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INFLUENCE OF MAGNETIC FIELD ALIGNMENT ON HEAT AND MASS TRANSFER IN AN UNSTEADY MHD FLOW WITH RADIATION, CHEMICAL REACTION, AND DUFOUR EFFECTS

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Abstract

This study presents an exact analytical solution for the transient magnetohydrodynamic (MHD) free convection flow of an incompressible, electrically conducting fluid confined between two infinite inclined plates. The analysis incorporates the combined influence of an externally applied magnetic field aligned with the flow, thermal radiation, and chemical reactions. The inclination of the plates introduces a gravitational component that alters buoyancy-driven flow dynamics, adding complexity to heat and mass transfer mechanisms. The investigation focuses on oscillatory flow conditions, which are crucial for modeling time-dependent phenomena in geophysical systems, industrial chemical processes, and thermal management applications. The Lorentz force, generated by the interaction between the magnetic field and fluid motion, is examined to assess its effects on velocity and temperature distributions. Thermal radiation is approximated using the Rosseland model, while a first-order chemical reaction term is included in the species concentration equation. The governing partial differential equations for momentum, energy, and mass transfer are solved analytically under specified initial and boundary conditions. The results demonstrate the significant impact of key parameters, including magnetic field strength, thermal radiation, chemical reaction kinetics, and plate inclination angle, on flow behavior, temperature profiles, and concentration distribution. This research advances the understanding of unsteady MHD convection flows under thermal and chemical influences, offering insights for optimizing high-temperature systems and electromagnetically controlled reactive processes. The findings have potential applications in enhancing industrial cooling systems, chemical reactors, and geophysical flow modeling.

Keywords: Unsteady MHD flow; Heat and mass transfer; Magnetic field alignment; Thermal radiation; Chemical reaction; Inclined plates.

ВПЛИВ ВИРІВНЮВАННЯ МАГНІТНОГО ПОЛЯ НА ТЕПЛО- І МАСОПЕРЕДАЧУ В НЕРІВНОМІРНОМУ МНД-ПОТОЦІ З ВПЛИВОМ РАДІАЦІЇ, ХІМІЧНОЇ РЕАКЦІЇ ТА ЕФЕКТУ ДЮФУРА

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Анотація

У цьому дослідженні представлено точне аналітичне рішення для перехідного магнітогідродинамічного (МГД) потоку вільної конвекції нестисливої електропровідної рідини, обмеженої двома нескінченними похилими пластинами. Аналіз враховує сукупний вплив зовнішнього магнітного поля, вирівняного з потоком, теплового випромінювання та хімічних реакцій. Нахил пластин вносить гравітаційну складову, яка змінює динаміку потоку, обумовлену плавучістю, додаючи складності механізмам тепло- та масообміну. Дослідження зосереджується на умовах коливального потоку, які мають вирішальне значення для моделювання залежних від часу явищ у геофізичних системах, промислових хімічних процесах та системах терморегулювання. Сила

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Лоренца, що виникає в результаті взаємодії магнітного поля та руху рідини, досліджується з метою оцінки її впливу на розподіл швидкості та температури. Теплове випромінювання апроксимується за допомогою моделі Росселанда, а до рівняння концентрації речовин включено член першого порядку хімічної реакції. Основні диференціальні рівняння для імпульсу, енергії та масопереносу вирішуються аналітично за заданих початкових та граничних умов. Результати демонструють значний вплив ключових параметрів, включаючи силу магнітного поля, теплове випромінювання, кінетику хімічної реакції та кут нахилу пластини, на поведінку потоку, температурні профілі та розподіл концентрації. Це дослідження сприяє розумінню нестационарних MHD-конвекційних потоків під впливом теплових та хімічних факторів, пропонуючи ідеї для оптимізації високотемпературних систем та електромагнітно керованих реакційних процесів. Отримані результати мають потенційне застосування в удосконаленні промислових систем охолодження, хімічних реакторів та моделюванні геофізичних потоків.

Keywords: нестационарний MГД-потік; тепломаообмін; орієнтація магнітного поля; теплове випромінювання; хімічна реакція; похилі пластини.

Introduction

Magneto hydrodynamic (MHD) flows involve the motion of electrically conducting fluids influenced by magnetic fields and are essential in numerous scientific and industrial applications such as nuclear fusion reactors, astrophysical plasmas, geothermal energy systems, and high-performance cooling technologies. The complexity of these flows increases when thermal and concentration gradients are introduced, resulting in the coupling of electromagnetic forces with buoyancy-driven convection, heat transfer, and mass diffusion. Previous research has addressed various aspects of unsteady MHD convection.

