}(y) + \epsilon e^{i \omega t} \theta_{21}(y)
\]

\[
C_2(y, t) = C_{20}(y) + \epsilon e^{i \omega t} C_{21}(y)
\]

Substitute the above set of equations into the equations (13) to (18) and equate the periodic and non-periodic terms, and neglect the terms containing \(\epsilon^2\), one can get the following set of ordinary differential equations:

**REGION I**

Non-Periodic Terms:

\[
\frac{\partial^2 U_{10}}{\partial y^2} + \frac{\partial U_{10}}{\partial y} - M^2 U_{10} = -P - Gr \theta_{10} + GrC_{10} \tag{22}
\]

\[
\frac{\partial^2 \theta_{10}}{\partial y^2} - Pr \frac{\partial \theta_{10}}{\partial y} - (F - \theta_1) \theta_{10} + Df \frac{\partial^2 C_{10}}{\partial y^2} = 0 \tag{23}
\]

\[
\frac{\partial^2 C_{10}}{\partial y^2} - Sc \frac{\partial C_{10}}{\partial y} = K_c C_{10} \tag{24}
\]

Periodic Terms:

\[
\frac{\partial^2 U_{11}}{\partial y^2} + \frac{\partial U_{11}}{\partial y} - (M^2 + i \omega) U_{11} = \frac{\partial U_{10}}{\partial y} - Gr \theta_{11} - GrC_{11} \tag{25}
\]

\[
\frac{\partial^2 \theta_{11}}{\partial y^2} - Pr \frac{\partial \theta_{11}}{\partial y} - (F + i \omega Pr - \theta_1) \theta_{11} = Pr \frac{\partial \theta_{10}}{\partial y} - Df \frac{\partial^2 C_{11}}{\partial y^2} \tag{26}
\]

\[
\frac{\partial^2 C_{11}}{\partial y^2} - Sc \frac{\partial C_{11}}{\partial y} - i \omega Sc C_{11} = Sc \frac{\partial C_{10}}{\partial y} + K_c C_{11} \tag{27}
\]

**REGION-II**

Non-periodic Terms:
The equations (22) to (33) are ordinary linear differential equations with constant coefficients. The following are the boundary and interface conditions:

**Non-Periodic Terms**

\[ U_{10}(1) = 0, \quad U_{20}(-1) = 0, \quad U_{10}(0) = U_{20}(0), \quad \frac{\partial U_{10}}{\partial y} = a_1 \frac{\partial U_{20}}{\partial y} \quad \text{at} \quad y = 0 \]  
(34)

\[ \theta_{10}(1) = 1, \quad \theta_{20}(-1) = 0, \quad \theta_{10}(0) = \theta_{20}(0), \quad \frac{\partial \theta_{10}}{\partial y} = \beta_1 \frac{\partial \theta_{20}}{\partial y} \quad \text{at} \quad y = 0 \]  
(35)

\[ C_{10}(1) = 1, \quad C_{20}(-1) = 0, \quad C_{10}(0) = C_{20}(0), \quad \frac{\partial C_{10}}{\partial y} = \gamma_1 \frac{\partial C_{20}}{\partial y} \quad \text{at} \quad y = 0 \]  
(36)

**Periodic Terms**

\[ U_{11}(1) = 0, \quad U_{21}(-1) = 0, \quad U_{11}(0) = U_{21}(0), \quad \frac{\partial U_{11}}{\partial y} = a_1 \frac{\partial U_{21}}{\partial y} \quad \text{at} \quad y = 0 \]  
(37)

\[ \theta_{11}(1) = 0, \quad \theta_{21}(-1) = 0, \quad \theta_{11}(0) = \theta_{21}(0), \quad \frac{\partial \theta_{11}}{\partial y} = \beta_1 \frac{\partial \theta_{21}}{\partial y} \quad \text{at} \quad y = 0 \]  
(38)

\[ C_{11}(1) = 1, \quad C_{21}(-1) = 0, \quad C_{11}(0) = C_{21}(0), \quad \frac{\partial C_{11}}{\partial y} = \gamma_1 \frac{\partial C_{21}}{\partial y} \quad \text{at} \quad y = 0 \]  
(39)

