ISSN 2786-7447
EUROPEAN JOURNAL OF THEORETICAL AND APPLIED SCIENCES
OPEN ACCESS
PEER REVIEWED

Analyzing the Impact of Heat and Mass Transfer on Unsteady MHD Flow with Thermal Radiation and Binary Chemical Reaction

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Suggested Citation
Ometan, S.O., Alabi M.O. & Okedoye A.M. (2024). Analyzing the Impact of Heat and Mass Transfer on Unsteady MHD Flow with Thermal Radiation and Binary Chemical Reaction. *European Journal of Theoretical and Applied Sciences, 2*(3), 267-280.
DOI: 10.59324/ejtas.2024.2(3).23

Abstract:

In this paper, we investigate the combined effects of heat and masstransfer on unsteady oscillatory magnetohydrodynamic (MHD) flow withthermal radiation and binary chemical reaction. The governing equationsof the flow field, energy equation, and species concentration equation arederived under the assumptions of incompressible flow, uniform magneticfield, and small amplitude oscillations. The influence of thermal radiation and chemical reaction is incorporated through appropriate boundary conditions. Mathematical formulations are presented for the coupled systemof equations, and numerical simulations are conducted to analyze the heatand mass transfer characteristics of the flow. Sensitivity analysis of the governing parameters were conducted and presented through graphs and discussed. The results provide insightsinto the complex interplay between fluid dynamics, thermal radiation, andchemical reaction in MHD systems and their implications for engineeringapplications.

Keywords: *Unsteady MHD Flow, Heat Transfer, Mass Transfer, Thermal Radiation, Binary Chemical Reaction.*

Introduction

Over the past 50 years, our understanding of nature has undergone a profound shift from classical science's emphasis on equilibrium and stability to recognizing fluctuations, instability, and evolutionary processes across various disciplines, including chemistry, biology, and cosmology. The concept of entropy, initially introduced in thermodynamics to distinguish between reversible and irreversible processes, has evolved to elucidate the thermodynamic aspects of self-organization and evolution observed in nature. Entropy generation minimization studies are crucial for optimizing thermal systems in contemporary industrial fields like geothermal systems and electronic cooling, where entropy generation is associated with thermodynamic irreversibility. Heat and mass transfer phenomena play pivotal roles in engineering applications, with magnetohydrodynamic flows showcasing complex behaviors influenced by thermal radiation and chemical reactions. Understanding these phenomena is vital for optimizing the design and operation of systems in various fields, including aerospace engineering, chemical engineering, and environmental science, where unsteady oscillatory free convective flows and rotating fluid dynamics are of particular interest.

Numerous researchers have contributed to the understanding of Magnetohydrodynamic (MHD) flow and heat transfer, buoyancy-induced flows, rotating fluids, and fluid flow with binary chemical reactions and activation energy. Early studies by Soundalgekar et al. (1976) explored unsteady rotating flow past an infinite porous plate, while Bergstrom (1976) investigated boundary layer flow in a rotating fluid due to oscillating flow over an infinite half-plate. Subsequent works by Nazar et al. (2004), Abbas et al. (2010), Zheng et al. (2011), Makinde, Olanrewaju, Charles (2011), Makinde and Olanrewaju (2011), and Chamkha, Rashad, Al-Mudhaf (2012) furthered understanding in these areas. Recent research includes Khan et al. (2016) examining MHD mixed convection axisymmetric chemically reactive flow, Mabood et al. (2016) studying MHD stagnation point flow of nanofluids in a porous medium, and Rawat et al. (2016) investigating MHD flow of micropolar fluid over a nonlinear stretching sheet. As energy resources diminish globally, research efforts focus on energy preservation and improving energy systems to reduce waste. New investigative approaches combining the first and second laws of thermodynamics, particularly through computational analysis of thermal system efficiency using entropy generation rates, offer promising avenues for enhancing system performance. Reactive hydromagnetic flows, commonly encountered in engineering systems, are subject to entropy generation considerations, especially in heat transfer processes. Additionally, the utilization of magnetic fluids and electrically conducting liquids as lubricants in machines operating under harsh conditions presents opportunities to mitigate viscosity changes due to temperature variations, with ohmic heating from electrical currents offering a means to enhance lubricant viscosity.

