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ORIGINAL RESEARCH ARTICLE

Suction/Injection and Double Stratification Effects on MHD Flow Between Infinite Vertical Porous Plates with Variable Temperature and Mass Diffusion

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ABSTRACT

The effects of thermal and mass stratification, combined with either suction or injection, on unsteady Newtonian MHD parabolic incompressible fluid flowing through infinite vertical stationary porous plates have been investigated, considering variable temperature and mass diffusion. Appropriate dimensionless quantities were used to represent the governing coupled partial differential equations in non-dimensional form. The perturbation method and the Laplace transform technique were used to decouple and transform these partial differential equations into ordinary differential equations. The analytical solutions were obtained for unitary Prandtl and Schmidt numbers using the characteristic method and the method of undetermined coefficients. Using shift and convolution theories, the result was presented in the time domain and numerically illustrated in MATLAB. The study indicates that the concentration, temperature, and velocity profiles increase with increasing suction and double stratification, and decrease with increasing injection in the presence of stratification. Increasing the thermal (Gr) and mass (Gc) Grashof numbers results in higher fluid velocity while lowering concentration and temperature. Temperature and concentration increase with increasing magnetic parameter, while the velocity decreases. As the Darcy number increases, the concentration, temperature, and velocity decrease. The study has applications in the design of reactor cooling systems.

ARTICLE HISTORY

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KEYWORDS

MHD flow, thermal stratification, mass stratification, perturbation, Laplace transform, suction/injection

INTRODUCTION

Magnetohydrodynamics (MHD) is the study of fluids that conduct electricity under the influence of a magnetic field. According to Das and Deka (2024), the study of MHD flows is highly relevant to industrial and engineering processes, such as cooling electronic equipment, solar collectors, solar cookers, and solar concentrators. Infinite plates simplify the geometry by eliminating edge effects of the flow, while the vertical orientation incorporates gravitational effects, manifesting as buoyancy forces driven by density gradients due to temperature or concentration variations. The unsteady nature of the flow mirrors real-world scenarios where conditions fluctuate, making it essential to understand how these factors interact over time. Numerous studies have investigated MHD flow in different scenarios over the decades. Early work on MHD flows over porous media laid the foundation for understanding fluid interaction with magnetic fields and porous boundaries. The study of MHD emerged in the early 20th century, with Hannes Alfvén's work earning the 1970 Nobel Prize. Alfvén (1942) introduced the concept of magnetohydrodynamic waves (now known as Alfvén waves), which describe oscillations in electrically conducting fluids in the presence of magnetic fields. Earlier, Hartmann (1937) analysed steady laminar MHD flow in channels, defining the Hartmann number ($Ha = B_0 L\sqrt{(\sigma/\mu)}$), a dimensionless parameter that balances magnetic and viscous forces. Shercliff (1965) extended MHD to convection in a foundational text that provided a comprehensive introduction to magnetohydrodynamics and systematically covered the theoretical principles, including the coupling of the Navier-Stokes and Maxwell equations.

Chamkha and Khaled (2000) investigated natural convection flow with heat and mass transfer over a semi-infinite vertical flat plate, considering internal heat absorption, a magnetic field, and permeability. Mbeledogu et al. (2006) used the perturbation technique

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to solve the nonlinear coupled partial differential equations governing the flow of a compressible free-convection Boussinesq fluid under the combined influence of buoyancy and a magnetic field. Joseph et al. (2014) explored unsteady MHD Couette flow with heat transfer and an inclined magnetic field between parallel plates. While accounting for a lower porous plate, the variable-separable technique was employed to deduce expressions for the Nusselt numbers, skin frictions, temperatures, and velocities. Sharma and Ahmad (2022) analytically examined an unsteady MHD flow past a vertically accelerated plate with a ramped wall temperature, incorporating thermal-diffusion, chemical reaction, and radiation effects. While Choudhury et al. (2024) considered the simultaneous action of thermal diffusion and diffusion-thermos past a vertical plate through a porous medium.

Porous plates enable fluid exchange through suction or injection, which helps control boundary-layer dynamics. This concept was pioneered by Prandtl in 1904 and later refined by von Karman in 1934. Seddek and Salama (2007) investigated the impact of variable suction on unsteady MHD through a vertical porous plate. Using the finite difference method, Rundora and Makinde (2013) investigated the unsteady flow of a non-Newtonian fluid in a porous medium with suction/injection. Jha et al. (2018) studied the suction/injection and magnetic field effects near an infinite vertical porous plate with impulsive and accelerated motion. The Laplace transform was used to solve the governing dimensionless PDEs for momentum and energy. It was concluded that injection reduces velocity while shear stress increases over time. Halima et al. (2023) used the iterative method of Crank-Nicolson to analyse unsteady MHD with suction/injection and chemical reaction. Noting that suction lowers temperature and concentration. The configuration of flow between porous plates is relevant to various applications, including enhanced oil recovery, filtration systems, and heat exchangers.

Mass and thermal stratification, driven by concentration and temperature gradients in the ambient fluid significantly influence convective dynamics. Gurminder (2010) examined steady MHD flow with thermal stratification past a non-isothermal moving vertical plate using the fourth-order Runga-Kutta method. The results revealed that the fluid temperature and velocity decrease with increasing stratified parameter. Deka and Paul (2013) shifted the trend toward unsteady incompressible flow over an infinite moving vertical cylinder with buoyancy effects and mass and thermal stratification. While Srinivasacharya and Surender (2015) focused on a non-scattering grey nanofluid that emits and absorbs radiation, in the presence of thermal stratification and viscous dissipation, Goud et al. (2023) analysed the flow of an unsteady MHD fluid. Recent studies have explored stratified MHD flows in porous media, Das and Deka (2024) analysed the cumulative impact of mass and thermal stratification on unsteady MHD vertical channel flow, Meanwhile, Sahu and Deka (2024) focused on the effects chemical reaction and thermal stratification in a similar configuration, demonstrating that stratification accelerates the system's transition to steady-state conditions compared to non-stratified cases. Considering a non-Newtonian nanofluid and double stratification, Reddy et al. (2024) utilized the numerical Keller box approach to examine the influence of suction on unsteady MHD flow over a flat sheet. Increasing the suction parameter increased the velocity gradient and simultaneously decreased the temperature and concentration profiles.

However, the combined effects of thermal stratification, mass stratification, and suction/injection on an unsteady Newtonian MHD fluid through a porous medium in a vertical channel with temperature variation and mass diffusion remain unexplored. This research, therefore, aims to bridge this gap by studying the combined effects of suction/injection and double stratification on the concentration, temperature, velocity, Sherwood number, Nusselt number and skin friction of a Newtonian fluid. Moreover, the influence of key parameters, including the thermal and mass Grashof numbers, the magnetic parameter M, and the Darcy number Da, on velocity, temperature, and concentration profiles was also studied. Then the results were compared with a scenario in which the flow field lacks both suction/injection and stratification effects, thus highlighting the significance of the combined effects. This research enhances predictive models for MHD systems, aiding the design of efficient reactors, energy converters and environmental remediation technologies.

