

RESEARCH ARTICLE

Heat and Mass transfer in unsteady oscillatory flow of a Second-Grade fluid through an irregular channel with slip conditions and inclined magnetic field

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Abstract - Identifying the enormous contributions of heat and mass transfer in the dynamics of biological fluids with magnetohydrodynamics (MHD) effect is significant to both engineering and industrial applications. More importantly, the behaviour of non-Newtonian second-grade fluid, the presence of oscillatory flow, inclined magnetic fields, and slip conditions in an irregular channel introduces complexities that require further investigation. This study examines the mass and heat transfer dynamics of oscillatory inclined magnetic effect for flow of second-grade fluid in a wavy channel while considering the effects of slip conditions. The controlling system equations were resolved into a dimensionless form with appropriate transformation variables. Analytical solutions for concentration, energy and velocity profiles are obtained. Graphical representation illustrates the physical effects of the involved parameters on flow distributions and engineering characteristics of interest. The findings identified that introduction of heat source increases the momentum field, while an increase in the chemical reaction leads to a decrease in velocity. Additionally, the heat transfer rate at both walls increases as the heat source rises. Evidently, these insights contribute to the understanding of MHD flows in irregular geometries, with potential applications in cooling technologies, industrial fluid transport, and energy systems.

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1. Introduction

Dynamics of mass and heat processes are fundamental to numerous industrial, environmental, and technological applications. Understanding mechanisms governing these processes is essential for optimising systems such as energy conversion systems, microfluidic devices, chemical reactors, and heat exchangers. The physical phenomena and configurations presented in fluid dynamics include: the interaction of oscillatory flows, thermophysical features, magnetohydrodynamics, irreversibility analysis, entropy generation, regular/irregular geometries to mention but a few all presents particularly intriguing and complex scenarios capable of addressing a real-life problem (Hill [1], Wang et al. [2], Nabavi and Dalir [3]).

The study of magnetohydrodynamic (MHD) flows has accumulated significant attention due to its extensive applications in engineering and industrial processes, such as cooling systems, petroleum extraction, and energy generation. Specifically, understanding this dynamical system of heat transfer mechanism in oscillatory inclined MHD flows within irregular channels under slip conditions is crucial for optimising performance (Akolade et al. [4,5], Nandkeolyar et al. [6], Titiloye et al. [7]). Kumar et al. [8] explored how heat transfer behaves in oscillatory flows of magnetised second-grade fluids within irregular channels. Their study revealed that variations in channel geometry have a significant impact on heat transfer rates, reinforcing the need to account for these irregularities in MHD analyses. Ullah and Alkinidri [9] on the transient and convective heating effects around a magnetically driven stretching cylinder highlighted the oscillatory nature of heat transfer in MHD systems and demonstrated how magnetic fields influence fluid flow behavior significantly.

Other numerous contributions include the work of Ali and Khan [10] that applied analytical methods to study on two-dimensional flow of magnetised oscillatory system. Their investigation provided insights into unsteady MHD behaviors in complex geometries, offering novel solutions that expand understanding of these systems. Nagaraju et al. [11] on the concept of thermal radiation and stratified immiscible fluids emphasised the importance of assumption of stratification effects when analysing MHD flows. Srinivas Acharya and Reddy [12] examined how injection and suction impacted oscillatory flow of fluids through asymmetric wavy channels in porous media. Their research uncovered how these factors significantly influence both heat transfer and flow dynamics. Moreover, Gireesha et al. [13] explored the movement of dusty fluid flow through inclined irregular channels subjected to transversely applied magnetic fields. Their study highlighted the combined effects of channel inclination and magnetic fields on flow dynamics and heat transfer.

Mass and heat dynamics in the presence of chemical reactions holds immense practical significance for engineers and scientists, as it is a critical factor in various industrial and scientific applications. In view of these, Sasikumar et al. [14,15] investigated these dynamics incorporating the phenomenon of chemical reaction, oscillatory flow, and MHD through wavy channel. They highlighted the impact of energy and solute variations, and slip boundary conditions, demonstrating the crucial role of fluid concentration in understanding chemically reactive flow in the presence of MHD effect. Other related study is the analytical solution oscillatory viscoelastic fluid flow in Darian medium accommodating the impact of heat source and chemical reaction involvement by Oahimire [16], Aly and Ebaid [17] investigation on the peristaltic flow of nanofluids in asymmetric channels, emphasizing the importance of second-order slip conditions and Abbas et al. [18] analysis on the heat transfer characteristics of oscillatory flow in a magnetized second-grade fluid within Darian wavy channel, with temperature jump and velocity slip. The respective results provide insights into the effects of various parameters on energy and momentum fields with novel contributions into the understanding of fluid dynamics in complex geometries and potential applications in engineering systems.

