SORET AND DUFOUR EFFECT ON THERMOSTATICALLY STRATIFIED MHD FLUID FLOW THROUGH INCLINED POROUS PLATE

By

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Abstract

This research analyzes the unsteady MHD flow via a porous medium past an inclined plate in a thermally stratified flow of fluid accompanied by Soret effect and Dufour effect is being considered. The governing equations are discretized by employing the Crank-Nicolson method by utilizing Mathematica software. The graphical discussion of the impact of physical parameters on the velocity, temperature and concentration profiles is undertaken. Table are used to show the impact of flow factors on skin friction, nusselt number and sherwood number.

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Keywords and Phrases: MHD, Porous media, Thermal Stratification, Soret effect, Dufour effect

Nomenclature

- $B_0$: Strength of magnetic field
- $q_r$: Radioactive heat flux;
- $M$: Magnetic parameter;
- $Pr$: Prandtl number;
- $Sr$: Soret number;
- $D_M$: Molecular diffusivity;
- $K_T$: Thermal diffusion ratio;
- $T_M$: Mean fluid temperature;
- $Gr$: Thermal Grashof number;
- $Sc$: Schmidt number;
- $Gm$: Solutal Grashof number;
- $T_w^*$: wall temperature;
- $T_M^*$: Mean fluid temperature;
- $C_w^*$: Wall concentration;
- $C_P$: Specific heat at constant pressure;
- $C_{\infty}^*$: Concentration far away from the plate;
- $\kappa$: Thermal conductivity;
- $g$: Gravitational acceleration;
- $\sigma$: Electrical conductivity;
- $\nu$: Kinematic viscosity;
- $\rho$: Fluid density;
- $K^*$: Permeability of porous medium;
- $K$: Porosity parameter,
- $R$: Radiation parameter;
- $\gamma$: Thermal stratification parameter,
- $\beta_C$: Coefficient of volume expansion for mass transfer;
- $\beta_T$: Volumetric coefficient of thermal expansion.

1 Introduction

Magnetohydrodynamics (MHD) is a branch of fluid mechanics that deals with the behavior of electrically conducting fluids, such as plasmas, when subjected to magnetic fields. It combines principles from both fluid dynamics and electromagnetism to study the interactions between magnetic fields and fluid motion. In MHD flow, the motion of the conducting fluid is influenced by magnetic fields, and in turn, the motion of the fluid can affect the magnetic field distribution. This coupling between fluid motion and magnetic fields has important applications in various fields, including astrophysics (e.g., studying the behavior of plasma in
stars and galaxies), geophysics (e.g., understanding the Earth’s magnetic field and its interactions with the fluid outer core), and engineering (e.g., designing and analyzing fusion reactors).

When heat and mass transfer occur simultaneously in a moving fluid, the relation between fluxed and driving potentials are of more complication in nature. It has been found that an energy flux can be generated not only by temperature gradient but also by concentration gradient as well. The energy flux caused by concentration gradient is called the Dufour or diffusion-thermo effect. On the other hand, mass flux can also be created by temperature gradient is called the Soret or thermal diffusion effect. In numerous studies the Soret and Dufour effects are neglected on the basis that these are second order effects and much smaller in magnitude. However some recent studies have proved that the Soret and Dufour effects in fluid flow through porous medium cannot always be neglected because of concentration and temperature gradient are high then these effects are very significant.

Thermal stratification in fluid mechanics refers to the phenomenon where a fluid (liquid or gas) exhibits distinct layers or regions with different temperatures, typically due to variations in heat transfer processes within the fluid. This can occur in natural environments, such as bodies of water, Earth’s atmosphere, or in industrial systems like tanks, reservoirs, or even in certain types of equipment like heat exchangers.