METHODOLOGY

We consider a coordinate system in which x^* and y^* axis are selected vertically upward and perpendicular to the plate, respectively. A uniform strength magnetic field B_0 is transversely applied to the flow direction. The fluid and the plates have the same initial concentration ${C^*}_0$ and temperature ${T^*}_0$ fluid. Also, the plate concentration and temperature level are elevated to ${T^*}_w$ and ${C^*}_w$ respectively at $y^* = 0$ and time $t^* > 0$. Suction/injection is assumed through the stationary porous plates. Due to the infinite length of the plate and the unsteady nature of the fluid in motion, all the flow variables are independent of x^* but only depend on y^* and t^*. The governing equations of motion, heat and mass transfer describing the parabolic flow of an unsteady incompressible Newtonian MHD fluid between a stationary infinite vertical porous plate with variable temperature and mass diffusion through porous medium, incorporating suction/injection, thermal and mass stratification, are formulated using the Standard Boussinesq approximation as;

$$\frac{\partial v^*}{\partial x^*} = 0 \qquad (1)$$

$$\frac{\partial u^*}{\partial t^*} + v^*\frac{\partial u^*}{\partial y^*} = \nu\frac{\partial^2 u^*}{\partial y^{*2}} + g\beta(T^* - T^*_0) + g\beta_c(C^* - C^*_0) - \frac{\sigma B_0{}^2 u^*}{\rho} - \frac{\nu u^*}{k^*} \quad (2)$$

$$\frac{\partial T^*}{\partial t^*} + v^*\frac{\partial T^*}{\partial y^*} = \frac{k}{\rho C_p}\frac{\partial^2 T^*}{\partial y^{*2}} - \gamma^* u^* \quad (3)$$

$$\frac{\partial C^*}{\partial t^*} + v^*\frac{\partial C^*}{\partial y^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} - \xi^* u^* \quad (4)$$

The initial and boundary condition are;

$$u^* = 0\,, T^* = T^*_0\,, C^* = C^*_0\,, for\ all\ \ y^*, t^* \le 0$$

$$u^* = 0\,,\quad T^* = T^*_0 + \Delta T^* A t^*\,,\ C^* = C^*_0 + \Delta C^* A t^*\,,\ at\ \ y^* = 0\,,\ t^* > 0 \quad (5)$$

$$u^* \to 0\,, T^* \to T^*_0\,, C^* \to C^*_0\,,\ as\ \ y^* \to \infty\,,\ t^* > 0$$

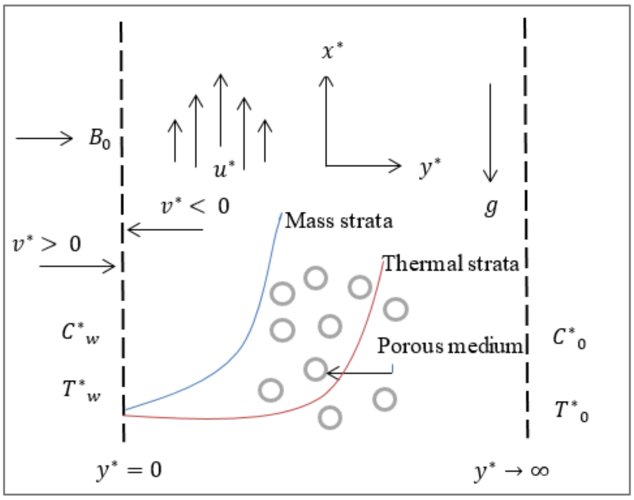

Figure 1: Problem Physical model

2.1 Solutions to Governing Equations

Equations (1) – (5) first need to be cleared of all dimensions. This is by considering the following achieved dimensionless quantities.

$$y = \frac{y^*}{L_R}\,,\quad x = \frac{x^*}{L_R}\,,\quad t = \frac{t^*}{t_R}\,,\quad \gamma = \frac{\gamma^* L_R}{\Delta T^*}\,,\quad \xi = \frac{\xi^* L_R}{\Delta C^*}\,,\quad A = \frac{1}{t_R}\,,$$

$$C = \frac{C^* - C^*_0}{\Delta C^*}\,,\quad T = \frac{T^* - T^*_0}{\Delta T^*}\,,\quad Gr = \frac{\nu g\beta\Delta T^*}{U_R{}^3}\,,\quad Gc = \frac{\nu g\beta_c\Delta C^*}{U_R{}^3}\,,$$

$$u = \frac{u^*}{U_R}\,,\quad v = \frac{v^*}{U_R}\,,\quad P_r = \frac{\mu C_p}{k}\,,\quad S_c = \frac{\nu}{D}\,,\quad M = \frac{\sigma B_0^2 \nu}{\rho U_R^2}\,,\quad Da = \frac{U_R{}^2 k^*}{\nu^2}\,, \quad (6)$$

$$t_R = \nu^{1/3}(g\beta\Delta T^*)^{-2/3}\,,\quad U_R = \nu^{1/3}(g\beta\Delta T^*)^{1/3}\,,\quad L_R = \nu^{2/3}(g\beta\Delta T^*)^{-1/3}\,,$$

$$\Delta T^* = T^*_w - T^*_0\,,\quad \Delta C^* = C^*_w - C^*_0\,.$$

Substituting equation (6) into (1) – (5), equations (7) – (11) are obtained as;

$$\frac{\partial v}{\partial x} = 0 \quad (7)$$

$$\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + GrT + GcC - \left(M + \frac{1}{Da}\right)u \quad (8)$$

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial y} = \frac{1}{P_r}\frac{\partial^2 T}{\partial y^2} - \gamma u \quad (9)$$

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial y} = \frac{1}{S_c}\frac{\partial^2 C}{\partial y^2} - \xi u \quad (10)$$

