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MHD FLUID FLOW UNDER THE INFLUENCE OF CHEMICAL REACTION AND THERMAL STRATIFICATION THROUGH INCLINED POROUS PLATE

NIDHI PANDYA and PRIYANKA KANNOUJIA ✉

Abstract

In this paper, we have investigated the chemical reaction and thermal stratification on the unsteady magnetohydrodynamic (MHD) flow over an inclined plate. After non dimensionalising the governing equations, we used Crank Nicolson method to plot the graphs. The effects of the non-dimensional parameters on the velocity, temperature and concentration are examined with graphs. Also the impact of different parameters on Skin friction, Nusselt number and Sherwood number are obtained.

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Nomenclature

- B_0 -Strength of magnetic field
- u_0 -velocity of plate;
- T -Fluid temperature;
- M -Magnetic parameter;
- Pr -Prandtl number;
- Gr -Thermal Grashof number;
- Gm -Solutal Grashof number;
- S -non-dimensional stratification parameter;
- T_W -wall temperature;
- T_∞ -Fluid temperature far away from the plate;
- C_W -Wall concentration;
- C_P -Specific heat at constant pressure;
- C_∞ -Concentration far away from the plate;
- u -Dimensionless velocity;
- κ -Thermal conductivity;
- g -Gravitational acceleration;
- σ -Electrical conductivity;
- ν -Kinematic viscosity;
- ρ -Fluid density;
- K -Porosity parameter;

- Sc -Schmidt number;
- P -Pressure;
- β_C :Coefficient of volume expansion for mass transfer;
- β_T :Volumetric coefficient of thermal expansion;
- K_r :Chemical reaction parameter.

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1. Introduction

The behavior of electrically conducting fluids in the presence of magnetic fields is studied in a branch of fluid dynamics. The motion of an electrically conducting fluid under the influence of both dynamics of fluid and electromagnetic forces, is characterized by the coupling of fluid velocity, magnetic field strength, and electrical conductivity in MHD flow.

Porous media refers to materials or substances that contain interconnected void spaces or pores. In fluid mechanics, the study of flow through porous media is essential for understanding processes in geology (such as groundwater flow), civil engineering (such as groundwater remediation), and petroleum engineering (for oil reservoirs). Fluid flow through porous media is often characterized by complex interactions between the fluid and solid matrix, including capillary forces and permeability.

Stratified fluids are characterized by distinct layers of fluid with different densities. These layers can form naturally due to variations in temperature, salinity, or other factors. Understanding stratified fluids is critical in oceanography, meteorology, and environmental science. It plays a significant role in phenomena like ocean circulation, atmospheric stability, and the mixing of pollutants in lakes and reservoirs.

Chemical reactions in fluid mechanics refer to the transformation of substances within a fluid. These reactions can alter the fluid's properties, such as density, viscosity, and chemical composition. Understanding chemical reactions is crucial in various applications, including combustion engineering (combustion of fuels), environmental engineering (pollutant dispersion and chemical reactions in water bodies), and chemical process engineering (chemical reactor design).

The influence of a chemical reaction on the behavior of an unsteady flow through an accelerating vertical plate was investigated, where the mass transfer was variable and stratification was not considered [12]. The interaction between thermal stratification and chemical reaction in the context of fluid flow past an accelerated vertical plate was determined by this research. Unsteady flow of a thermally stratified fluid past a vertically accelerated plate was investigated under a variety of conditions by [11] and [4]. Steady flows in a stable stratified fluid were investigated by researchers [1], [5], and [3], with a focus on infinite vertical plates. Buoyancy-driven flows in a stratified fluid were investigated by both [7] and [6]. The change in MHD flow for vertical stretching surfaces due to the interaction between thermal stratification and chemical reaction was studied by researchers [10] and [8]. These two phenomena were also the subject of investigation by [2], who studied the impact of non-Newtonian fluid flow in a porous medium. Research into unsteady MHD flow past an accelerating vertical plate with a constant heat flux and ramped plate temperature was conducted by [9] and [13]. Darcy-Brinkman flow in an anisotropic rotating porous channel under the influence of magnetic field was investigated by [14].