Several researchers have contributed valuable insights into magnetohydrodynamic (MHD) flows with thermal radiation and chemical reactions. Seddeek et al. [1] pioneered work on radiation and variable viscosity effects in MHD flow across a semi-infinite plate under magnetic influence. Building on this foundation, Raghunath et al. [2] investigated Soret effects and mixed convection in unsteady MHD flow along permeable vertical plates, incorporating radiation, heat absorption, and chemical reactions.

Recent studies have expanded these concepts to various geometries and conditions. Endalew et al. [3] conducted exact analyses of radiative MHD flow across tilted parabolic surfaces in porous media, examining variable concentration and temperature fields under slanted magnetic fields. Khan et al. [4] advanced understanding of non-Newtonian fluids by analyzing Casson fluid behavior with Neumann conditions, considering magnetic, radiation, and porous media effects. Buzuzi et al. [5] contributed to oscillatory flow research by studying inclined surfaces with constant suction and chemical reactivity under inclined magnetic fields.

The literature reveals growing complexity in MHD investigations. Mohan et al. [6] examined combined radiation, heat generation/absorption, and aligned magnetic fields on Casson fluid flow through porous inclined plates. Krishna et al. [7]

explored oscillatory second-grade fluids between permeable vertical walls with transverse magnetic fields. Bilal et al. [8] introduced nonlinear convection concepts with variable thermal conductivity and phase change effects.

Recent innovations include Naz et al.'s [9] work on non-uniform magnetic fields at varying orientations and temporal conditions. Sahu et al. [10] investigated thermal stratification effects on accelerating vertical plates with exponential mass diffusion. Das et al. [11] and Alharbi et al. [12] further enriched the field by examining thermal diffusion in natural convection and magnetic characteristics of charged fluids, respectively, providing comprehensive analyses of transport phenomena at heated vertical surfaces [13–18]. explored magnetohydrodynamics in complex fluids, incorporating nanoparticle interactions. [19–23] developed analytical models for ferroconvection in porous media, while [24–28] studied chemically reactive flows with thermal radiation, systematically quantified coupled heat-mass transfer phenomena, providing comprehensive insights into transport mechanisms for industrial applications [29–47].

This body of work demonstrates progressive sophistication in modeling MHD systems, from fundamental analyses to complex multi-physics simulations incorporating various boundary conditions, fluid types, and geometric configurations. The collective findings establish a robust theoretical framework for understanding coupled momentum, heat, and mass transfer in magnetized fluid systems.

The present study offers an exact analytical solution for such a complex physical scenario, providing valuable insights into how parameters such as magnetic field intensity, thermal radiation, chemical reactivity, and inclination angle influence flow behavior. These analytical results serve as reliable benchmarks for validating computational models and contribute to a deeper understanding of magneto-thermal-reactive interactions. The findings have direct relevance to

the design and optimization of engineering systems involving electromagnetic regulation, reactive flow control, and thermal energy management in inclined geometries.

Mathematical Formulation

This research examines the transient, two-dimensional flow of an incompressible, electrically conducting viscous fluid confined between infinite inclined parallel plates. The study incorporates three key physical phenomena: (1) a uniform magnetic field aligned with the flow direction, (2) thermal radiation effects, and (3) a homogeneous chemical reaction. The plates are inclined at an angle α to the vertical, with the x^* -axis representing the flow direction and the y^* -axis normal to the plates.

A low magnetic Reynolds number assumption allows neglect of the induced magnetic field's

$$\frac{\partial u^*}{\partial t^*} = \frac{\partial p^*}{\partial x^*} + \nu_1 \frac{\partial^2 u^*}{\partial y^{*2}} + \nu_2 \frac{\partial^3 u^*}{\partial y^{*2} \partial t^*} - \frac{\nu}{K^*} u^* - \frac{\sigma B_0^2 \sin^2 \delta}{\rho} u^* + g\beta_T^*(T^* - T_0^*) \sin \alpha + g\beta_C^*(C^* - C_0^*) \cos \alpha \quad (1)$$

Energy equation:

$$\rho C_p \frac{\partial T^*}{\partial t^*} = k \frac{\partial^2 T^*}{\partial y^{*2}} - \frac{\partial q_r}{\partial y^*} + \frac{\rho D_m K r}{C_s} \frac{\partial^2 C^*}{\partial y^{*2}} - Q(T^* - T_0^*) + Q_c(C^* - C_0^*) \quad (2)$$

Species diffusion equation:

$$\frac{\partial C^*}{\partial t^*} = D_m \frac{\partial^2 C^*}{\partial y^{*2}} - Kr(C^* - C_0^*) \quad (3)$$

The boundary conditions are

$$u^* = 0, T^* = T_0^*, C^* = C_0^* \text{ at } y^* = 0, \quad u^* = 0, T^* = T_w^*, C^* = C_w^* \text{ at } y^* = 1, \quad (4)$$

For a fluid that is optically thin, there is $\frac{\partial q_r}{\partial y^*} = 4\alpha^2(T_0^* - T^*)$

Where $\alpha^2 = \int_0^\infty \delta \lambda \frac{\partial B_\lambda}{\partial T}$ is the absorption coefficient, δ is radiation absorption coefficient λ is frequency, and B is Planck's function.