With the following initial and boundary conditions obtained from similar substitution

$$u = 0\,,\ T = 0\,,\ C = 0\,,\ for\ all\quad y, t \le 0$$

$$u = 0\,,\ T = t\,, C = t\,, \text{at}\quad y = 0\,,\ t > 0 \quad (11)$$

$$u \to 0\,, T \to 0\,, C \to 0\,, \text{as}\quad y \to \infty\,,\ t > 0$$

setting $P_r = S_c = 1$, then for a sufficiently small parameter $(\varepsilon \ne 0)$ and some constants $\lambda_1\ and\ \lambda_2$ such that $\gamma = \varepsilon\lambda_1\ and\ \xi = \varepsilon\lambda_2$

$$u = u_0 + \varepsilon u_1 + O(\varepsilon^2)$$

$$T = T_0 + \varepsilon T_1 + O(\varepsilon^2) \quad (12)$$

$$C = C_0 + \varepsilon C_1 + O(\varepsilon^2)$$

For ε^0

$$\frac{\partial u_0}{\partial t} + v\frac{\partial u_0}{\partial y} = \frac{\partial^2 u_0}{\partial y^2} + GrT_0 + GcC_0 - N_a u_0 \quad (13)$$

$$\frac{\partial T_0}{\partial t} + v\frac{\partial T_0}{\partial y} = \frac{\partial^2 T_0}{\partial y^2} \quad (14)$$

$$\frac{\partial C_0}{\partial t} + v\frac{\partial C_0}{\partial y} = \frac{\partial^2 C_0}{\partial y^2} \quad (15)$$

And

$$u_0(0,t) = 0\,,\quad T_0(0,t) = t\,,\quad C_0(0,t) = t\,,$$

$$\lim_{y\to\infty} u_0(y,t) = 0\,, \lim_{y\to\infty} T_0(y,t) = 0\,, \lim_{y\to\infty} C_0(y,t) = 0 \quad (16)$$

For ε^1

$$\frac{\partial u_1}{\partial t} + v\frac{\partial u_1}{\partial y} = \frac{\partial^2 u_1}{\partial y^2} + GrT_1 + GcC_1 - N_a u_1 \quad (17)$$

$$\frac{\partial T_1}{\partial t} + v\frac{\partial T_1}{\partial y} = \frac{\partial^2 T_1}{\partial y^2} + \lambda_1 u_0 \quad (18)$$

$$\frac{\partial C_1}{\partial t} + v\frac{\partial C_1}{\partial y} = \frac{\partial^2 C_1}{\partial y^2} + \lambda_2 u_0 \quad (19)$$

And

$$u_1(0,t) = 0\,, T_1(0,t) = 0\,,\ C_1(0,t) = 0\,,$$

$$\lim_{y\to\infty} u_1(y,t) = 0\,,\ \lim_{y\to\infty} T_1(y,t) = 0\,, \lim_{y\to\infty} C_1(y,t) = 0 \quad (20)$$

Taking the Laplace transform, we have the solution in 's' domain

$$u(y,t) = e^{\frac{yv}{2}}[F_1 - F_3(\gamma Gr + \xi Gc)]\left[\mathcal{L}^{-1}\left\{\frac{1}{s^2}e^{-y\sqrt{k_1}}\right\} - \mathcal{L}^{-1}\left\{\frac{1}{s^2}e^{-y\sqrt{k_2}}\right\}\right] \quad (21)$$

$$T(y,t) = e^{\frac{yv}{2}}\left((1-\gamma F_2)\mathcal{L}^{-1}\left\{\frac{1}{s^2}e^{-y\sqrt{k_1}}\right\} + \gamma F_2\mathcal{L}^{-1}\left\{\frac{1}{s^2}e^{-y\sqrt{k_2}}\right\}\right) \quad (22)$$

$$C(y,t) = e^{\frac{yv}{2}}\left((1-\xi F_2)\mathcal{L}^{-1}\left\{\frac{1}{s^2}e^{-y\sqrt{k_1}}\right\} + \xi F_2\mathcal{L}^{-1}\left\{\frac{1}{s^2}e^{-y\sqrt{k_2}}\right\}\right) \quad (23)$$

where $k_1 = \frac{v^2}{4} + s,\ k_2 = \frac{v^2}{4} + N_a + s,\ F_1 = \frac{(Gr+Gc)}{N_a}\ ,\ F_2 = \frac{(Gr+Gc)}{{N_a}^2},\ \ F_3 = \frac{(Gr+Gc)}{{N_a}^3}$

From equation (7)

$$\frac{\partial v}{\partial x} = 0\,, \qquad \Rightarrow v = constant \quad (24)$$

Considering shift theory, convolution theory and a known transform of $e^{-y\sqrt{s}}$ (Schiff 1999)

The solutions in time domain are;

$$u(y,t) = \frac{y}{2\sqrt{\pi}}(I_1 - I_2 e^{-N_a t})[F_1 - F_3(\gamma Gr + \xi Gc)]e^{\frac{yv}{2}-\frac{v^2 t}{4}} \quad (25)$$

$$T(y,t) = \frac{y}{2\sqrt{\pi}}[I_1(1-\gamma F_2) + \gamma F_2 I_2 e^{-N_a t}]e^{\frac{yv}{2}-\frac{v^2 t}{4}} \quad (26)$$

$$C(y,t) = \frac{y}{2\sqrt{\pi}}[I_1(1-\xi F_2) + \xi F_2 I_2 e^{-N_a t}]e^{\frac{yv}{2}-\frac{v^2 t}{4}} \quad (27)$$

where,

$$F_1 = \frac{(Gr+Gc)}{N_a}\,, \quad F_2 = \frac{(Gr+Gc)}{{N_a}^2}\,, \quad F_3 = \frac{(Gr+Gc)}{{N_a}^3}\,, \quad N_a = M + \frac{1}{Da}$$

$$I_1 = \int_0^t \frac{\tau}{\sqrt{(t-\tau)^3}} e^{\frac{v^2\tau}{4} - \frac{y^2}{4(t-\tau)}} d\tau \quad \& \quad I_2 = \int_0^t \frac{\tau}{\sqrt{(t-\tau)^3}} e^{\left(\frac{v^2}{4}+N_a\right)\tau - \frac{y^2}{4(t-\tau)}} d\tau$$

Utilizing equations (21) to (23), The skin friction, Nusselt and Sherwood numbers are computed as follows:

2.2 Skin Friction

The skin friction measures the flow resistance at the plate and is given as:

$$\mathrm{S_f} = -\left.\frac{\mathrm{du}}{\mathrm{dy}}\right|_{\mathrm{y=0}} \quad (28)$$

$$\Rightarrow \mathrm{S_f} = [F_1 - F_3(\gamma Gr + \xi Gc)]\left[\mathcal{L}^{-1}\left\{\frac{1}{s^2}(\sqrt{k_1})\right\} - \mathcal{L}^{-1}\left\{\frac{1}{s^2}(\sqrt{k_2})\right\}\right] \quad (29)$$