Evidence from the literatures identified that flow geometry plays a critical role in determining flow behaviour. While much of the existing literature has focused on regular geometries (e.g., parallel plates or cylindrical tubes), irregular geometries more closely resemble practical systems such as natural porous formations, biological conduits, or industrial channels with imperfections. These irregularities can induce secondary flows, modify boundary layer development, and enhance mixing, all of which significantly impact thermal and concentration fields. Furthermore, the inclusion of slip boundary conditions acknowledges real-world scenarios where the no-slip assumption may not hold. In microscale and nanoscale systems, as well as certain types of non-Newtonian fluids, partial slip at the boundary becomes significant. This deviation from classical fluid behaviour alters the velocity profile, modifies shear stress distributions, and impacts the rates of heat and mass transfer. The presence of a magnetic field introduces Lorentz forces (the combination of magnetic and electric force on a point charge due to electromagnetic fields) that interact with the oscillatory flow, enhancing fluid motion depending on the configuration. These effects have practical relevance in designing electromagnetic pumps, controlling fluid flow in micro devices, and enhancing heat transfer in energy systems. The coupling of oscillatory motion, inclined flow, magnetic fields, irregular channel geometries, and slip conditions poses a challenging problem, requiring a thorough analysis to capture the interplay between these factors. This research aims to bridge gaps in the current understanding of such systems by developing theoretical models and analysing the behaviour of oscillatory inclined magnetic flows in irregular channels with slip conditions.

2. Methodology

An incompressible and unsteady flow of chemically reacting and thermally radiating second-grade fluid is examined within a wavy channel. A uniform magnetic field B_0 is applied perpendicular to the fluid convection analysis. The motion along the x -axis is imposed by the oscillatory pressure gradient, as depicted in the physical sketch of the problem (Figure 1). The fluid temperatures at the channel walls are denoted as T_1 and T_2 respectively. The inner and outer walls of the channel subject to ψ and parameters a_1, b_1, d_1, d_2 , represented by H_1 and H_2 are described by the following equations:

$$H_2 = -d_2 + b_1 \cos\left(\frac{2\pi x}{\lambda} + \psi\right), \quad H_1 = d_1 + a_1 \cos\frac{2\pi x}{\lambda}, \quad (1)$$

$$a_1^2 + b_1^2 + 2a_1b_1 \cos\psi \leq (d_1 + d_2)^2, \quad 0 \leq \psi \leq \pi.$$

Resistance to fluid motion known as Darcy resistance with unsteady flow is modelled for a second-grade fluid. This approach follows the formulation presented by Maqbool et al. [19] who analysed the inertial flow of viscoelastic second-grade fluids in ciliated channels under magnetic fields and Darcy's resistance.

$$R = -\frac{\mu\psi}{k^*} \left(1 + \frac{\alpha_1}{\mu} \frac{\partial}{\partial t}\right) V. \quad (2)$$

where: ψ is the medium porosity, and K^* is the permeability term.

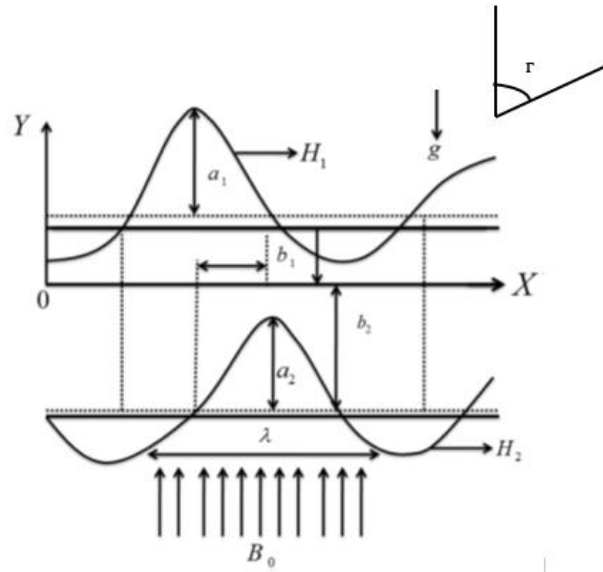


Figure 1. Physical sketch of the problem

Subject to the above mentioned assumptions, we present the mathematical systems of PDEs under the conservation of momentum, temperature, and concentration equations where the flow of the assumed second-grade fluid is induced by pressure gradient, Darcian law, solute and thermal convection, heat source and thermal radiation effect:

$$\frac{\partial \bar{u}}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \frac{\partial^2 \bar{u}}{\partial y^2} + g\beta_r(\bar{T} - T_2) - \frac{\sigma B_0^2 \sin^2 \Gamma \bar{u}}{\rho} + \beta_0 \frac{\partial^3 \bar{u}}{\partial y^2 \partial t} - \frac{\psi}{k^*} \left(\nu + \beta_0 \frac{\partial}{\partial t} \right) \bar{u} + g\beta_c(\bar{C} - C_2), \quad (3)$$

$$\frac{\partial \bar{T}}{\partial t} = \frac{k}{\rho C_p} \frac{\partial^2 \bar{T}}{\partial y^2} - \frac{1}{\rho C_p} \frac{\partial q}{\partial y} + \frac{Q_H}{\rho C_p} (\bar{T} - T_2), \quad (4)$$