The objective of this paper is to examine the effect of chemical reaction on MHD unsteady flow through inclined porous plates embedded in porous medium when the thermal startification 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 different values of flow parameters on velocity, temperature and concentration.

2. Mathematical Formulation

Consider an unsteady MHD flow of a viscous incompressible electrically conducting fluid past an infinite inclined plate. The plate is embedded in porous medium and inclined at angle α to the vertical. $x'-$axis is taken along the plate and $y'-$axis is normal to it. We assume a uniform magnetic field B_0 along the $z'-$axis, and we consider the $y'-$axis to be normal to the $x'-z'$ plane. The flow variables are functions of y' and t' only, due to the infinite length in the $x'-$direction.

$$\frac{\partial u^*}{\partial t^*} = \nu\frac{\partial^2 u^*}{\partial y^{*2}} + g\beta_T(T^* - T_\infty{}^*)cos\alpha + g\beta_C(C^* - C_\infty{}^*)cos\alpha - (\frac{\sigma {B_0}^2}{\rho})u^* - \frac{\nu}{K^*}u^* \tag{2.1}$$

$$\frac{\partial T^*}{\partial t^*} = \frac{\kappa}{\rho C_P}\frac{\partial^2 T^*}{\partial y^{*2}} - \gamma u^* \tag{2.2}$$

$$\frac{\partial C^*}{\partial t^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} - K_r^{'}(C^* - C_\infty{}^*) \tag{2.3}$$

where $\gamma = \frac{dT_\infty}{dz} + \frac{g}{C_P}$, here, thermal stratification is $\frac{dT_\infty}{dz}$, the term $\frac{g}{C_P}$ is pressure work.
The boundary conditions are:

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

$$t^* > 0, u^* = At^*, T^* = T_W{}^*, C^* = C_W{}^* \quad at \quad y^* = 0$$

$$u^* \to 0, T^* \to T_\infty{}^*, C^* \to C_\infty{}^* \quad as \quad y^* \to \infty \tag{2.4}$$

Where A=$\frac{\gamma u_0}{\Delta T^*}$ is specified as constant acceleration, the temperature and concentration of plate are $T^*{}_w$ and $C^*{}_w$.
The following non dimensional quantities are introduced:

$$Gr = \frac{g\beta_T(T_w{}^* - T_\infty{}^*)}{A}, Gm = \frac{g\beta_C(C_w{}^* - C_\infty{}^*)}{A}, \theta = \frac{(T^* - T^*{}_\infty)}{(T^*{}_W - T^*{}_\infty)}, t = At^*,$$

$$\mu = \rho\nu, S = \frac{\gamma}{A(T^*{}_W - T^*{}_\infty)}, u = u^*, \phi = \frac{(C^* - C^*{}_\infty)}{(C^*{}_W - C^*{}_\infty)}, K = \frac{K^*A}{\nu}, M = \frac{\sigma {B_0}^2}{\rho A},$$

$$K_r = \frac{K_r{}'}{A}A = \frac{\gamma u_0}{\Delta T^*}, u = u^*, , Pr = \frac{\mu C_P}{\kappa}, Sc = \frac{\nu}{D}, y = y^*\sqrt{\frac{A}{\nu}}.$$

It is possible to simplify equations using dimensionless values.

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + Gr\theta cos\alpha + Gm\phi cos\alpha - (M + \frac{1}{K})u \tag{2.5}$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr}\frac{\partial^2 \theta}{\partial y^2} - Su \tag{2.6}$$

$$\frac{\partial \phi}{\partial t} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} - K_r\phi \tag{2.7}$$