2.3 Nusselt Number

The Nusselt number is defined as heat transfer rate and is given as:

$$\mathrm{N_u} = -\left.\frac{\mathrm{dT}}{\mathrm{dy}}\right|_{\mathrm{y=0}} \quad (30)$$

$$\Rightarrow \mathrm{N_u} = \left((1-\gamma F_2)\mathcal{L}^{-1}\left\{\frac{1}{s^2}(\sqrt{k_1})\right\} + \gamma F_2\mathcal{L}^{-1}\left\{\frac{1}{s^2}(\sqrt{k_2})\right\}\right) - \frac{vt}{2} \quad (31)$$

2.4 Sherwood Number

The Sherwood number is defined as mass transfer rate and is given as:

$$\mathrm{S_h} = -\left.\frac{\mathrm{dC}}{\mathrm{dy}}\right|_{\mathrm{y=0}} \quad (32)$$

$$\Rightarrow \mathrm{S_h} = \left((1-\xi F_2)\mathcal{L}^{-1}\left\{\frac{1}{s^2}(\sqrt{k_1})\right\} + \xi F_2\mathcal{L}^{-1}\left\{\frac{1}{s^2}(\sqrt{k_2})\right\}\right) - \frac{vt}{2} \quad (33)$$

2.5 Classical Scenario Solution

Setting $\xi = \gamma = v = 0$ for the classical scenario (where suction/injection and stratification effect are not present), equation (25) and (26) reduce to;

$$T_c(y,t) = C_c(y,t) = t\left[\left(1+\frac{y^2}{2t}\right)erfc\left(\frac{y}{2\sqrt{t}}\right) - \frac{ye^{-\frac{y^2}{4t}}}{\sqrt{\pi t}}\right] \quad (34)$$

with the classical Nusselt and Sherwood numbers;

$$N_u = S_h = 2\sqrt{\frac{t}{\pi}} \quad (35)$$

For the classical velocity, equation (25) is reduced to obtain;

$$u_c(y,t) = tF_1.T_c(y,t) - \frac{y}{2\sqrt{\pi}}e^{-N_a t}\int_0^t \frac{\tau}{\sqrt{(t-\tau)^3}}e^{N_a\tau - \frac{y^2}{4(t-\tau)}}d\tau \quad (36)$$

while the classical skin friction is obtained using equation (21) as,

$$S_f = F_1\left[\mathcal{L}^{-1}\left\{\frac{1}{s^2}(\sqrt{s})\right\} - \mathcal{L}^{-1}\left\{\frac{1}{s^2}\left(\sqrt{N_a+s}\right)\right\}\right] \quad (37)$$

RESULTS AND DISCUSSIONS

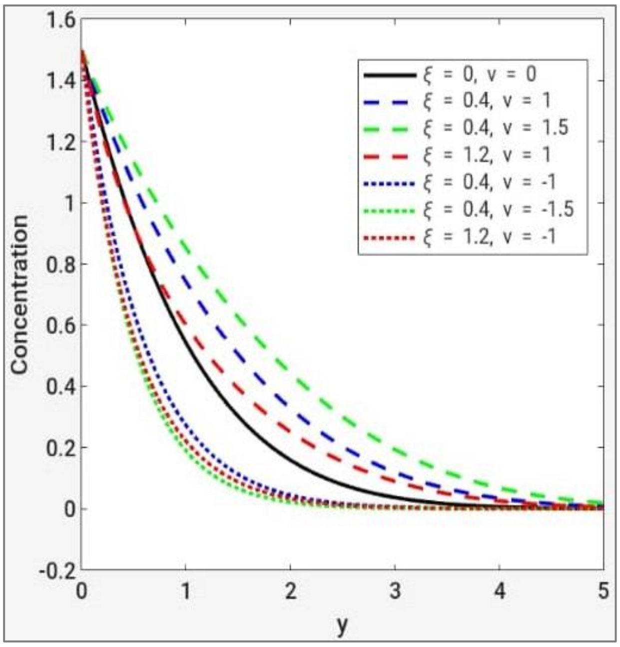

Figure 2: Showing suction/injection and stratification effects on C against distance (y)

Using MATLAB software, the concentration, temperature, and velocity profiles (equations 25 to 27) under the influence of various parameters are illustrated in Figures 2 to 16 (2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16). These graphs are plotted against the classical scenario (equations 34 and 35), where neither suction/injection nor double stratification is present. Meanwhile, the effects of suction/injection and double stratification on the Sherwood number, Nusselt number, and skin friction (in equations 29, 31, and 33) are displayed in Figures 17 to 21 (17, 18, 19, 20 and 21), with an explicit comparison drawn against their classical counterparts (in equations 34 and 37). The values of the pertinent parameters used are taken as Sahu and Deka (2024): $y = 1.5,\ t = 1.5,\ Gr = 5,\ Gc = 5,\ \xi = 0.4,\ \gamma = 0.5,\ v = \pm 1,\ M = 4\ and\ Da = 0.5$; This values are chosen to suit Boussinesq approximation for various engineering and industrial applications.

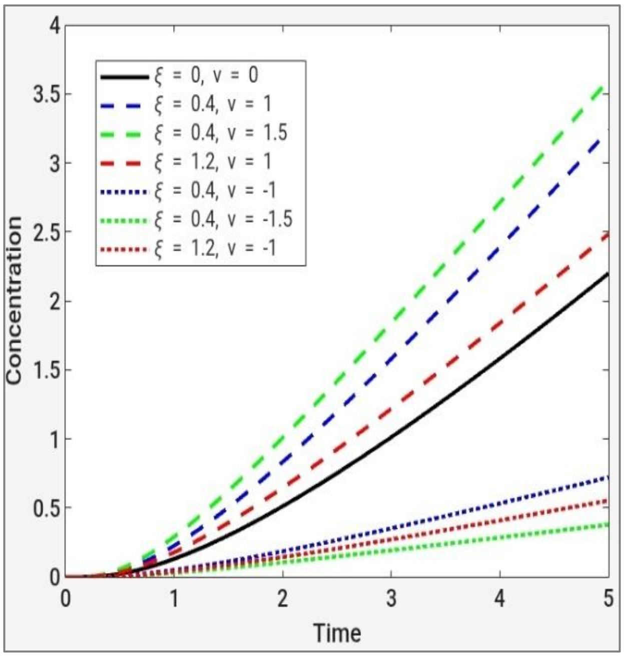

Figure 3: Showing suction/injection and stratification effects on C against time (t)