$$\frac{\partial \bar{C}}{\partial t} = D \frac{\partial^2 \bar{C}}{\partial y^2} + Kc(\bar{C} - C_2), \quad (5)$$

with boundary conditions:

$$\bar{T} - \alpha^* \frac{\partial \bar{T}}{\partial y} = T_1, \quad \bar{u} - \gamma^* \frac{\partial \bar{u}}{\partial y} = 0, \quad \bar{C} - \beta^* \frac{\partial \bar{C}}{\partial y} = C_1, \quad \text{on} \quad \bar{y} = H_1, \quad (6)$$

$$\bar{T} + \alpha^* \frac{\partial \bar{T}}{\partial y} = T_2, \quad \bar{u} + \gamma^* \frac{\partial \bar{u}}{\partial y} = 0, \quad \bar{C} + \beta^* \frac{\partial \bar{C}}{\partial y} = C_2, \quad \text{on} \quad \bar{y} = H_2. \quad (7)$$

Following the recent study of Abbas et al. [18], the radiative heat flux for optically thin fluid is presented accordingly;

$$\frac{\partial q}{\partial y} = 4\alpha_2(T_2 - \bar{T}). \quad (8)$$

To simplify the effect of the controlling variables, the following dimensionless parameters are provided to scale the systems of equations into a solvable form;

$$u = \frac{\bar{u}}{U_0}, \quad y = \frac{\bar{y}}{d_1}, \quad x = \frac{x}{\lambda}, \quad t = \frac{\bar{t}U_0}{d_1}, \quad Da = \frac{k^*}{d_1^2}, \quad p = \frac{d_1^2 p}{\rho \nu \lambda U_0}, \quad d = \frac{d_2}{d_1}, \quad a = \frac{a_1}{d_1}, \quad b = \frac{b_1}{d_1},$$

$$h_1 = \frac{H_1}{d_1}, h_2 = \frac{H_2}{d_2}, Cr = \frac{K_c d_1^2}{D}, Sc = \frac{U_0 d_1}{D}, Re = \frac{U_0 d_1}{\nu}, R = \frac{4\alpha^2 d_1^2}{k}, M = \frac{\sigma B_0^2 d_1^2}{\rho \nu},$$

$$\Theta = \frac{\bar{T} - T_2}{T_1 - T_2}, \Phi = \frac{\bar{C} - C_2}{C_1 - C_2}, Gr = \frac{g \beta_f (T_1 - T_2) d_1^2}{\nu U_0}, Gc = \frac{g \beta_c (C_1 - C_2) d_1^2}{\nu U_0}, Pe = \frac{U_0 d_1 \rho C_p}{k}, Q = \frac{Q_H d_1^2}{k}.$$

In view of non-dimensional parameters defined above, equations (3)-(5) are presented as thus:

$$\left(Re + \frac{\beta}{Da} \right) \frac{\partial u}{\partial t} = -\frac{\partial P}{\partial x} + \frac{\partial^2 u}{\partial y^2} + Gr\Theta + Ge\Phi - \left(M^* + \frac{1}{Da} \right) u + \beta \frac{\partial^3 u}{\partial y^2 \partial t}, \quad (9)$$

$$Pe \frac{\partial \Theta}{\partial t} = \frac{\partial^2 \Theta}{\partial y^2} + (R + Q)\Theta, \quad (10)$$

$$Sc \frac{\partial \Phi}{\partial t} = \frac{\partial^2 \Phi}{\partial y^2} + Cr\Phi. \quad (11)$$

Subject to:

$$\begin{aligned} \Theta - \alpha \frac{\partial \Theta}{\partial y} = 1, \quad u - \gamma \frac{\partial u}{\partial y} = 0, \quad \Phi - \beta \frac{\partial \Phi}{\partial y} = 0, \quad \text{on } y = h_1, \\ \Theta + \alpha \frac{\partial \Theta}{\partial y} = 1, \quad u + \gamma \frac{\partial u}{\partial y} = 0, \quad \Phi + \beta \frac{\partial \Phi}{\partial y} = 0, \quad \text{on } y = h_2. \end{aligned}$$

3. Method of Solution

Solutions to the dimensionless equations (9)-(12) are sought in closed-form. A perturbation technique decoupled and linearised systems of equations into a simpler solvable form. The assumption of purely oscillatory flow is proposed. As such, the imposed pressure gradient along x -axis is presumed as thus:

$$-\frac{\partial P}{\partial x} = \lambda e^{i\omega t}$$

where ω represent the oscillation frequency and λ is a constant. Hence, we assume the momentum, concentration and energy profile solutions to take the form:

$$u(y, t) = u_0(y) e^{i\omega t}, \quad \Theta(y, t) = \Theta_0(y) e^{i\omega t}, \quad \Phi(y, t) = \Phi_0(y) e^{i\omega t}, \quad -\frac{\partial P}{\partial x} = \lambda e^{i\omega t}. \quad (13)$$