The solutions of the differential equations (22) to (33) using the above boundary conditions (34) to (39) are:

\[ U_{10}(y) = C_{5}e^{m_{10}y} + C_{6}e^{m_{1y}y} + K_{1} + K_{2}e^{m_{1y}y} + K_{3}e^{m_{2y}y} + K_{4}e^{m_{3y}y} + K_{5}e^{m_{4y}y} + K_{6}e^{m_{4y}y} \]  
(40)

\[ U_{20}(y) = C_{17}e^{m_{1y}y} + C_{18}e^{m_{1y}y} + K_{20} + K_{21}e^{m_{13y}y} + K_{22}e^{m_{14y}y} + K_{23}e^{m_{15y}y} + K_{24}e^{m_{14y}y} + K_{25}e^{m_{15y}y} + K_{26}e^{m_{16y}y} \]  
(41)

\[ \theta_{10}(y) = C_{7}e^{m_{1y}y} + C_{8}e^{m_{2y}y} + K_{39}e^{m_{1y}y} + K_{40}e^{m_{2y}y} \]  
(42)

\[ \theta_{20}(y) = C_{13}e^{m_{13y}y} + C_{14}e^{m_{14y}y} + K_{53}e^{m_{15y}y} + K_{54}e^{m_{16y}y} \]  
(43)

\[ C_{10}(y) = C_{3}e^{m_{3y}y} + C_{4}e^{m_{4y}y} \]  
(44)

\[ C_{20}(y) = C_{15}e^{m_{15y}y} + C_{16}e^{m_{16y}y} \]  
(45)

**Periodic Terms**

\[ U_{11}(y) = C_{11}e^{m_{11y}y} + C_{12}e^{m_{12y}y} + K_{10}e^{m_{1y}y} + K_{11}e^{m_{2y}y} + K_{12}e^{m_{3y}y} + K_{13}e^{m_{4y}y} \]  
(46)
meters. It also shows us that velocity decreases as the existence of magnetic field becomes stronger. This conclusion agrees with the analytical results show that an increase in either of the heat absorption parameter or the Dufour effect leads to a delay in the velocity field while it enhances with an increase in the value of the Dufour number.

The influence of the Schmidt number $Sc$ on velocity profiles are plotted in Fig. 2. The Schmidt number $Sc$ embodies the ratio of the momentum to the mass diffusivity. It is noticed that as the Schmidt number $Sc$ decrease in the velocity field in region I and upper part of region II while the variation in the velocity is not significant even if the Schmidt number has no significance on the velocity in the lower part of region II.

Fig. 3 illustrates the dimensionless velocity $u$ for different values of the Prandtl number $Pr$. The analytical results show that the velocity of the flow decreases with slight alteration in the porous region while the variation in the velocity is not significant even if the Prandtl number increases for the region II.

It is observed from Fig. 4 that an increase in Grashof number for heat transfer $Gr$ leads to a rise in the values of velocity $u$ due to enhancement in buoyancy force.

Figure 5 plots the velocity profiles against for different magnetic field parameter $M$. This illustrates that velocity decreases as the existence of magnetic field becomes stronger. This conclusion agrees with the fact that magnetic field exerts retarding force on the free-convection flow.

From Fig. 6 that an increase in Grashof number for mass transfer $Gc$ increases the velocity of the fluid more than the Grashof number for heat transfer.

Figure 7 illustrates the velocity profiles for different values of the Dufour number $Df$. The analytical results show that the effect of increasing values of Dufour number results in a decreasing velocity.

From Fig. 8, it is observed that an increase in the Prandtl number results a decrease of the thermal boundary layer thickness and in general lower average temperature within the boundary layer.

Figure 9 represents the effects of Dufour number on the concentration profile. As the Dufour number increases, the concentration profile of the flow is having a slight change in the Region I and in the upper part of the clear Region II one can see the difference of various parameters. It also shows us...
that the increase in the value of the concentration of the fluid increases in the boundary layer region but no effect is observed from onwards in the figures.

Conclusion

In this study, we examined the Dufour effect on Unsteady MHD Free convective flow of two Immiscible Fluid flow in a Horizontal channel in the presence of chemical reaction and heat source. The leading governing equations are solved analytically by perturbation method. We present results to illustrate the flow characteristics for the velocity, temperature and concentration and show how the flow fields are influenced by the material parameters of the flow problem. We can conclude from these results that

1. An increase in $Gr$, $Gc$, increases the velocity field, while an increase in $M$, $Pr$, $Sc$ and $Dufour$ decreases the velocity field.
2. An increase in $R$ increases the temperature distribution, while an increase in $Pr$, $Dufour$ decrease the temperature distribution.
3. An increase in $Sc$ decreases the concentration distribution, while an increase in $Df$ decreases the concentration distribution.
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