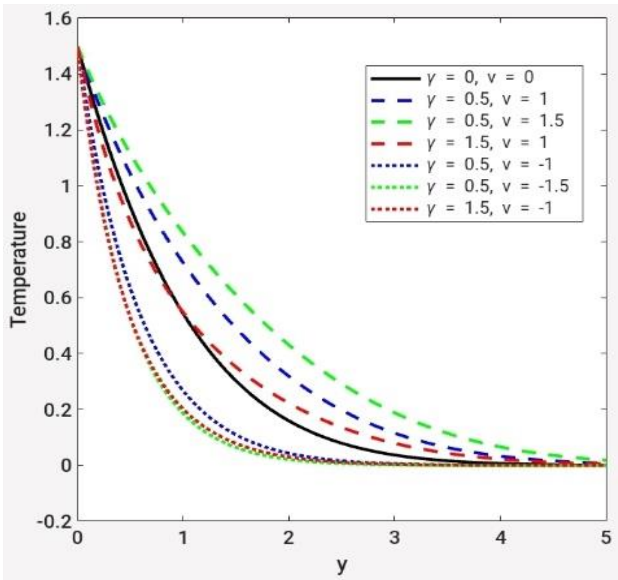

Figure 4: Showing suction/injection and stratification effects on T against distance (y)

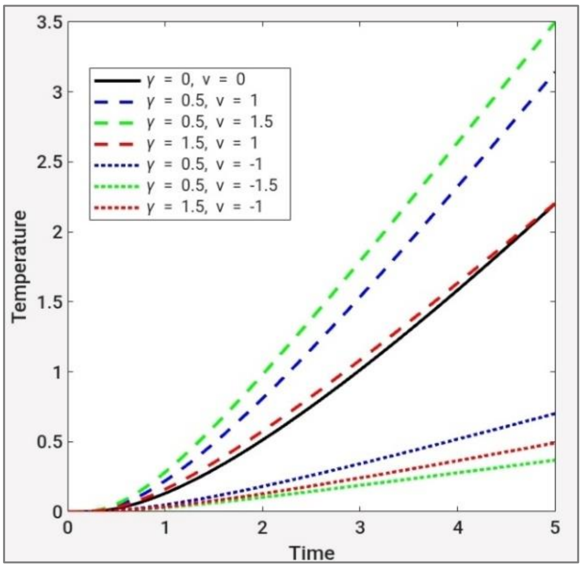

Figure 5: Showing suction/injection and stratification effects on T against time (t)

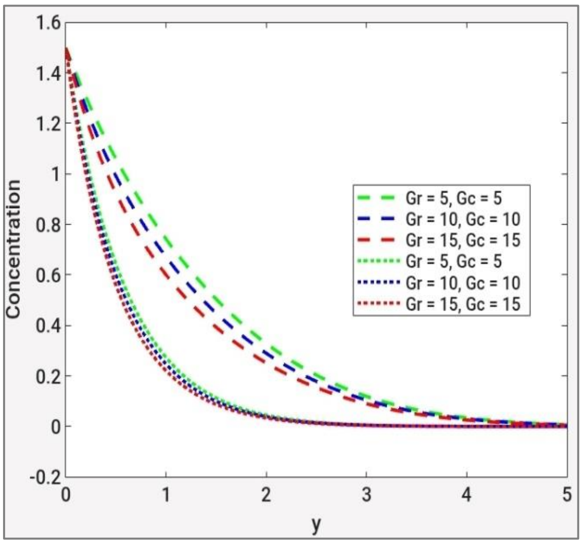

Figure 6: Showing Gr and Gc effects on C with suction/injection and stratification

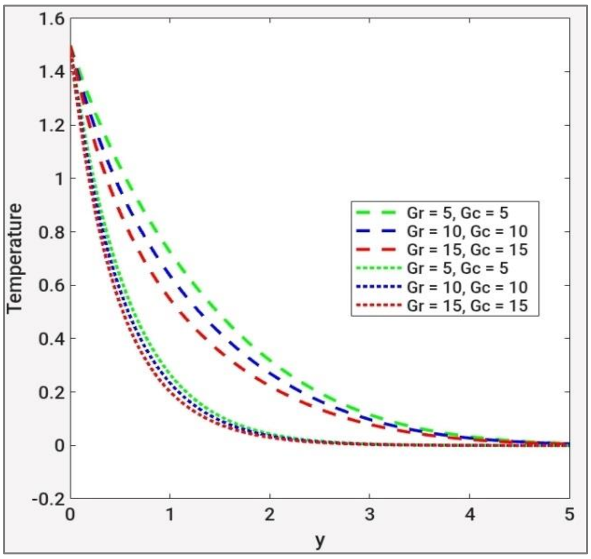

Figure 7: Showing Gr and Gc effects on T with suction/injection and stratification

Figures 2 and 3 revealed that the concentration profile decreases with an increase in suction and the mass stratification parameter, increases with an increase in injection while mass stratification is held constant, and decreases with an increase in mass stratification while injection is held constant. In a similar way, Figures 4 and 5 showed that the temperature profile is lowered with an increase in suction and thermal stratification parameters, rises with an increase in injection while keeping thermal stratification constant, and diminishes with an increase in thermal stratification while keeping injection constant. This is because the fluid at the initial condition is drawn toward the heated plate; in suction, the hotter, more concentrated fluid near the plate is removed, while in injection the opposite holds. Stratification prevents or reduces vertical mixing between fluid layers, hence lowering temperature and concentration.

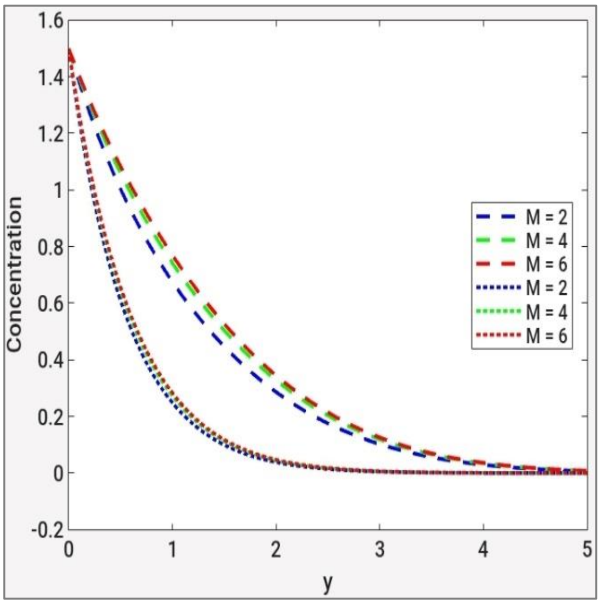

Figure 8: Showing the effects of M on C with suction/injection and stratification