Substituting Equation (13) into Equations (9)-(12), results to

$$(1 + i\beta\omega) \frac{\partial^2 u_0}{\partial y^2} - n^2 u_0 = -\lambda - Gr\Theta_0 - Ge\Phi_0 \quad (14)$$

$$\frac{\partial^2 \Theta_0}{\partial y^2} + m^2 \Theta_0 = 0 \quad (15)$$

$$\frac{\partial^2 \Phi_0}{\partial y^2} + f^2 \Phi_0 = 0, \quad (16)$$

subject to:

$$u_0 - \gamma \frac{\partial u_0}{\partial y} = 0 \quad \Theta_0 - \alpha \frac{\partial \Theta_0}{\partial y} = 1 \quad \phi_0 - \beta \frac{\partial \phi_0}{\partial y} = 0 \quad \text{on } y = h_1, \quad (17)$$

$$u_0 + \gamma \frac{\partial u_0}{\partial y} = 0, \quad \Theta_0 + \alpha \frac{\partial \Theta_0}{\partial y} = 0, \quad \Phi_0 + \beta \frac{\partial \Phi_0}{\partial y} = 0 \quad \text{on } y = h_2. \quad (18)$$

Following the method of underdetermined coefficients, solutions to the respective equations (14)-(16) with the boundary conditions in (17) and (18) are as follows:

$$U(y, t) = \{C_5 e^{\frac{n^2 U}{\sqrt{(1+i\beta\omega)}y}} + C_6 e^{\frac{n^2 U}{\sqrt{(1+i\beta\omega)}y}} + \frac{\lambda}{n^2} + \frac{Gr[C_1 \cos(my) + C_2 \sin(my)]}{(1+i\beta\omega)(m^2 + n^2)} + \frac{Gc[C_3 \cos(fy) + C_4 \sin(fy)]}{(1+i\beta\omega)(m^2 + n^2)}\} e^{i\omega t}. \quad (19)$$

$$\Theta(y, t) = (C_1 \cos(my) + C_2 \sin(my)) e^{i\omega t} \quad (20)$$

$$\Phi(y, t) = (C_3 \cos(fy) + C_4 \sin(fy)) e^{i\omega t} \quad (21)$$

where:

$$f^2 = C_r + i \frac{\omega}{Sc}, \quad m^2 = Q + R - i\omega Pe, \quad n^2 = M + \frac{1}{K} + i\omega Re.$$

The expression for the Sherwood number, Nusselt number and coefficient of skin friction are as thus:

$$\tau = \mu \left(\frac{\partial u}{\partial y} \right)_{y=h_1, h_2} = \mu \left\{ \frac{-nC_5 e^{\frac{-ny}{\sqrt{1+i\beta\omega}}}}{\sqrt{1+i\beta\omega}} + \frac{nC_6 e^{\frac{-ny}{\sqrt{1+i\beta\omega}}}}{\sqrt{1+i\beta\omega}} + \frac{Gr[-mC_1 \cos(my) + mC_2 \sin(my)]}{(1+i\beta\omega)(m^2 + n^2)} + \frac{Gc[-fC_3 \cos(fy) + fC_4 \sin(fy)]}{(1+i\beta\omega)(m^2 + n^2)} \right\} e^{i\omega t}. \quad (22)$$

$$Nu = \left(\frac{-\partial \Theta}{\partial y} \right)_{y=h_1, h_2} = -[C_2 m \sin(my) - C_1 m \cos(my)] e^{i\omega t} \quad (23)$$

$$Sh = \left(\frac{-\partial \Phi}{\partial y} \right)_{y=h_1, h_2} = -[C_4 f \sin(fy) - C_3 f \cos(fy)] e^{i\omega t} \quad (24)$$

4. Results and Discussion

This section provides a comprehensive overview of the obtained result from the closed form solution. Figure 2-14 are parabolic in nature and satisfied the prescribed boundary conditions, demonstrates effects of varied parameters over range of flow distributions along the channel. Chosen kinematic viscosity, acceleration due to gravity, thermal expansion coefficient, hot temperature, cold temperature, characteristic length, characteristic velocity, porosity factor, electrical conductivity, magnetic field strength, density, thermal conductivity, and absorption coefficient as the default parameters for the plot.

The physical responses of the dimensionless Hartmann number, thermal Grashof number, and solutal Grashof number are illustrated in Figures 2-14. The key contributions of magnetohydrodynamics (MHD) to electrically conducting fluids (such as plasmas) under the influence of a magnetic field are highlighted. The impact of the Hartmann number (M) on velocity, as shown in Figure 2, reveals that the electromagnetic field generates a retarding force, which slows down fluid motion due to induced Lorentz forces. Essentially, the MHD effect suppresses fluid velocity, thereby reducing momentum and slowing the flow. Thermal buoyancy, on the other hand, results from higher wall temperatures compared to the ambient fluid, causing fluid expansion, density reduction, and the generation of an upward buoyancy force. Similarly, solutal buoyancy arises from a higher solute concentration at the surface, creating a density gradient (e.g., lighter, solute-rich fluid rises), which also induces buoyancy forces. The effects of thermal and solutal buoyancy, as illustrated in Figures

3 and 4, respectively, enhance the fluid motion through buoyancy-driven forces, leading to increased momentum and stronger convective and mass-induced flow.