The appropriate nondimensional boundary conditions are

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

$$t > 0, u = t, \theta = 1, \phi = 1 \quad at \quad y = 0$$

$$u \to 0, \theta \to 0, \phi \to 0 \quad as \quad y \to \infty \tag{2.8}$$

2.1. Skin Friction Skin friction is given by:

$$\tau = -(\frac{\partial u}{\partial y})_{y=0} \tag{2.9}$$

2.2. Nusselt Number Nusselt number is given by:

$$Nu = -(\frac{\partial \theta}{\partial y})_{y=0} \tag{2.10}$$

2.3. Sherwood Number Sherwood number is given by:

$$Sh = -(\frac{\partial \phi}{\partial y})_{y=0} \tag{2.11}$$

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

$$\begin{aligned}\frac{u_{i,j+1} - u_{i,j}}{\Delta t} = (&\frac{u_{i-1,j} - 2u_{i,j} + u_{i+1,j} + u_{i-1,j+1} - 2u_{i,j+1} + u_{i+1,j+1}}{2(\Delta y)^2}) \\ &+Grcos(\alpha)(\frac{\theta_{i,j+1} + \theta_{i,j}}{2}) + Gmcos(\alpha)(\frac{\phi_{i,j+1} + \phi_{i,j}}{2}) \\ &-(M + \frac{1}{K})(\frac{u_{i,j+1} + u_{i,j}}{2})\end{aligned} \tag{3.1}$$

$$\frac{\theta_{i,j+1}-\theta_{i,j}}{\Delta t} = \frac{1}{Pr}\left(\frac{\theta_{i-1,j}-2\theta_{i,j}+\theta_{i+1,j}+\theta_{i-1,j+1}-2\theta_{i,j+1}+\theta_{i+1,j+1}}{2(\Delta y)^2}\right) - S\left(\frac{u_{i,j+1}+u_{i,j}}{2}\right) \tag{3.2}$$

$$\frac{\phi_{i,j+1}-\phi_{i,j}}{\Delta t} = \frac{1}{Sc}\left(\frac{\phi_{i-1,j}-2\phi_{i,j}+\phi_{i+1,j}+\phi_{i-1,j+1}-2\phi_{i,j+1}+\phi_{i+1,j+1}}{2(\Delta y)^2}\right) + K_r\left(\frac{\phi_{i,j+1}+\phi_{i,j}}{2}\right) \tag{3.3}$$

corresponding boundary conditions

$$u_{i,0}=0, \theta_{i,0}=0, \phi_{i,0}=0 \quad \forall i$$

$$u_{0,j}=t, \theta_{0,j}=1, \phi_{0,j}=1$$

$$u_{L,j}\to 0, \theta_{L,j}\to 0, \phi_{L,j}\to 0 \tag{3.4}$$

In the context provided, index i is referred to as y, and j is referred to as time. Additionally, Δt is defined as $t_{j+1}-t_j$, and Δy as $y_{i+1}-y_i$. Given the values of u, θ, and ϕ at a time t, the values at a time $t+\Delta t$ can be calculated as follows: the equations, which constitute a tridiagonal system of equations, are substituted with $i = 1, 2, 3, ...L-1$. This system can be solved using the Thomas algorithm. Consequently, θ and ϕ become known for all y values at $t+\Delta t$. These values of θ and ϕ are then substituted into equation, and the solution is obtained by the same procedure, considering the initial and boundary conditions, resulting in a solution for u until the desired time t.