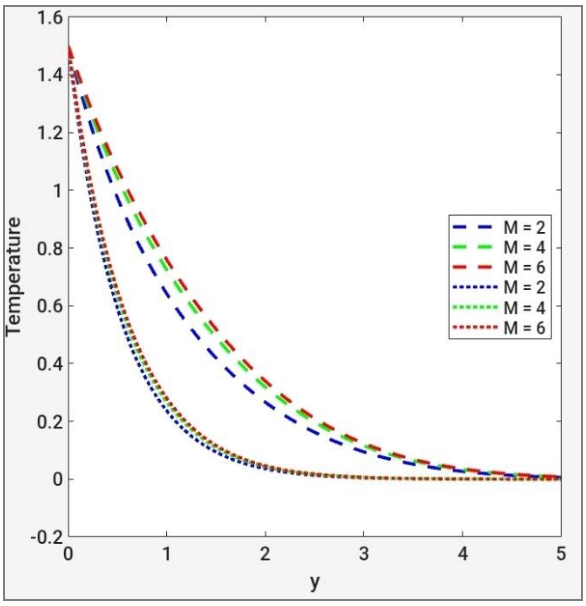

Figure 9: Showing the effects of M on T with suction/injection and stratification

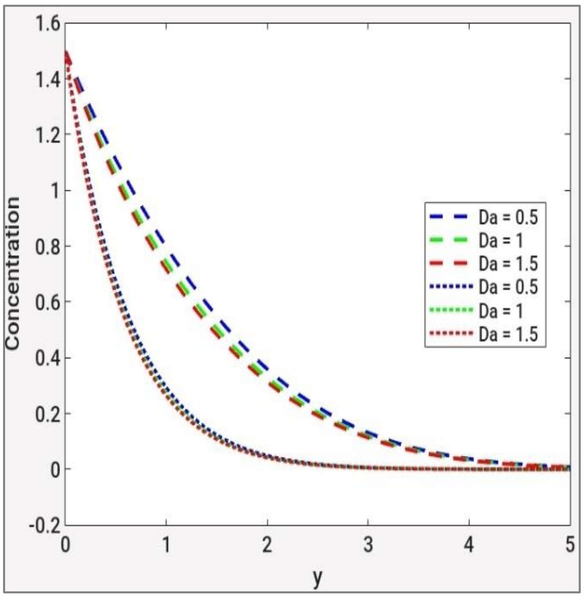

Figure 10: Showing the effects of Da on C with suction/injection and stratification

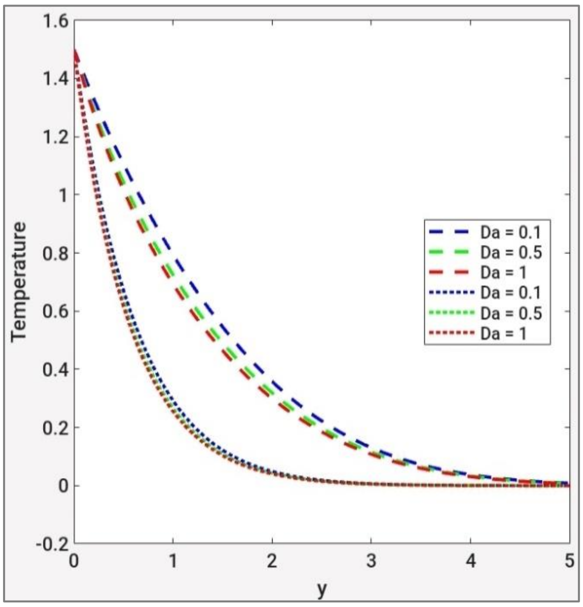

Figure 11: Showing the effects of Da on T with suction/injection and stratification

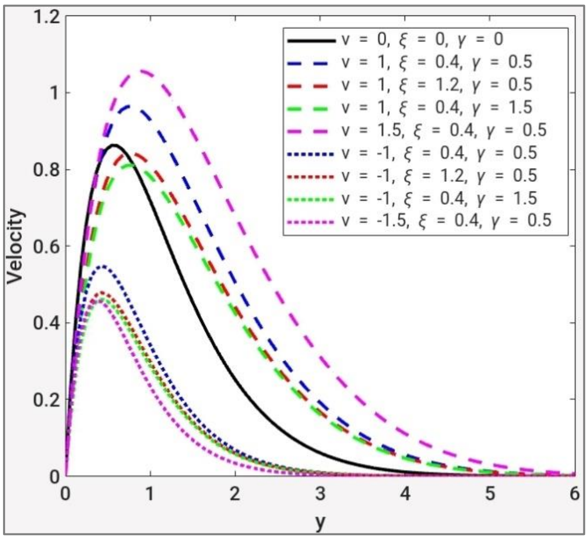

Figure 12: Showing suction/injection and stratification effects on u against distance (y)

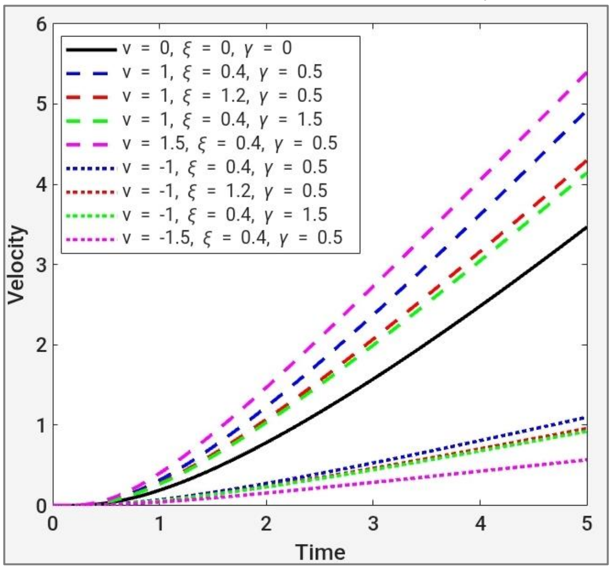

Figure 13: Showing suction/injection and stratification effects on u against time (t)

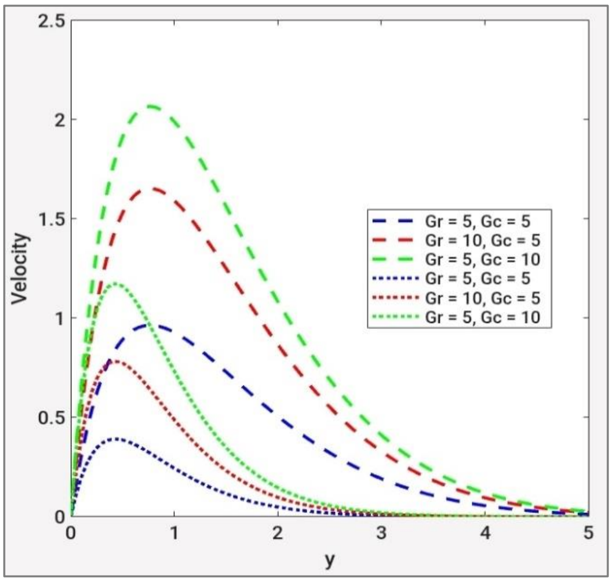

Figure 14: Showing Gr and Gc effects on u with suction/injection and stratification