The current version of MHD has been contributed to by many authors, including Alfen[1], Shecliff[15], Cowling[5], etc. Among them, Rani et al. [16], Javed et al.[8], Manjula and Chandra Sekhar[11] have conducted studies on fluid flow in the presence of viscous dissipation over an inclined plate. An exploration of an unsteady magneto-hydrodynamic (MHD) convection flow of a double-diffusive, viscoelastic fluid across an inclined permeable plate in the presence of viscous dissipation and heat absorption was carried out by Ali et al. [4]. The effects of viscous dissipation on a magneto-hydrodynamic nanofluid in a permeable medium, subjected to homogeneous heat and mass flux along an inclined plate, were investigated by Palani and Arutchelvi[13]. The investigation into the effects of viscous dissipation and a heat source or sink on the magneto-hydrodynamic laminar boundary layer flow of a Jeffrey fluid past a vertical plate was conducted by Hillary and Shateyi[12]. Effects of thermal radiation and magnetic fields on a viscous dissipative free convection fluid flow across an inclined infinite plate were examined by Kumar et al. [10] in the presence of an induced magnetic field. Kumar et al. [6] constitute a group of researchers who have been engaged in a variety of projects. Viscous dissipation and the ohmic heating effect on heat and mass transfer flow, in the presence of thermal diffusion, radiation effect, and later diffusion thermo, were analyzed by K. Balamunugan et al. [3]. The radiation effect on a moving inclined porous plate on unsteady MHD heat and mass transfer flow, in the presence of chemical radiation effect, was elucidated by Zyauddin and Kumar [17]. Dynamics of a nanofluid along a plane in two dimensions, with uniform, incompressible, and free characteristics, were studied by Alsenafi and Ferdows[2]. Thermal diffusion and diffusion thermo impacts on MHD were explored using an analytical solution by D. Kumar et al. [9]. The exploration of unsteady two-dimensional heat and mass transfer free convection flow around a vertical plate immersed in porous media, in the presence of a magnetic field and the radiation effect, was conducted by Jahir et al. [7]. Combined Soret and Dufour effects, in the presence of Hall current and continuous heat flux, for investigating unsteady MHD natural convective heat and mass transfer flow through a semi-infinite vertical porous plate in a rotating system, was addressed by Quader and Alam[14].

The objective of this paper is to examine the effect of Soret and Dufour on inclined porous plates when the variable temperature and concentration are present and thermal stratification is involved. The implicit finite difference approach of Crank-Nicolson is used to solve numerically the governing equation of the non-dimensional form of flow fields. Graphs are used to illustrate the effects of various physical parameters on temperature, concentration, and velocity.

2 Formulation

An investigation has been conducted on the study of an unsteady MHD flow of electrically conducting fluid past an infinite inclined porous plate with variable temperature and concentration, including Soret and Dufour effects, in the presence of thermal stratification. The plate is embedded in a porous medium and inclined at an angle α to the vertical. The \(x^*\)-axis is defined along the plate, and the \(y^*\)-axis is oriented perpendicular to it. A uniform magnetic field \(B_0\) is assumed in the \(z^*\)-axis, and the \(y^*\)-axis is considered to be normal to the \(x^*-z^*\) plane.

\[
\frac{\partial u^*}{\partial t^*} = \nu \frac{\partial^2 u^*}{\partial y^*^2} + g\beta_T (T^* - T_{\infty}^*) \cos \alpha + g\beta_C (C^* - C_{\infty}^*) \cos \alpha - \left( \frac{\sigma B_0^2}{\rho} \right) u^* - \frac{\nu}{K^*} u^*,
\]  

\(2.1\)
\[
\frac{\partial T^*}{\partial t^*} = \frac{K}{\rho C_P} \frac{\partial^2 T^*}{\partial y^2} - \gamma u^* - \frac{1}{\rho C_P} \frac{\partial q_r}{\partial y^*} + \frac{\rho D_M K_T}{\rho C_P C_S} \frac{\partial^2 C^*}{\partial y^2}, \tag{2.2}
\]

where \( \gamma = \frac{dT^*}{dy^*} + \frac{\gamma}{C_p^*} \), here, thermal stratification is \( \frac{dT^*}{dy^*} \), the term \( \frac{\gamma}{C_p^*} \) is pressure work.