4. Results and discussion

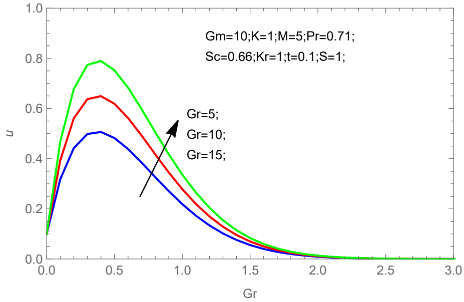

FIGURE 1. Variation of thermal grashof number on velocity

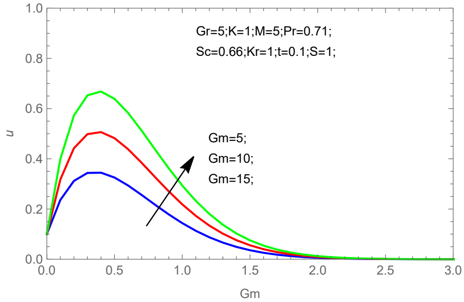

FIGURE 2. Variation of solutal grashof number on velocity

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

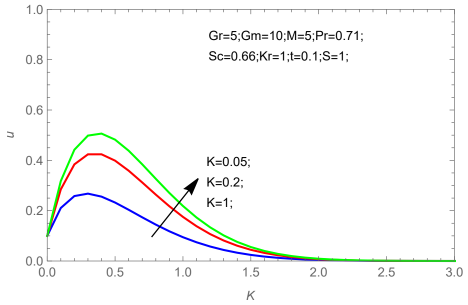

FIGURE 3. Variation of porosity parameter on velocity

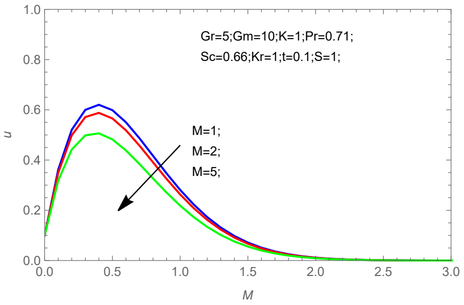

FIGURE 4. Variation of magnetic parameter on velocity

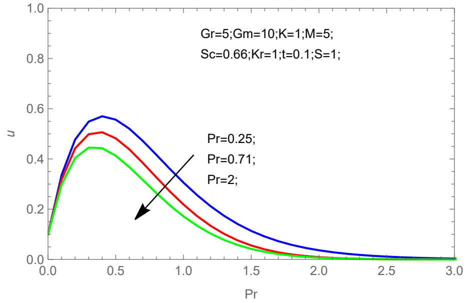

FIGURE 5. Variation of Prandtl number on velocity

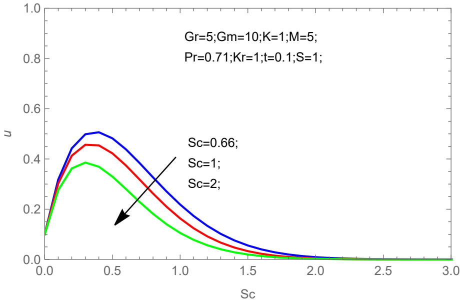

FIGURE 6. Variation of Schimdt number on velocity

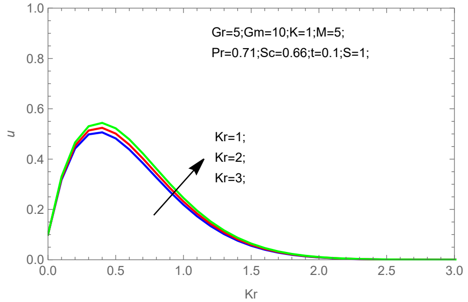

FIGURE 7. Variation of chemical reaction parameter on velocity

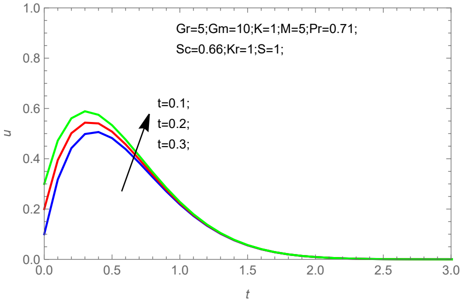

FIGURE 8. Variation of time on velocity

number Gm, Hartmann number M, thermal Grashof number Gr, chemical reaction parameter Kr on velocity distribution, temperature and concentration field have been analyzed graphically, which are depicted in Figures 1-14.

Figure [1-3] and figure [7-8] shows the increase in thermal Grashof number, solutal Grashof number, porosity parameter, chemical reaction and time respectively increases the velocity. In figure [4-6] and figure [9-10], velocity decreases on increasing