The non-dimensional variables are

$$x = \frac{x^*}{a}, y = \frac{y^*}{a}, u = \frac{u^*}{U}, t = \frac{t^* U}{a}, Re = \frac{Ua}{\nu_1}, \theta = \frac{(T^* - T_0^*)}{(T_w^* - T_0^*)}, \phi = \frac{(C^* - C_0^*)}{(C_w^* - C_0^*)}, c = \frac{g\beta_C^*(C_w^* - C_0^*)a^2}{\nu_1 U},$$

$$GGr = \frac{g\beta_T^*(T_w^* - T_0^*)a^2}{\nu_1 U}, P = \frac{aP^*}{\rho\nu_1 U}, Du = \frac{KrD_m(C_w^* - C_0^*)}{a^2 C_s (T_w^* - T_0^*)}, J = \frac{Kra}{U}, Q = \frac{Q^* \nu}{\rho C_p u_0^2}, K^2 = \frac{a^2 \sigma B_0^2}{\rho\nu_1}, Q_1 = \frac{a^2 Q_c (C_w^* - C_0^*)}{k(T_w^* - T_0^*)}, Pe = \frac{Ua\rho C_p}{k}, R = \frac{4a^2 \alpha^2}{k}, Sc = \frac{a}{D_m}, S^2 = \frac{a}{D_u}, E = \frac{Qa^2}{k}. \quad (5)$$

Equations with the aforementioned replacement (1) to (3), the equation system reduced to a form with no dimensions as $Re \frac{\partial u}{\partial t} = -\frac{\partial p}{\partial x} + \frac{\partial^2 u}{\partial y^2} + \gamma \frac{\partial^3 u}{\partial y^2 \partial t} + (S^2 + H^2)u + Gr_1 \theta + Gc_1 \phi$ (6)

$$Pe \frac{\partial \theta}{\partial t} = \frac{\partial^2 \theta}{\partial y^2} + Du \frac{\partial^2 c}{\partial y^2} + (R^2 - E)\theta + Q_1 \phi \quad (7)$$

$$\frac{\partial \phi}{\partial t} = Sc \frac{\partial^2 \phi}{\partial y^2} - J\phi \quad (8)$$

The boundaries on velocity, temperature and concentration in no dimensional forms are

$$u = 0, \theta = 1, \phi = 1 \text{ at } y = 0, \quad u = 0, \theta = 0, \phi = 0 \text{ at } y = 1. \quad (9)$$

Solution of the problem: To solve (6-8) equations with boundaries (9) considering only oscillatory flow, let's suppose

$$-\frac{\partial p}{\partial x} = \lambda e^{i\omega t}, \quad u(y,t) = u_0(y) e^{i\omega t}, \quad \theta(y,t) = \theta_0(y) e^{i\omega t}, \quad \phi(y,t) = \phi_0(y) e^{i\omega t} \quad (10)$$

influence. Thermal radiation is modeled using the Rosseland approximation, treating the fluid as a gray, absorbing-emitting medium without scattering effects. The analysis includes a first-order chemical reaction in the species transport equation.

The governing equations for momentum, energy, and concentration are derived using the Boussinesq approximation, accounting for buoyancy forces due to thermal and solutal gradients. This formulation captures the coupled effects of electromagnetic, thermal, and chemical interactions in an inclined geometry, providing a comprehensive framework for analyzing unsteady magnetohydrodynamic (MHD) convective flow with heat and mass transfer. The study offers insights into complex fluid dynamics relevant to industrial and engineering applications.

Momentum equation:

Substituting equation (10) into equations (6) to (8), we get,

$$(1 + i\omega\gamma) \frac{d^2 u_0}{dy^2} - M_1^2 u_0 = -\lambda - Gr_1 \theta_0 - Gc_1 \phi_0 \quad (11)$$

$$\frac{d^2 \theta_0}{dy^2} + M_2^2 \theta_0 = -(Q_1 + DuM_3^2) \phi_0 \quad (12)$$

$$\frac{d^2 \phi_0}{dy^2} - M_3^2 \phi_0 = 0 \quad (13)$$

The corresponding boundary conditions are

$$u = 0, \theta_0 = 1, \phi_0 = 1 \text{ at } y = 1,$$

$$u = 0, \theta_0 = 0, \phi_0 = 0 \text{ at } y = 0. \quad (14)$$

Solving equations (11) through (13) with boundaries in (14) yields the distributions for velocity, temperature, and concentration as follows: $u(y, t) =$