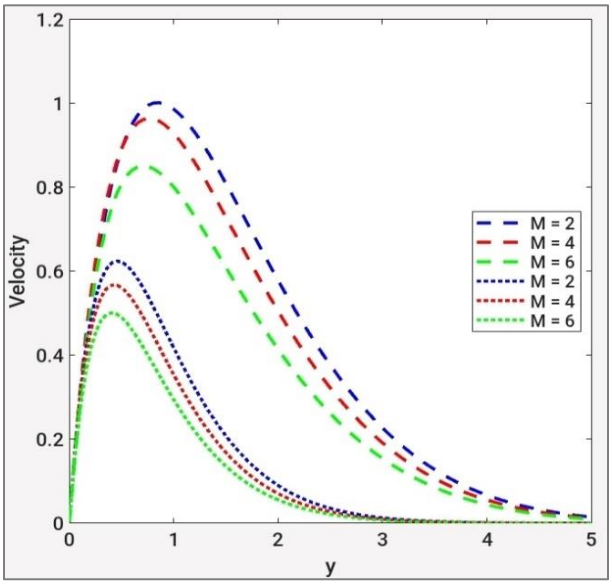

Figure 15: Showing the effects of M on u with suction/injection and stratification

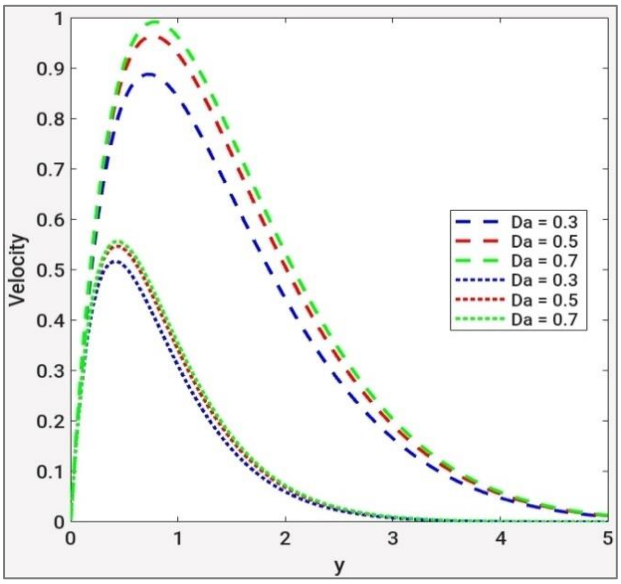

Figure 16: Showing the effects of Da on u with suction/injection and stratification

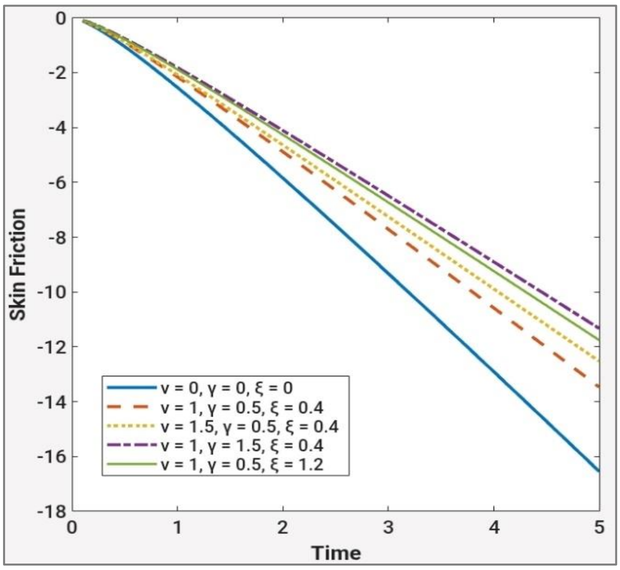

Figure 17: Showing the effects of suction/injection and stratification on skin friction

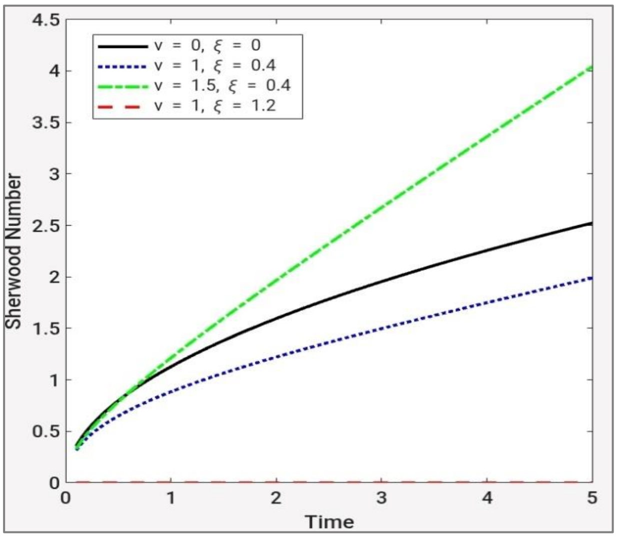

Figure 18: Showing the effects of injection and stratification on Sherwood number