The boundary conditions are:

\[
t^* \leq 0;\ u^* = 0,\ T^* = T_{\infty},\ C^* = C_{\infty} \quad \forall y^*,
\]

\[
t^* > 0,\ u^* = u_0,\ T^* = T_{\infty} + (T_W^* - T_{\infty}^*) e^{-At^*},\ C^* = C_{\infty} + (C_W^* - C_{\infty}^*) e^{-At^*} \quad \text{at} \quad y^* = 0,
\]

\[
u u^* \rightarrow 0,\ T^* \rightarrow T_{\infty}^*,\ C^* \rightarrow C_{\infty}^* \quad \text{as} \quad y^* \rightarrow \infty,
\]

where \( A = \frac{\gamma u_0}{C_p^* T_{\infty}^*} \), the temperature and concentration of plate are \( T_{\infty}^* \) and \( C_{\infty}^* \). It is assumed that there is thermal radiation present. The radiative heat flow, denoted by \( q_r \), may be calculated using an estimate given by Rosseland

\[
q_r = -\frac{4\sigma}{3k_1} \frac{\partial T^*}{\partial y^*}. \tag{2.5}
\]

In this equation, \( \sigma \) denotes the Stefan-Boltzmann Constant, while \( k_1 \) is the mean absorption coefficient. By extending \( T^* \) in a Taylor series around \( T_{\infty}^* \), and ignoring higher order components, we may get a linear version if the temperature gradients within the flow are small sufficiently in the form

\[
T^* = 4T_{\infty}^* T^* - 3T_{\infty}^*. \tag{2.6}
\]

Given equations (2.5) and (2.6), the solution to equation (2.2) may be written as

\[
\frac{\partial T^*}{\partial t^*} = \frac{K}{\rho C_P} \frac{\partial^2 T^*}{\partial y^2} - \gamma u^* + \frac{16\sigma T_{\infty}^*}{3k_1} \frac{\partial^2 T^*}{\partial y^2} + \frac{\rho D_M K_T}{\rho C_P C_S} \frac{\partial^2 C^*}{\partial y^2}. \tag{2.7}
\]

The following nondimensional quantities are introduced:

\[
Gr = \frac{g \beta T(T_w - T_{\infty}) \Delta T^*}{\gamma u_0^2}, \quad \theta = \frac{(T^* - T_{\infty})}{(T_w^* - T_{\infty}^*)}, \quad t = \frac{t^* \gamma u_0}{\Delta T^*}, \quad u^* = \frac{u^*}{u_0},
\]

\[
\phi = \frac{(C^* - C_{\infty}^*)}{(C_{\infty}^* - C_{\infty}^*)}, \quad \gamma u_0 K^* \quad \nu \Delta T^*, \quad M = \frac{\sigma B_0^2 \Delta T^*}{\gamma \rho u_0}, \quad A = \frac{\gamma u_0}{\Delta T^*},
\]

\[
Pr = \frac{\mu \rho C_P}{k^*}, \quad R = \frac{4\sigma \gamma u_0 T_{\infty}^*}{k^*}, \quad D_u = \frac{D_M K_T(C_{\infty}^* - C_{\infty}^*)}{C_S C_P \nu (T_w^* - T_{\infty}^*)},
\]

\[
Sr = \frac{D_M K_T(T_{w}^* - T_{\infty}^*)}{\nu T_{\infty}^* (C_{\infty}^* - C_{\infty}^*)}, \quad \Delta T^* = T_{w}^* - T_{\infty}^*, \quad Sc = \frac{\nu}{D},
\]

\[
y = y^* \sqrt{\frac{\gamma u_0}{\Delta T^*}}, \quad Gm = \frac{\gamma \beta C(C_{\infty}^* - C_{\infty}^*) \Delta T^*}{\gamma u_0^2}.
\]