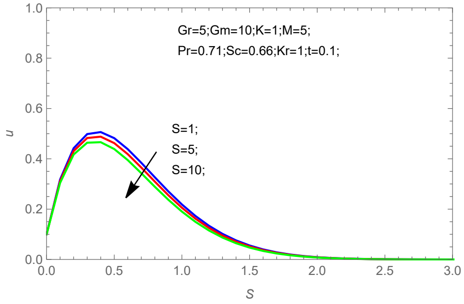

FIGURE 9. Variation of stratification parameter on velocity

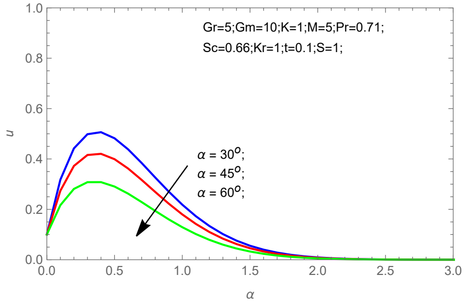

FIGURE 10. Variation of inclination angle on velocity

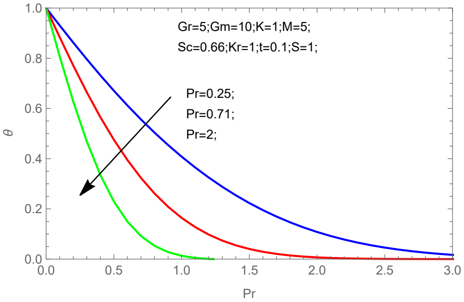

FIGURE 11. Variation of Prandtl number on temperature

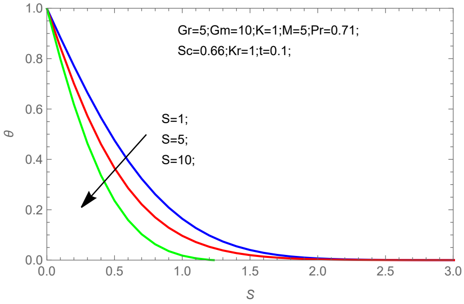

FIGURE 12. Variation of stratification parameter on temperature

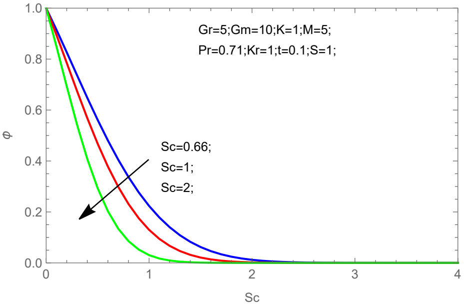

FIGURE 13. Variation of Schimdt number on concentration

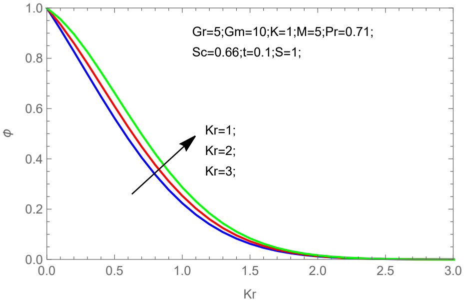

FIGURE 14. Variation of chemical reaction parameter on concentration

the value of magnetic field parameter, Prandtl number, Schmidt number, stratificatiion parameter and inclined angle respectively. Further in figure [11-12], it can be seen that the temperature of the fluid falls on raising the value of Prandtl number and stratification parameter respectively. Figure 13 depicts that the concentration decreases with increase in Schmidt number. Figure 14 display the effect of chemical reaction on concentration. The concentration increases on increasing the value of chemical