$$\left\{ Gr_1 \left(\left[\frac{1+k_1}{M_1^2 + L^2 M_2^2} \right] \frac{\sin M_2 y}{\sin M_2} + \left[\frac{k_1}{L^2 M_3^2 - M_1^2} \right] \frac{\sin H M_3 y}{\sin H M_3} - \left[\frac{1+k_1}{M_1^2 + L^2 M_2^2} + \frac{k_1}{L^2 M_3^2 - M_1^2} \right] \frac{\sin H \frac{M_1 y}{L}}{\sin H \frac{M_1}{L}} \right) \right. \\ \left. + \frac{Gc_1}{L^2 M_3^2 - M_1^2} \left(\frac{\sin H \frac{M_1 y}{L}}{\sin H \frac{M_1}{L}} + \frac{\sin H M_3 y}{\sin H M_3} \right) + \frac{\lambda}{M_1^2} \left(\frac{\sin H \frac{M_1 y}{L}}{\sin H \frac{M_1}{L}} \left(\cosh \frac{M_1}{L} - 1 \right) - \cosh \frac{M_1 y}{L} + 1 \right) \right\} e^{i\omega t}$$

$$\theta(y, t) = \left\{ (1 + k_1) \frac{\sin M_2 y}{\sin M_2} - k_1 \frac{\sin H M_3 y}{\sin H M_3} \right\} e^{i\omega t}$$

$$\phi(y, t) = \frac{\sin H M_3 y}{\sin H M_3} e^{i\omega t}$$

Nusselt Numbers:

$$Nu_1 = - \left(\frac{\partial \theta}{\partial y} \right)_{y=0} = - \left\{ (1 + k_1) \frac{M_2}{\sin M_2} - k_1 \frac{M_3}{\sin H M_3} \right\} e^{i\omega t}, Nu_2 = - \left(\frac{\partial \theta}{\partial y} \right)_{y=1} = - \left\{ (1 + k_1) \frac{M_2 \cos M_2}{\sin M_2} - k_1 \frac{M_3 \cosh M_3}{\sin H M_3} \right\} e^{i\omega t}$$

Sherwood numbers:

$$SH_1 = - \left(\frac{\partial \phi}{\partial y} \right)_{y=0} = - \frac{M_3}{\sin H M_3} e^{i\omega t}, SH_2 = - \left(\frac{\partial \phi}{\partial y} \right)_{y=1} = - \frac{M_3 \cosh M_3}{\sin H M_3} e^{i\omega t}$$

$$\text{Where } k_1 = \frac{Q_1}{M_1^2 + M_3^2}, M_1^2 = R^2 - E - i\omega Pe, M_2^2 = S^2 + H^2 + i\omega Re, M_3^2 = \frac{J+i\omega}{Sc} S^2.$$

Results and Discussions

The study presents graphical solutions for velocity, temperature, and concentration profiles using fixed parameter values: $H = 1, Pe = 0.71, E = 0.5, Gr = 4, Gc = 4, J = 2, Q_1 = 1.5, R = 1.9, Sc = 0.6, \alpha = \pi/4,$ and $\delta = \pi/4$ for velocity; $Pe = 0.71, E = 5, Du = 0.5, J = 0.05, Q_1 = 0.1, R = 1, Sc = 0.6$ for temperature; and $J = 2, Sc = 0$ for concentration. Figures (1-10) depict velocity ($u(y,t)$), (11-14) illustrate temperature ($\theta(y,t)$), and (15-16) display concentration ($\phi(y,t)$). Key influences include the Hartmann number (H), thermal radiation (R), Dufour effect (Du), inclination angle (α), and chemical reaction (J), with results analyzed through graphs and tables.

Velocity Profile Dynamics in Buoyancy-Assisted Flow

Figures (1-3) analyze buoyancy-assisted flow ($Gr > 0, Gc > 0$), showing that increasing the Hartmann number (H) reduces velocity due to Lorentz force resistance. Higher heat source ($E > 0$) and Dufour (Du) parameters also diminish velocity, weakening the momentum boundary layer. Conversely, Figures (4-7) reveal that Gr, Gc, R, α , and J enhance velocity in buoyancy-assisted zones, emphasizing boundary layer dynamics.

Industrial applications often involve interactions between thermal radiation (R) and chemical reactions (J), which jointly influence flow behavior. Figures (8-10) demonstrate that aligned magnetic field (δ), radiation absorption (Q_1), and Schmidt number (Sc) reduce velocity, further suppressing momentum transfer.

Temperature and Concentration Profile Variations

Figures (11-13) show that increasing E, Du, and Q_1 flattens the temperature profile by reducing thermal diffusivity. A positive Q_1 (heat source) elevates temperature, while a negative Q_1 (heat absorption) alters distribution significantly. Notably, higher radiation (R) intensifies the thermal field (Fig. 14). For concentration (Figs. 15-16), a rise in chemical reaction parameter (J) decreases concentration due to reactant consumption, whereas higher Schmidt number (Sc) increases it. Since Sc represents the ratio of kinematic viscosity to thermal diffusivity, its increase typically enhances viscosity while reducing thermal diffusion, thereby affecting concentration gradients.