The influence of the Peclet and Reynolds numbers on the channel flow is analysed in Figures 5 and 6. These dimensionless parameters significantly affect the momentum field positively. The Reynolds number quantifies the ratio of inertial (momentum) forces to viscous forces, while the Peclet number characterizes the ratio of convective to diffusive transport of heat, as defined in Equation (10). Physically, large Peclet numbers indicate efficient heat and mass transport by the flow, minimizing conduction or diffusion effects. Therefore, accurate estimation of these dimensionless parameters (Re and Pe) is crucial in the design of thermal systems, reactors, and solar collectors.

Figure 7 shows that the axial velocity rises with increasing Darcy number (Da), since greater Da signifies a more permeable medium and thus reduced viscous resistance. A rise in Da create more porous matrix, thus enhanced the momentum field. In Figure 8, velocity likewise grows as the thermal radiation parameter R increases, because stronger radiative heating weakens interlayer cohesion and lowers effective viscosity. As such, a rise in R decoupled the intermolecular force thereby up surged the momentum field. The effect of inclination angle (Γ) on the velocity profile as displayed in Figure 9. The parameter plays a key role in shaping the velocity of the fluid. As decrease from $\frac{\Gamma}{5}$ to $\frac{\Gamma}{2}$ the peak velocity in the middle of the flow region gradually reduces. This happens because the modified magnetic parameter, becomes smaller, meaning the opposing force from the magnetic field gets stronger and slows down the fluid. Physically, when the inclination angle is larger, the velocity profile has a sharp peak, showing that the fluid moves more vigorously. However, as the angle gets smaller, the profile flattens, indicating a slower and more evenly spread-out flow. This suggests that at lower inclination angles, the magnetic force is more effective at resisting the motion of the fluid.

Figures 10 and 11 then plot temperature profiles under varying heat-source parameter Q and Peclet number Pe. An elevated Q thickens the thermal boundary layer and uniformly raises temperature by internal heat generation, while a larger Pe means advection dominates diffusion, ushering heat downstream, steepening the near-wall gradient and lowering the entrance-region temperature. When both Q and Pe are high, the result is a sharp thermal spike at the wall that convicts rapidly downstream, producing a pronounced thermal plume. In Figure 12, increasing the Peclet number (Pe) causes a marked attenuation of the energy field across the channel. Physically, a higher Pe indicates that convective transport of thermal energy by the bulk flow vastly outpaces diffusive transport by conduction. As Pe grows, heat introduced at the wall is swept downstream more rapidly before it can diffuse laterally into the core of the flow. This “short-circuiting” of thermal diffusion leads to a thinner thermal boundary layer and a lower temperature within the channel’s interior hence the observed reduction of the energy field. In the extreme, very large Pe yields almost plug-like temperature profiles, with most of the temperature change confined to a narrow region adjacent to the heated surface.

In Figure 13, the chemical reaction parameter (Cr) acts to deplete the solute concentration throughout the flow domain. When a first-order reaction consumes the transported species, the local concentration decays not only by diffusion and convection but also by reaction. A larger accelerates this reactive sink term in the species conservation equation, so as solute is carried along by the flow it is simultaneously consumed. The net result is a substantially reduced concentration field everywhere, with the most pronounced drop occurring near the wall where the reaction diffusion interplay is strongest. Also in Figure 14, raising the Schmidt number (Sc) further suppresses the concentration field at both channel walls. A higher Sc means molecular diffusivity is small relative to momentum diffusivity, so solute spreads more slowly by diffusion. As a result, concentration gradients at the boundaries steepen, and the core region receives less replenishment of solute from the walls. In combination with convective outflow and chemical reaction, this diminished cross-diffusion causes the concentration to fall off sharply near both walls and remain low throughout the channel. Thus, large Sc intensifies mass-boundary-layer thinning and reinforces the overall depletion of the species.