Table 1. Skin friction for different values of parameter

Gr	**Gm**	**K**	**M**	**Pr**	**Sc**	**Kr**	**t**	**S**	α	τ
5	10	1	5	0.71	0.66	1	0.1	1	30^0	-2.17685
10	10	1	5	0.71	0.66	1	0.1	1	30^0	-2.93086
15	10	1	5	0.71	0.66	1	0.1	1	30^0	-3.67651
5	**5**	1	5	0.71	0.66	1	0.1	1	30^0	-1.36179
5	**10**	1	5	0.71	0.66	1	0.1	1	30^0	-2.17685
5	**15**	1	5	0.71	0.66	1	0.1	1	30^0	-2.99192
5	10	**0.05**	5	0.71	0.66	1	0.1	1	30^0	-1.10741
5	10	**0.2**	5	0.71	0.66	1	0.1	1	30^0	-1.84664
5	10	**1**	5	0.71	0.66	1	0.1	1	30^0	-2.17685
5	10	1	**1**	0.71	0.66	1	0.1	1	30^0	-2.61451
5	10	1	**2**	0.71	0.66	1	0.1	1	30^0	-2.49247
5	10	1	**5**	0.71	0.66	1	0.1	1	30^0	-2.17685
5	10	1	5	**0.25**	0.66	1	0.1	1	30^0	-2.35504
5	10	1	5	**0.71**	0.66	1	0.1	1	30^0	-2.17685
5	10	1	5	**2**	0.66	1	0.1	1	30^0	-1.97612
5	10	1	5	0.71	**0.66**	1	0.1	1	30^0	-2.17685
5	10	1	5	0.71	**1**	1	0.1	1	30^0	-2.02734
5	10	1	5	0.71	**2**	1	0.1	1	30^0	-1.76383
5	10	1	5	0.71	0.66	**1**	0.1	1	30^0	-2.17685
5	10	1	5	0.71	0.66	**2**	0.1	1	30^0	-2.23843
5	10	1	5	0.71	0.66	**3**	0.1	1	30^0	-2.30534
5	10	1	5	0.71	0.66	1	**0.1**	1	30^0	-2.17685
5	10	1	5	0.71	0.66	1	**0.2**	1	30^0	-1.94992
5	10	1	5	0.71	0.66	1	**0.3**	1	30^0	-1.72298
5	10	1	5	0.71	0.66	1	0.1	**1**	30^0	-2.17685
5	10	1	5	0.71	0.66	1	0.1	**5**	30^0	-2.11625
5	10	1	5	0.71	0.66	1	0.1	**10**	30^0	-2.04357
5	10	1	5	0.71	0.66	1	0.1	1	$\mathbf{30^0}$	-2.17685
5	10	1	5	0.71	0.66	1	0.1	1	$\mathbf{45^0}$	-1.73812
5	10	1	5	0.71	0.66	1	0.1	1	$\mathbf{60^0}$	-1.16499

reaction parameter as shown in figure 14.

The skin friction, nusselt number and sherwood number are presented in Table 1, Table 2 and Table 3 respectively, where the effect of various parameters on skin friction, nusselt number and sherwood number is displayed.

Table 2. Nusselt number for different values of parameter

Gr	**Gm**	**K**	**M**	**Pr**	**Sc**	**Kr**	**t**	**S**	α	**Nu**
5	10	1	5	0.71	0.66	1	0.1	1	30^0	1.16252
10	10	1	5	0.71	0.66	1	0.1	1	30^0	1.18928
15	10	1	5	0.71	0.66	1	0.1	1	30^0	1.21574
5	**5**	1	5	0.71	0.66	1	0.1	1	30^0	1.13298
5	**10**	1	5	0.71	0.66	1	0.1	1	30^0	1.16252
5	**15**	1	5	0.71	0.66	1	0.1	1	30^0	1.19206
5	10	**0.05**	5	0.71	0.66	1	0.1	1	30^0	1.12171
5	10	**0.2**	5	0.71	0.66	1	0.1	1	30^0	1.14996
5	10	**1**	5	0.71	0.66	1	0.1	1	30^0	1.16252
5	10	1	**1**	0.71	0.66	1	0.1	1	30^0	1.17892
5	10	1	**2**	0.71	0.66	1	0.1	1	30^0	1.17438
5	10	1	**5**	0.71	0.66	1	0.1	1	30^0	1.16252
5	10	1	5	**0.25**	0.66	1	0.1	1	30^0	0.692733
5	10	1	5	**0.71**	0.66	1	0.1	1	30^0	1.16252
5	10	1	5	**2**	0.66	1	0.1	1	30^0	1.92709
5	10	1	5	0.71	**0.66**	1	0.1	1	30^0	1.16252
5	10	1	5	0.71	**1**	1	0.1	1	30^0	1.15213
5	10	1	5	0.71	**2**	1	0.1	1	30^0	1.13699
5	10	1	5	0.71	0.66	**1**	0.1	1	30^0	1.16252
5	10	1	5	0.71	0.66	**2**	0.1	1	30^0	1.16498
5	10	1	5	0.71	0.66	**3**	0.1	1	30^0	1.16762
5	10	1	5	0.71	0.66	1	**0.1**	1	30^0	1.16252
5	10	1	5	0.71	0.66	1	**0.2**	1	30^0	1.17521
5	10	1	5	0.71	0.66	1	**0.3**	1	30^0	1.18789
5	10	1	5	0.71	0.66	1	0.1	**1**	30^0	1.16252
5	10	1	5	0.71	0.66	1	0.1	**5**	30^0	1.54847
5	10	1	5	0.71	0.66	1	0.1	**10**	30^0	2.00705
5	10	1	5	0.71	0.66	1	0.1	1	$\mathbf{30^0}$	1.16252
5	10	1	5	0.71	0.66	1	0.1	1	$\mathbf{45^0}$	1.14673
5	10	1	5	0.71	0.66	1	0.1	1	$\mathbf{60^0}$	1.12609