Quantitative Analysis of Nusselt and Sherwood Numbers

Tables 1 and 2 summarize Nusselt (Nu1, Nu2) and Sherwood (Sh1, Sh2) numbers. Table 1 indicates that Nu1 (lower plate) and Nu2 (upper plate) increase with R, Du, J, and Q1 but decrease with E and Sc. Table 2 reveals that Sh1 rises while Sh2 falls with increasing J, whereas the opposite occurs for Sc. These trends highlight the competing effects of thermal and solutal parameters on heat and mass transfer rates,

providing insights for optimizing industrial and geophysical systems.

Potential applications

- Design of heat transfer systems with enhanced convective cooling.
- Understanding fluid flow in geophysical phenomena like magma movement.
- Optimizing the performance of MHD devices like plasma confinement systems.

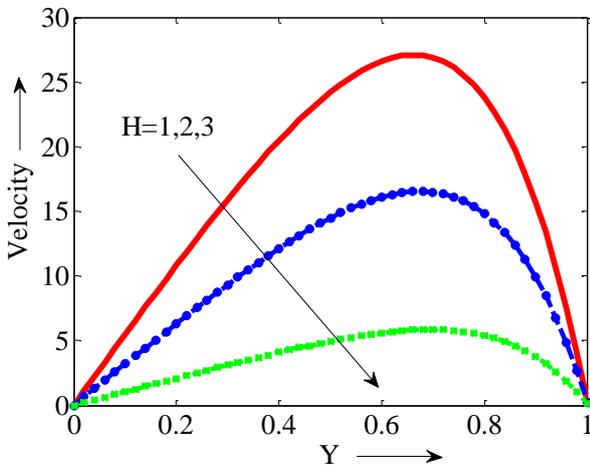


Fig. 1. Velocity variate for H

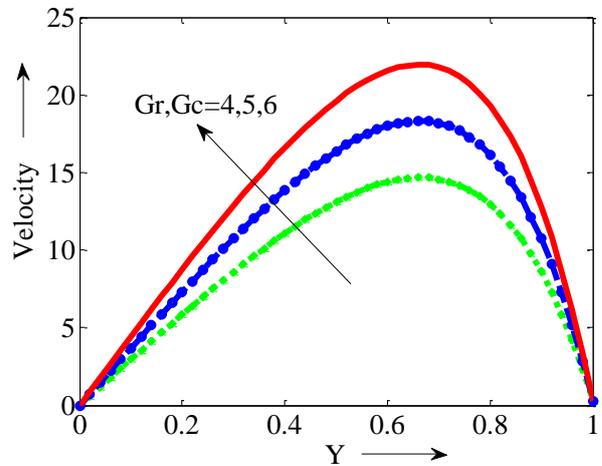


Fig. 4. Velocity variate for Gc, Gr

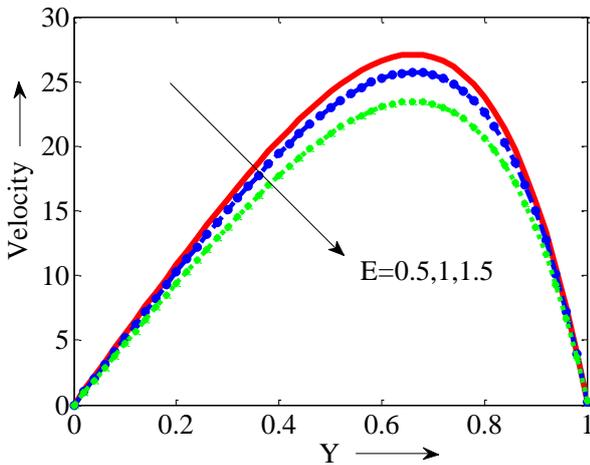


Fig. 2. Velocity variate for E

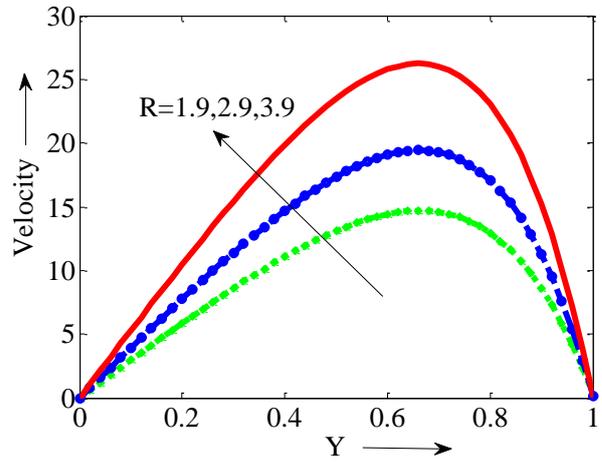


Fig. 5. Velocity variate for R

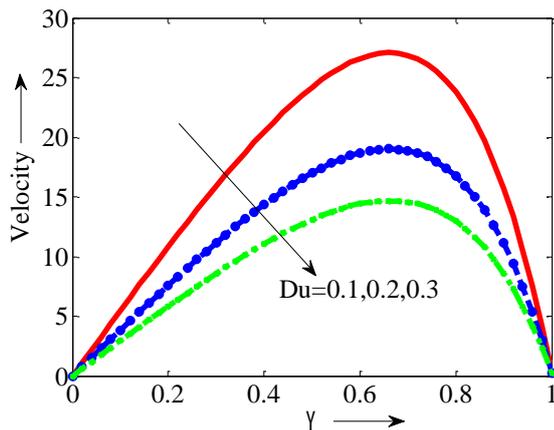


Fig. 3. Velocity variate for Du

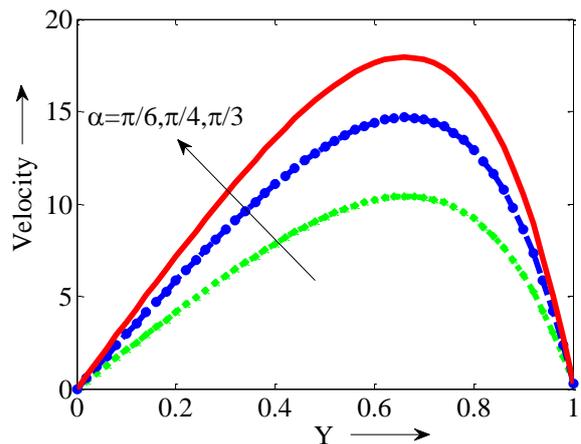


Fig. 6. Velocity variate for alpha

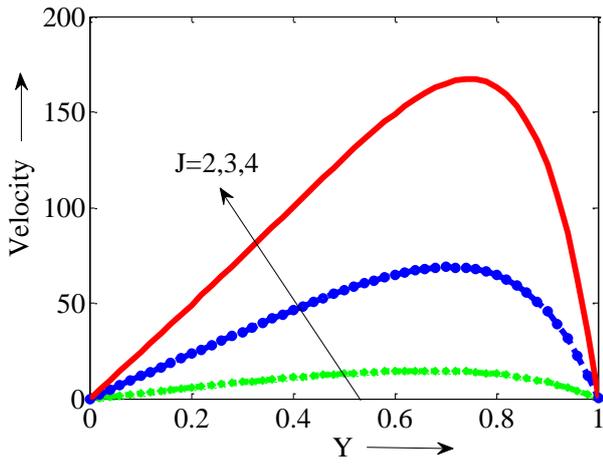


Fig. 7. Velocity variate for J

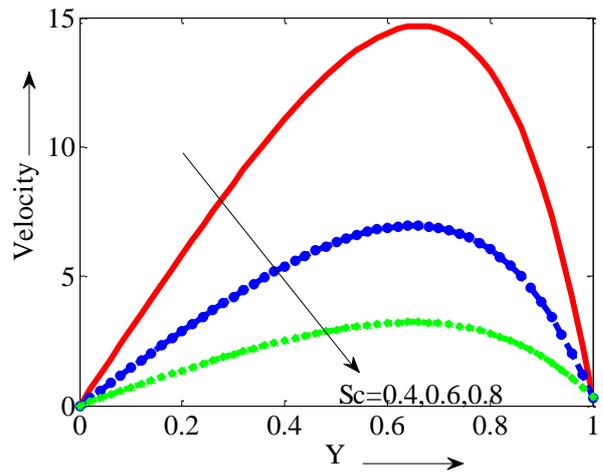


Fig. 10. Velocity variate for Sc.