It is possible to simplify equations using dimensionless values

\[
\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + Gr \theta \cos \alpha + Gm \phi \cos \alpha - (M + \frac{1}{K}) u, \tag{2.7}
\]

\[
\frac{\partial \theta}{\partial t} = \frac{1}{Pr} (1 + \frac{4R}{3}) \frac{\partial^2 \theta}{\partial y^2} + D_u \frac{\partial^2 \phi}{\partial y^2} - u, \tag{2.8}
\]

\[
\frac{\partial \phi}{\partial t} = \frac{1}{Sc} \frac{\partial^2 \phi}{\partial y^2} + Sr \frac{\partial^2 \theta}{\partial y^2}. \tag{2.9}
\]

The appropriate nondimensional boundary conditions are:

\[
t \leq 0; u = 0, \theta = 0, \phi = 0 \quad \forall y,
\]

\[
t > 0, u = 1, \theta = e^{-t}, \phi = e^{-t} \quad \text{at} \quad y = 0,
\]

\[
u u \rightarrow 0, \theta \rightarrow 0, \phi \rightarrow 0 \quad \text{as} \quad y \rightarrow \infty.
\]
2.1 Skin Friction
Skin friction is given by:
\[ \tau = -\left( \frac{\partial u}{\partial y} \right)_{y=0}. \]  
(2.10)

2.2 Nusselt Number
Nusselt number is given by:
\[ Nu = -\left( \frac{\partial \theta}{\partial y} \right)_{y=0}. \]  
(2.11)

2.3 Sherwood Number
Sherwood number is given by:
\[ Sh = -\left( \frac{\partial \phi}{\partial y} \right)_{y=0}. \]  
(2.12)

3 Solution of the problem
After setting up the proper initial and boundary conditions, the non-linear momentum, and energy equations, and may be resolved by employing the implicit finite difference approach of the Crank and Nicolson model that is being employed. Using the Nicolson approach, we discretize the appropriate finite difference equations
\[
\frac{u_{i,j+1} - u_{i,j}}{\Delta t} = \left( \frac{u_{i-1,j} - 2u_{i,j} + u_{i+1,j}}{2(\Delta y)^2} \right)
+ Gr\cos(\alpha) \left( \frac{\theta_{i,j+1} + \theta_{i,j}}{2} \right)
+ Gm\cos(\alpha) \left( \frac{\phi_{i,j+1} + \phi_{i,j}}{2} \right)
- (M + \frac{1}{K}) \left( \frac{u_{i,j+1} + u_{i,j}}{2} \right),
\]  
(3.1)

\[
\frac{\theta_{i,j+1} - \theta_{i,j}}{\Delta t} = \frac{1}{Pr} \left( 1 + \frac{4R}{3} \right) \left( \frac{\theta_{i-1,j} - 2\theta_{i,j} + \theta_{i+1,j}}{2(\Delta y)^2} \right)
+ Du \left( \frac{\phi_{i-1,j} - 2\phi_{i,j} + \phi_{i+1,j}}{2(\Delta y)^2} \right)
- \left( \frac{u_{i,j+1} + u_{i,j}}{2} \right),
\]  
(3.2)

\[
\frac{\phi_{i,j+1} - \phi_{i,j}}{\Delta t} = \frac{1}{Sc} \left( \frac{\phi_{i-1,j} - 2\phi_{i,j} + \phi_{i+1,j}}{2(\Delta y)^2} \right)
+ Sr \left( \frac{\theta_{i-1,j} - 2\theta_{i,j} + \theta_{i+1,j}}{2(\Delta y)^2} \right), [width = .55]
\]  
(3.3)

corresponding boundary conditions
\[
u_{i,0} = 0, \theta_{i,0} = 0, \phi_{i,0} = 0 \quad \forall i,
\]  
(3.4)
\[
u_{0,j} = 1, \theta_{0,j} = e^{-j\Delta t}, \phi_{0,j} = e^{-j\Delta t},
\]  
u_{L,j} \rightarrow 0, \theta_{L,j} \rightarrow 0, \phi_{L,j} \rightarrow 0.