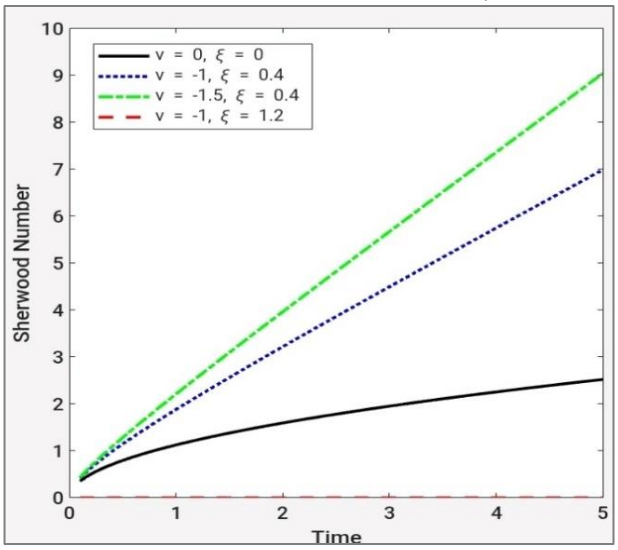

Figure 19: Showing the effects of suction and stratification on Sherwood number

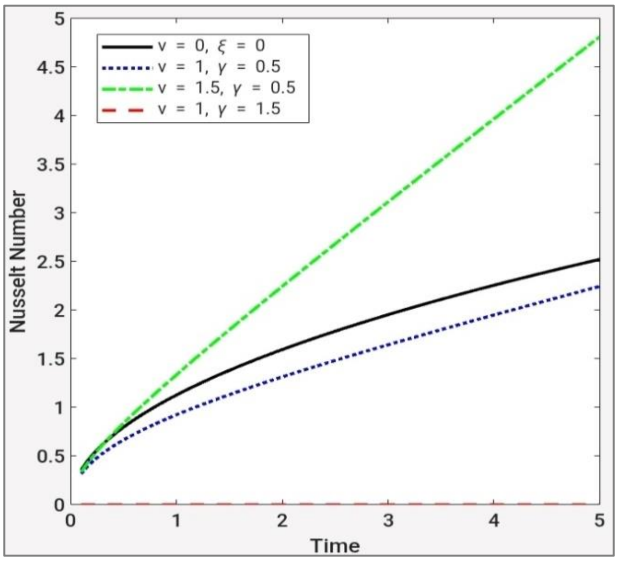

Figure 20: Showing the effects of injection and stratification on Nusselt number

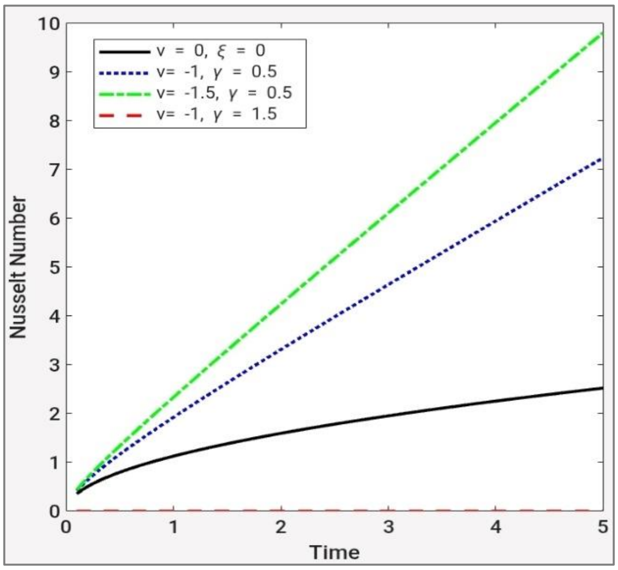

Figure 21: Showing the effects of suction and stratification on Nusselt numbe

Figures 6, 7, 8 and 9 illustrated that irrespective of suction or injection both temperature and concentration profiles vary directly with magnetic parameter and inversely with thermal and mass Grashof numbers. The profiles drop more sharply with injection than with suction, but settle to zero more quickly with suction due to boundary-layer thinning. As buoyancy forces dominate viscous forces due to the increase in Gr and Gc, the fluid layers become more stable. Thus, reducing vertical mixing.

It is noted in Figures 10 and 11 that temperature and concentration reduce with increase in Darcy number. High Darcy number implies more permeability allowing the fluid move faster with enhance heat and mass transfer which reduces the concentration and temperature.

Figures 12 and 13 depict a decreasing velocity profile due to a rise in suction and double stratification parameters, and an increase in stratification in the case of fixed injection. But the profile increases with increasing injection value for a fixed stratification parameter. The plots in Figures 3, 5, and 13 indicate that increasing suction and stratification stabilise the concentration, temperature, and velocity profiles over time toward the steady state, similar to the case of fixed injection and growing stratification. In the case of growing injection and fixed stratification, the profiles grow infinitely with time, as in the case when suction/injection and stratification are absent. Suction enhances velocity by thinning the boundary layer, thereby creating a larger cross-section for the free stream, which results in gravitational damping.

The velocity profile decreases with an increase in the magnetic parameter, while increasing with rising values of the thermal Grashof number, mass Grashof number, and Darcy number, as shown in Figures 14, 15, and 16. In Figure 17, suction and injection have exactly the same effect on skin friction. Moreover, the skin friction increases with suction/injection and with double stratification compared to the classical scenario. Increase in the magnetic field strength creates a more flow-resisting force (Lorenz's force), making the fluid move more slowly, while buoyancy dominance over viscous force enhances the velocity.

Figures 18 to 21 showed that both Sherwood and Nusselt numbers flatten to zero with increasing stratification, keeping suction/injection constant; they increase with rising suction/injection in the presence of stratification, as compared to the classical scenario cases. The obtained results for suction/injection agree with those of Halima *et al.* (2023). For stratification, Da Gr and Gc, it agrees with Sahu and Deka (2024) and Das and Deka (2024). And for the magnetic parameter, it agrees with Goud *et al.* (2023) and Joseph *et al.* (2014).

CONCLUSION

This study examined the effect of mass and thermal stratification, combined with suction or injection, on unsteady Newtonian incompressible MHD fluid flowing through an infinite vertical stationary porous plate. The analysis incorporates variable-temperature and mass-diffusion effects. Based on the results obtained, suction, double stratification, and magnetic field significantly influence the flow dynamics, heat transfer, and mass diffusion in porous media. The results highlight the opposing effects of suction (reducing profiles) and injection (enhancing profiles) under stratification. Additionally, buoyancy forces Gr and Gc, and the magnetic field, enhance the velocity while lowering both temperature and concentration. The findings provide valuable insights into controlling thermal and mass transport in engineering systems, particularly where porous media and MHD effects are relevant. Future research may consider extending the study to non-unitary Prandtl and Schmidt numbers to broaden its applicability.

NOMENCLATURE

A – Reference time inverse

B_0 – Magnetic field strength

C^* – Fluid concentration

$C^*{}_0$ – Initial fluid concentration

$C^*{}_w$ – Fluid concentration at $y = 0$

C_p – Specific heat at constant pressure

D – Molecular diffusivity

Da – Darcy number

g – Gravitational acceleration

Gr – Thermal Grashof number

Gc – Mass Grashof number

L_R – Reference length

$\mathrm{N_u}$ – Nusselt number

k – Thermal conductivity of fluid

k^* – Porosity parameter

P_r – Prandtl number

S_c – Schmidt number

$\mathrm{S_f}$ – Skin friction

$\mathrm{S_h}$ – Sherwood number

t^* – Time

t_R – Reference time

T^* – Fluid temperature

$T^*{}_0$ – Initial fluid temperature

$T^*{}_w$ – Fluid temperature at $y = 0$

u^* – Velocity of the fluid

U_R – Reference velocity

v^* – Suction/injection parameter

y^*, x^* – Cartesian coordinates

β – Volumetric thermal expansion coefficient

β_c – Volumetric coefficient of expansion by concentration

γ^* – Thermal stratification parameter

ξ^* – Mass stratification parameter

ρ – Fluid reference density

μ – Dynamic viscosity

ν – Kinematic viscosity

σ – Electrical conductivity of the fluid

Note: the (*) was used distinguish dimensional parameters from non-dimensional parameters (e.g. y^* is dimensional spartial parameter while y is non dimensional spartial parameter).

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