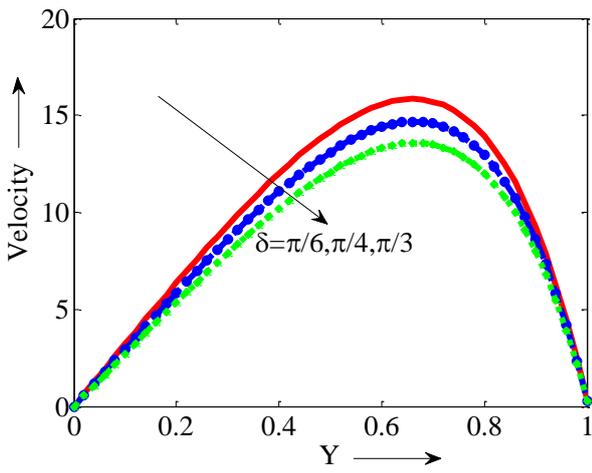


Fig. 8. Velocity variate for δ

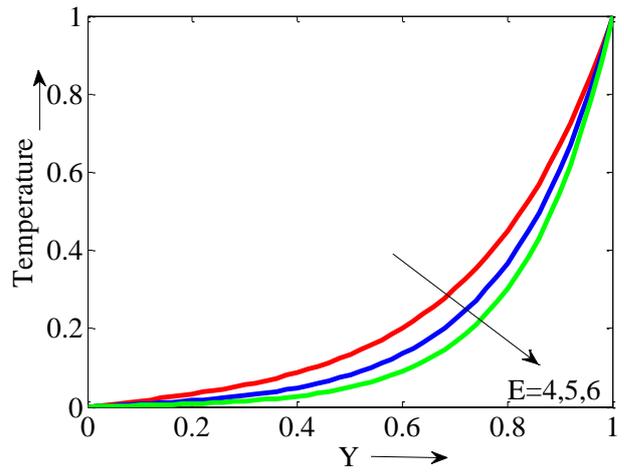


Fig. 11. Temperature variate for E

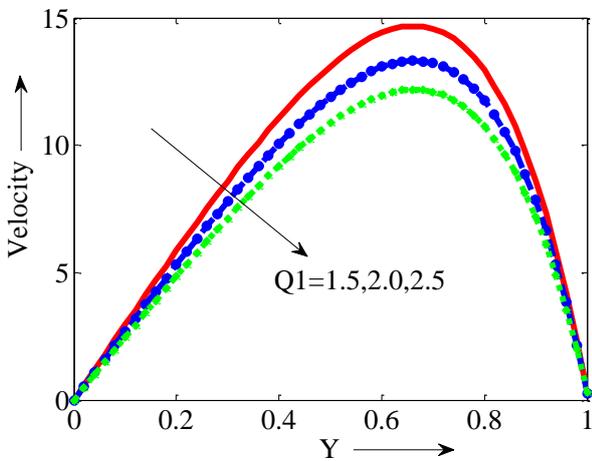


Fig. 9. Velocity variate for Q1

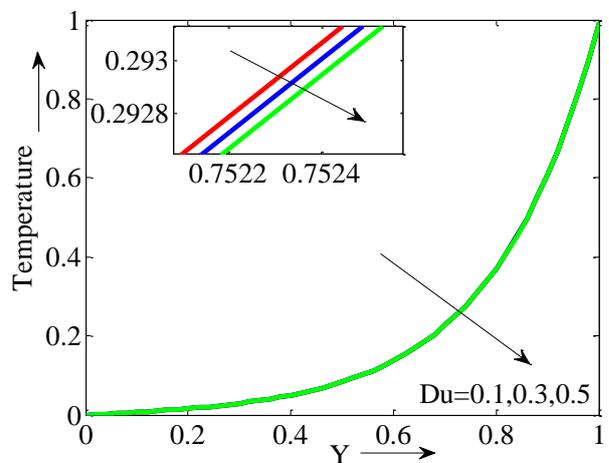


Fig. 12. Temperature variate for Du

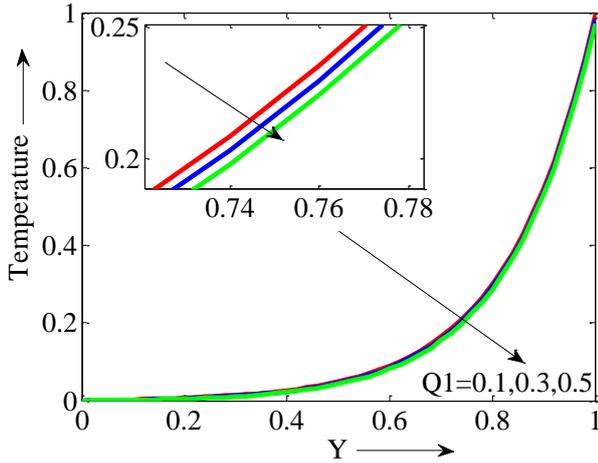


Fig. 13. Temperature variate for $Q1$

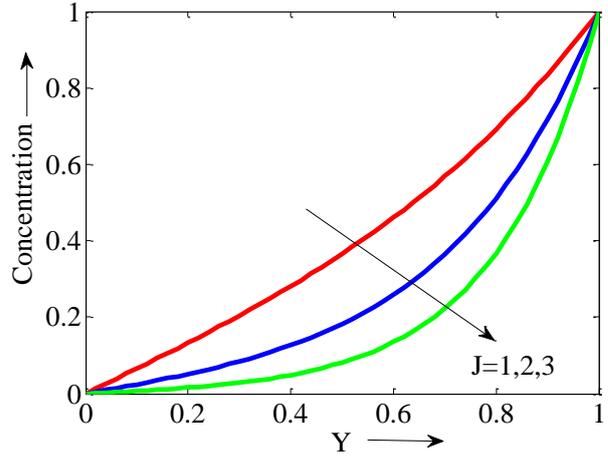


Fig. 15. Concentration variate for J

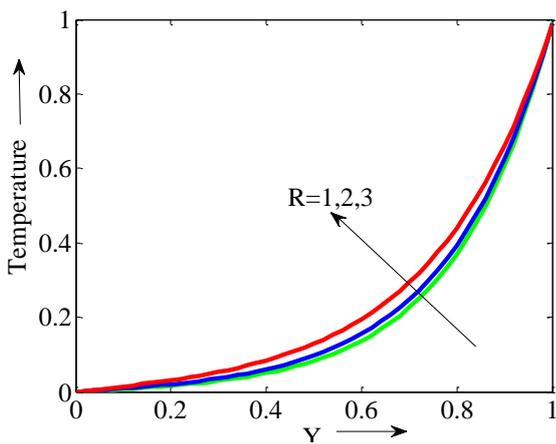


Fig. 14. Temperature variate for R

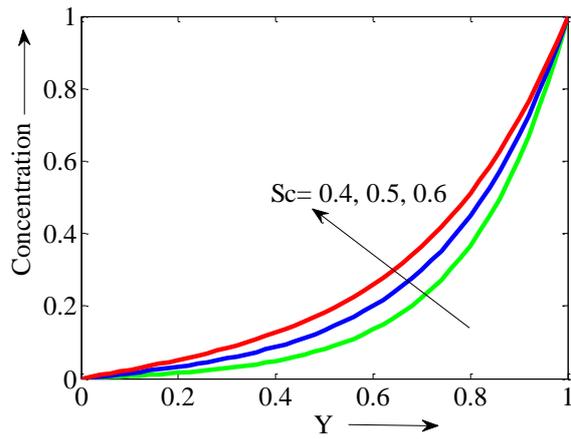


Fig. 16. Concentration variate for Sc

Table 1

Nusselt number			
J	Sc	Sh_1	Sh_2
2	0.6	-0.2381	-3.3418
3	0.6	-0.0674	-5.0005
4	0.6	-0.0170	-6.6667
4	0.7	-0.3293	-2.8761
4	0.8	-0.4132	-2.5339

Table 2

Sherwood number							
R	E	$Q1$	Sc	Du_1	J	Nu_1	Nu_2
1	4	1	0.60	1	2	1.0823	18.6031
1.5	4	1	0.60	1	2	1.7461	28.6634
2	4	1	0.60	1	2	5.9851	89.3525
1	5	1	0.60	1	2	0.2194	2.8445
1	6	1	0.60	1	2	0.1050	-1.2226
1	4	2	0.60	1	2	1.1850	20.4592
1	4	3	0.60	1	2	1.2877	22.3153
1	4	1	0.7	1	2	0.4962	5.1739
1	4	1	0.8	1	2	0.3147	1.4350
1	4	1	0.60	2	2	2.2232	20.4592
1	4	1	0.60	3	2	3.3640	22.3153
1	4	1	0.60	1	2.1	1.6347	31.6950
1	4	1	0.60	1	2.2	3.0771	66.2103

Conclusions

This study presents an exact analytical solution for unsteady magnetohydrodynamic (MHD) free convection flow of a viscous, incompressible, electrically conducting fluid between two infinite inclined plates. The analysis incorporates the combined effects of an aligned magnetic field, thermal radiation, and a first-order chemical reaction. The governing momentum, energy, and concentration equations were non-dimensionalized and solved analytically.

Key findings indicate that the aligned magnetic field significantly alters flow dynamics by generating a Lorentz force, which suppresses fluid motion and reduces velocity profiles. Thermal radiation enhances the thermal boundary layer thickness, elevating fluid temperature, particularly near the heated plate. Additionally, chemical reactions dampen species concentration,

thinning the concentration boundary layer as reaction rates increase. The Nusselt numbers (Nu_1 and Nu_2) rise with increasing radiation, Dufour number, chemical reaction, and radiation absorption parameters but decline with higher heat source and Schmidt number values.

Future scope

Future research will explore perturbation methods and numerical solutions to analyze the Soret effect in unsteady MHD flows. Investigations will extend to two-dimensional porous sheets to optimize heat transfer in Maxwell nanofluids. Additionally, the study will examine unsteady MHD convective flow of Casson hybrid nanofluids over oscillating plates. Further exploration will focus on the role of thermal radiation in diverse fluid dynamics scenarios, enhancing understanding of heat and mass transfer in advanced engineering applications.

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