Here, index \( i \) refers to \( y \) and \( j \) refers to time. Also \( \Delta t = t_{j+1} - t_j \) and \( \Delta y = y_{i+1} - y_i \) knowing the values of \( u \), \( \theta \) and \( \phi \) at a time \( t \), we can calculate the values at a time \( t + \Delta t \) as follows we substitute \( i = 1, 2, 3, ..., L - 1 \) in the equations which constitute a tridiagonal system of equations, can be solved by Thomas algorithm. Thus, \( \theta \) and \( \phi \) are known for all values of \( y \) at \( t + \Delta t \). Substitute these values of \( \theta \) and \( \phi \) in equation and solved by same procedure with initial and boundary condition, we obtain solution for \( u \) till desired time \( t \).
4 Results and discussion
The velocity profile, concentration profile and temperature profile are shown through graphs for different values of flow parameters. The effects of several parameters such as porosity parameter $K$, thermal stratification parameter $S$, solutal Grashof number $Gm$, Magnetic field parameter $M$, Soret effect $Sr$, thermal Grashof number $Gr$, radiation parameter $R$, Dufour effect $Du$ on velocity distribution, temperature and concentration field have been analyzed graphically, which are depicted in Figures 4.1 to 4.18.

Figure 4.1 to 4.4 shows the increase in Prandtl number, magnetic field parameter, angle and Schmidt number respectively decreases the velocity. In figure 4.5 to 4.10, velocity increases on increasing the value of porosity parameter, thermal Grashof number, solutal Grashof number, Soret number, Dufour number and radiation parameter respectively. Further in figure 4.11, it can be seen that the temperature of the fluid falls on raising the value of Prandtl number. Figure 4.12 and figure 4.13 depicts that the concentration increases with increase in Dufour number and radiation parameter. Figure 4.14 display that on increasing the value of Prandtl number, concentration decreases. The concentration decreases on increasing the value of Schmidt number as shown in figure 4.15. Effect of Soret number on concentration can be seen in figure 4.16. Concentration increases on increasing Soret number. Further we can see on increasing Dufour number and radiation parameter, the concentration of the fluid decreases as shown in figure 4.17 and figure 4.18 respectively.

The skin friction, nusselt number and sherwood number are presented in Table 4.1, Table 4.2 and Table 4.3 respectively, where the effect of various parameters on skin friction, nusselt number and sherwood number is displayed.

![Figure 4.1: Variation of Prandtl number on velocity](image1)

![Figure 4.2: Variation of magnetic field parameter on velocity](image2)
Figure 4.3: Variation of angle on velocity

Figure 4.4: Variation of Schmidt number on velocity

Figure 4.5: Variation of Porosity parameter on velocity
Figure 4.6: Variation of thermal Grashof number on velocity

Figure 4.7: Variation of solutal Grashof number on velocity

Figure 4.8: Variation of soret number on velocity
Figure 4.9: Variation of Dufour number on velocity

Figure 4.10: Variation of Radiation parameter on velocity

Figure 4.11: Variation of Prandtl number on temperature
Figure 4.12: Variation of dufour number on temperature

Figure 4.13: Variation of radiation parameter on temperature

Figure 4.14: Variation of Prandtl number on concentration
Figure 4.15: Variation of Schmidt number on concentration

Figure 4.16: Variation of Soret number on concentration

Figure 4.17: Variation of Dufour number on concentration
Figure 4.18: variation of Radiation parameter on concentration

Table 4.1: Skin Friction for different values of parameter

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<td>0.15</td>
<td>0.66</td>
<td>1</td>
<td>3</td>
<td>30°</td>
<td>0.601371</td>
</tr>
</tbody>
</table>

5 Conclusion
In this work, we have concluded the Soret effect and Dufour effect with thermal stratification on unsteady MHD flow through inclined porous plate immersed in porous medium. The Finite Difference technique is applied to implement numerical solutions. Graphs and tabular data displays are used to show the findings. The following are the significant observations:

- On increasing Prandtl number, magnetic parameter, angle and Schmidt number, velocity decreases.
- Temperature decreases on increasing Prandtl number.
- On increasing dufour number and radiation parameter, temperature increases.
- Concentration increases on increasing Prandtl number and soret number.
- On increasing Schmidt number, Dufour number and radiation parameter, concentration decreases.

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References
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