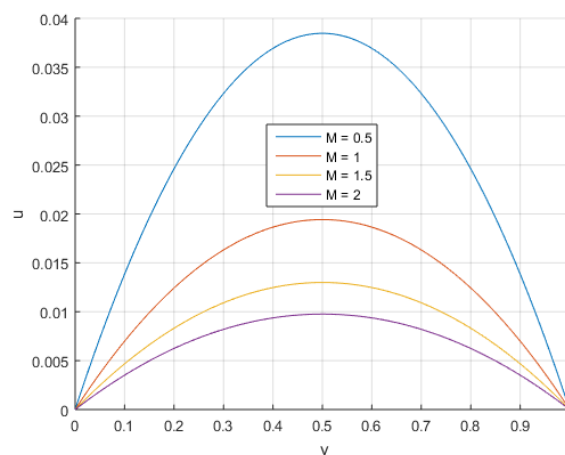


Figure 2. Momentum field with Hartmann number variations

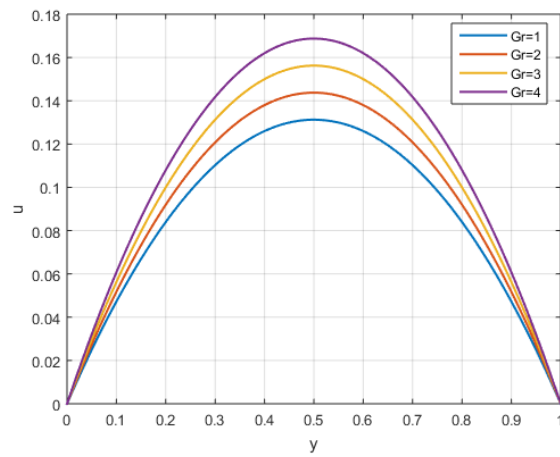


Figure 3. Momentum field with thermal Grashof number variations

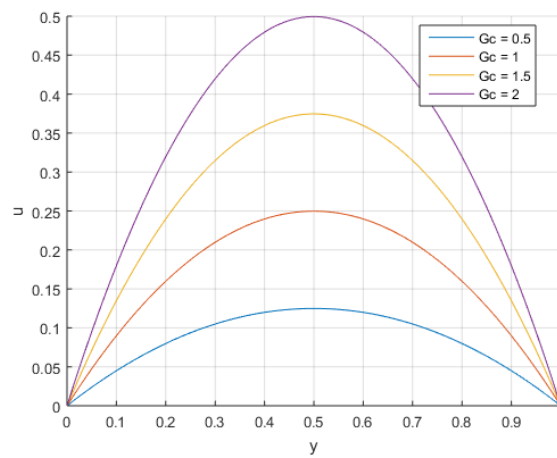


Figure 4. Momentum field with Solutal Grashof number variations

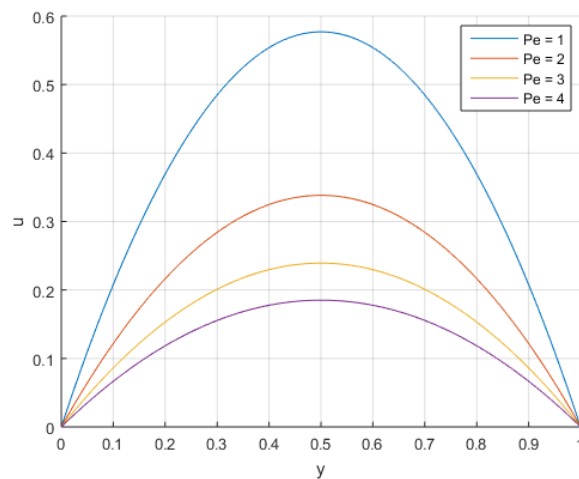


Figure 5. Momentum field with Peclet number variations

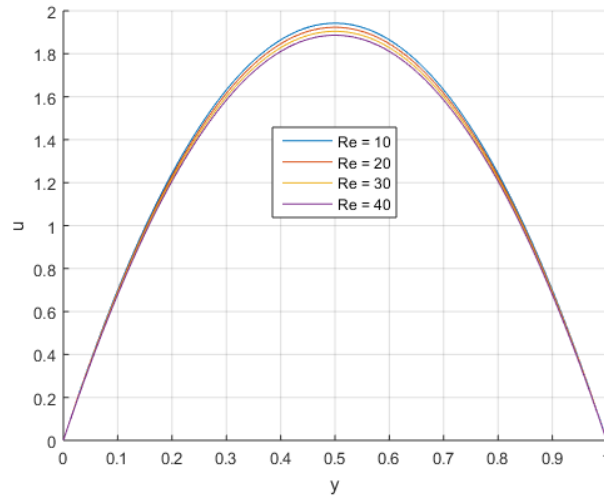


Figure 6. Momentum field with Reynolds number variations

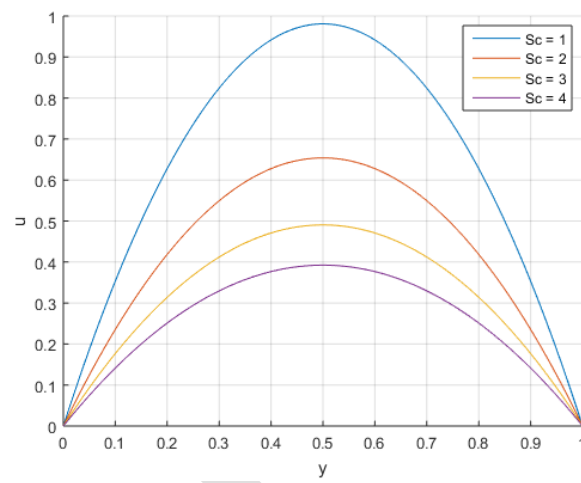


Figure 7. Momentum field with Schmidt number variations

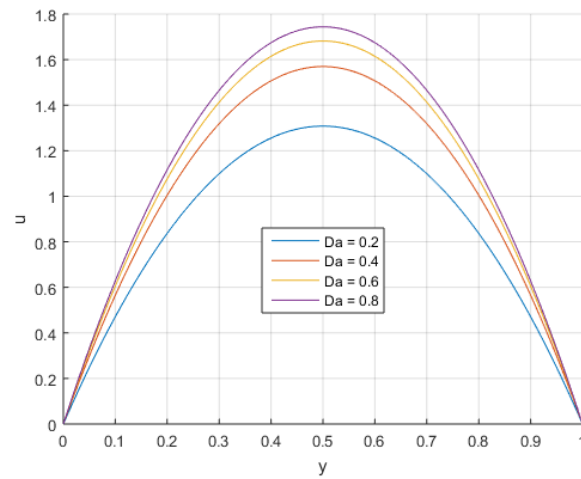


Figure 8. Momentum field with Darcy number variations

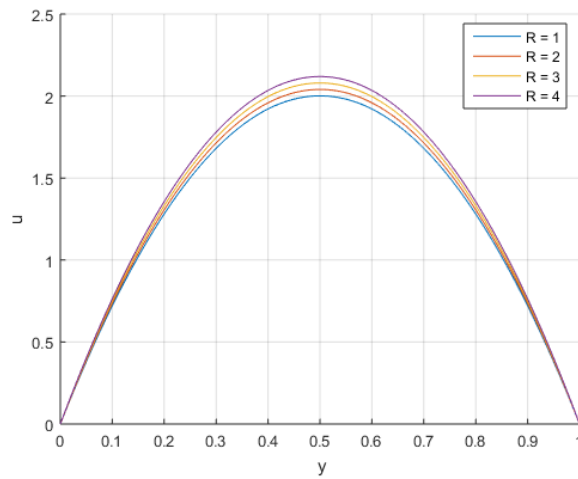


Figure 9. Momentum field with radiation parameter variations

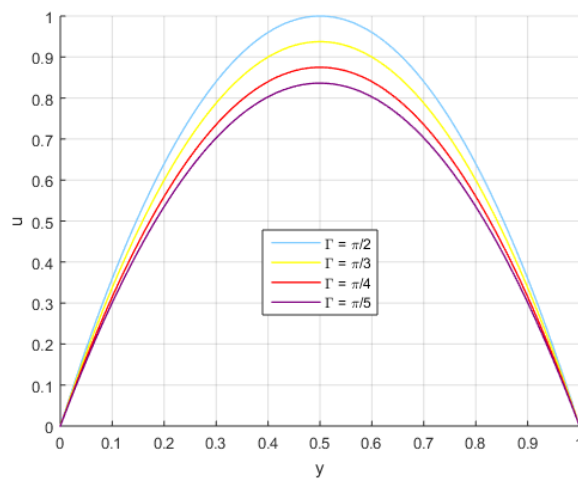


Figure 10. Momentum field with inclination angle variations

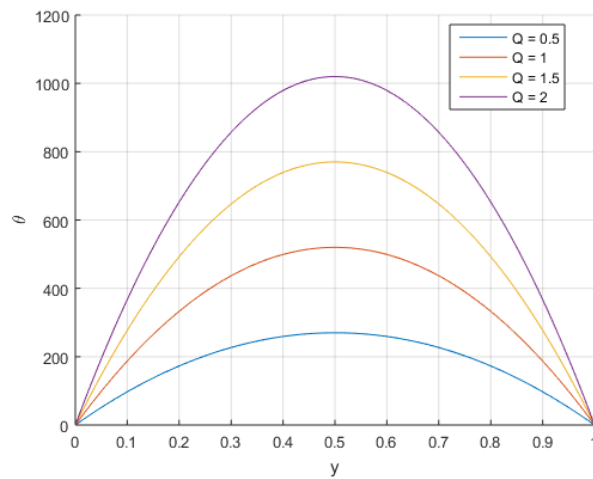


Figure 11. Energy field with heat source variations

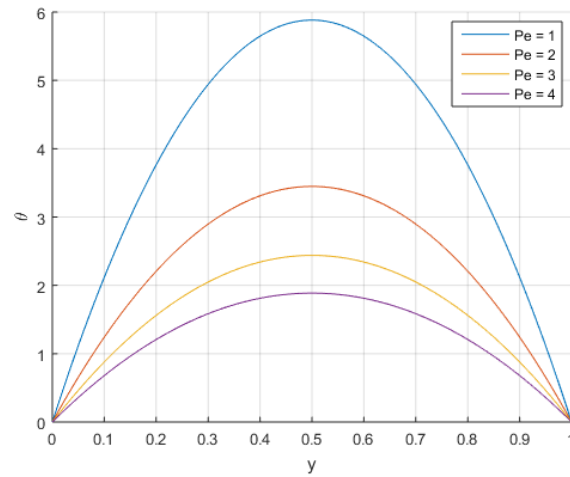


Figure 12. Energy field with Peclet number variations

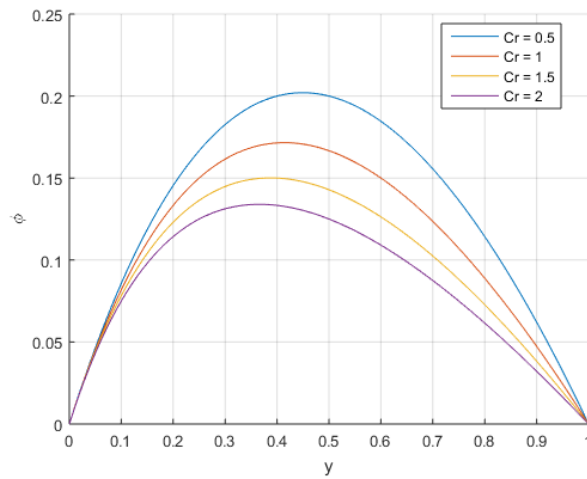


Figure 13. Energy field with chemical reaction parameter variations

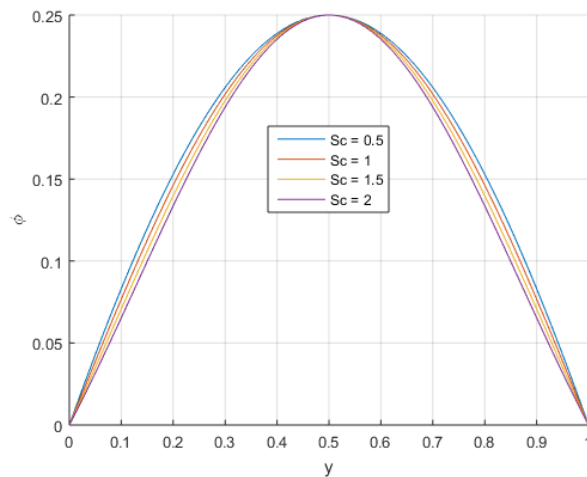


Figure 14. Energy field with Schmidt number variations

Table 1 present the results of the present study to that of Venkateswarlu et al. [20] and Abbas et al. [18] when $Gc=Sc=Cr=0$, and $d = 0.1$, $t = 0.1$, $Pe = 0.71$, $x = 0.2$, $Q = 0.5$, $R = 2$, $Re = 2$, $Q = 0.5$, $Gr = 10.0$, $M = 2$, $K = 1$, $a = 0.2$, $b = 0.1$. A good agreement of the present study is reached comparing with both the heat transfer coefficient and the skin friction