Table 3. Sherwood number for different values of parameter

Gr	**Gm**	**K**	**M**	**Pr**	**Sc**	**Kr**	**t**	**S**	α	**Sw**
5	10	1	5	0.71	0.66	1	0.1	1	30^0	0.845657
10	10	1	5	0.71	0.66	1	0.1	1	30^0	0.845657
15	10	1	5	0.71	0.66	1	0.1	1	30^0	0.845657
5	**5**	1	5	0.71	0.66	1	0.1	1	30^0	0.845657
5	**10**	1	5	0.71	0.66	1	0.1	1	30^0	0.845657
5	**15**	1	5	0.71	0.66	1	0.1	1	30^0	0.845657
5	10	**0.05**	5	0.71	0.66	1	0.1	1	30^0	0.845657
5	10	**0.2**	5	0.71	0.66	1	0.1	1	30^0	0.845657
5	10	**1**	5	0.71	0.66	1	0.1	1	30^0	0.845657
5	10	1	**1**	0.71	0.66	1	0.1	1	30^0	0.845657
5	10	1	**2**	0.71	0.66	1	0.1	1	30^0	0.845657
5	10	1	**5**	0.71	0.66	1	0.1	1	30^0	0.845657
5	10	1	5	**0.25**	0.66	1	0.1	1	30^0	0.845657
5	10	1	5	**0.71**	0.66	1	0.1	1	30^0	0.845657
5	10	1	5	**2**	0.66	1	0.1	1	30^0	0.845657
5	10	1	5	0.71	**0.66**	1	0.1	1	30^0	0.845657
5	10	1	5	0.71	**1**	1	0.1	1	30^0	1.04822
5	10	1	5	0.71	**2**	1	0.1	1	30^0	1.50295
5	10	1	5	0.71	0.66	**1**	0.1	1	30^0	0.845657
5	10	1	5	0.71	0.66	**2**	0.1	1	30^0	0.650927
5	10	1	5	0.71	0.66	**3**	0.1	1	30^0	0.439147
5	10	1	5	0.71	0.66	1	**0.1**	1	30^0	0.845657
5	10	1	5	0.71	0.66	1	**0.2**	1	30^0	0.845657
5	10	1	5	0.71	0.66	1	**0.3**	1	30^0	0.845657
5	10	1	5	0.71	0.66	1	0.1	**1**	30^0	0.845657
5	10	1	5	0.71	0.66	1	0.1	**5**	30^0	0.845657
5	10	1	5	0.71	0.66	1	0.1	**10**	30^0	0.845657
5	10	1	5	0.71	0.66	1	0.1	1	$\mathbf{30}^0$	0.845657
5	10	1	5	0.71	0.66	1	0.1	1	$\mathbf{45}^0$	0.845657
5	10	1	5	0.71	0.66	1	0.1	1	$\mathbf{60}^0$	0.845657

5. Conclusion

In this work, we have concluded the Soret effect and Dufour effect on thermostatically stratified MHD fluid flow through inclined porous plate which have following conclusions:

- On increasing magnetic parameter, Prandtl number, Schmidt number ,stratification parameter and angle, velocity decreases.
- Velocity increases on increasing thermal and solutal Grashof number, porosity parameter, chemical reaction parameter and time.
- Temperature decreases on increasing Prandtl number and stratification parameter.
- Concentration increases on increasing chemical reaction parameter.
- On increasing Schmidt number, concentration decreases.

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Nidhi Pandya, Department of Mathematics and Astronomy, University of Lucknow, Lucknow, India
e-mail: dr.nidh23@gmail.com

Priyanka Kannoujia, Department of Mathematics and Astronomy, University of Lucknow, Lucknow, India
e-mail: priyankakannoujia1@gmail.com