Table 1. Results of heat transfer and skin friction coefficient with varying values of M and Q

M	τ			Q	Nu		
	Venkateswarlu et al. [20]	Abbas et al. [18]	Present		Venkateswarlu et al. [20]	Abbas et al. [18]	Present
1.0	3.2578	3.257683	3.257683	0.1	1.4152	1.415587	1.415587
2.0	3.2847	3.284695	3.284695	0.3	2.0280	2.028342	2.028342
3.0	3.3297	3.322859	3.322859	0.5	3.1336	3.133548	3.133548
3.0	3.3928	3.392673	3.392673	0.7	5.8087	5.808621	5.808621

5. Conclusions

The computational analysis herein discussed the heat and mass dynamics in unsteady oscillatory flow of a second-grade fluid through an irregular channel. The model analysis assumed a slip flow, inclined magnetic field, heat source, thermal radiation and first order chemical reaction effect. Assumption of the oscillatory flow, Darcy law, chemical reaction and inclined magnetic influence are considered paramount due to the physical phenomenon. From the mathematical models, we identified the response of the controlling parameters on careful implementation of the right dimensionless variables while the results of the analytical response compare favourably with the existing studies. The plots of the respective parameters on fluid velocity, temperature, and concentration are presented in the respective figures. The key findings are as follows:

- Slip conditions reduce friction at the walls, changing how the fluid flows and affecting the extent of heat and mass transported.
- Irregular channel shapes disrupt the flow, creating uneven velocity and transfer patterns.
- Chemical reaction parameter (Cr) acts to deplete the solute concentration throughout the flow domain.
- The inclined magnetic field parameter plays a key role in shaping the velocity of the fluid.
- Raising the Schmidt number (Sc) further suppresses the concentration field at both channel walls.

These findings show that by carefully adjusting factors like magnetic field strength, wall slip, and flow oscillations, we can better control heat and mass transfer in practical situations such as designing cooling systems, improving chemical processes, or even modelling blood flow in arteries.

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Declaration of Competing Interest

The authors declare no conflict of interest.

CRediT Authorship Contribution Statement

Blessing Ruth Oladeji (Conceptualization; Formal analysis; Visualization)
 Moses Sunday Dada (Methodology; Data curation; Writing - original draft; Resources; Supervision)
 Timothy Lanre Oyekunle (Code validation; Correction - original draft; Resources).
 Mojeed Taiwo Akolade (Code validation; Correction - original draft; Resources).

Availability of the Data and Materials

The data used to support the findings of this study are included within the article.

Ethical Declarations

No artificial intelligence tools were used in the preparation of this manuscript. All content was developed manually by the authors. This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations

The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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