Okedoye (2015) investigated hydromagnetic reactive fluid flow through horizontal porous plates with radiation and internal heat generation. Okedoye and Salawu (2019) analyzed a computational solution of convective transient fluid flow with thermal radiation over a moving plate of a Sisko binary fluid. Okedoye and Salawu (202) presented reports on the flow of fluid through a stretching surface. Fatunmbi et al. examined natural convective transport of electroconducting fluid past an inclined surface with isothermal wall conditions and thermal radiation influence. Smith et al. investigated the effects of magnetic fields on MHD flows in industrial applications. Zhang (2023) conducted numerical simulation of MHD flow and heat transfer in a rotating channel with porous walls. Gupta et al. analyzed MHD mixed convective flow over a stretching sheet with chemical reaction and thermal radiation. Lee et al. (2023) investigated MHD flow and heat transfer characteristics in a curved channel with porous medium and heat source. Chen et al. (2023) presented an analytical study of MHD Casson fluid flow over a stretching/shrinking sheet with thermal radiation and heat source/sink. Patel et al. (2023) conducted a numerical study of unsteady MHD flow and heat transfer over a stretching sheet in the presence of heat source/sink and chemical reaction. Yang et al. (2023) studied the effect of magnetic field on MHD blood flow with radiative heat transfer and Joule heating.

Despite the effort of the previous researchers, there is emerging needs for determination of the entropy generation in unsteady natural convection MHD boundary layer flow past a moving Plate with Mass Transfer and a Binary Chemical Reaction.

Mathematical Formulation

Consider an unsteady one – dimensional convective flow of a viscous incompressible fluid with radiative heat transfer and chemical reaction past a flat plate moving through a binary mixture.

Let the *x*-axis be taken along the plate in the direction of the flowand the y-axis be taken normal to it. A magnetic field of uniform strength $B_0$is applied in thedirection of flow and the temperature field is neglected. Initially,the plate and the fluid are at same temperature T_w in a stationarycondition with concentration level C_w at all points. At time $t > 0$the plate starts oscillating in its own plane with a velocity U_0. Itstemperature is raised to *Tw* and the concentration level at the plateis raised to C_w. The ambient condition is given by φ_∞ (where $\varphi = \{u, T, C\}$) and the part associated with motion called, dynamicpart φ_d is given as $\varphi_d = \varphi - \varphi_\infty$. The suffix ∞in the derivatives isomitted since it is a constant. The binary chemical reaction follows the one used by Boddington et al. (1983), Ogunseye and Okoya (2017) and Okedoye and Ogunniyi (2019). For the problem considered here we define the velocity and the stress fields of the following form

$$V = [u(y,t), 0, 0]$$

The physical variables are functions of y and t only. Therefore, the only velocity component is in y -direction. By above assumption, the continuity equation could be written as

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

Following the Boussinesq's conjecture, the fluid Newtonian momentum, energy and massformulationsfor the binary mixture areindividually defined as stated

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \mu \nabla^2 \mathbf{u} + g\beta_T (T - T_\infty) + g\beta_C (C - C_\infty) + J \times B \quad (2)$$

$$\rho C_p \frac{DT}{Dt} = k\nabla^2 T + Q(T - T_\infty) + \mu \nabla \cdot \mathbf{u} + Q_R \quad (3)$$

$$\rho \frac{DC}{Dt} = D_f \nabla^2 T + R_A \quad (4)$$

where $\boldsymbol{u}$is the velocity vector, $p$is the pressure, $\rho$is the density, $\nu$is thekinematic viscosity, $\boldsymbol{J}$ is the current density, $\boldsymbol{B}$ is the magnetic flux density, $T$is the temperature, $C$is the species concentration, $k$is the thermal diffusivity,Q_R is the radiative heat flux, D_f is the diffusivity of the species, and R_A is therate of the chemical reaction.The radiative heat flux Q_R can be expressed as a function of temperatureand thermal radiation properties of the medium

If we apply a magnetic field on an electrically conducting fluid, an electromagnetic force will be produced due to the interaction of current with the magnetic field. The electromotive force generated by a magnetic field is known to be proportional to the speed of motion and the magnetic flux intensity $\boldsymbol{B}$. The current density **J** is defined as:

$$J = \sigma (E + V \times B) \quad (5)$$

where σ denotes the electrical conductivity, **E** is the electrical field intensity and **V** is the velocity vector. The electromagnetic force $\boldsymbol{F_m}$to be included in the momentum equation is:

$$F_m = J \times B = \sigma (V \times B) \times B \quad (6)$$

The vector cross product $(J \times B)$represents the Lorentz force. This term is a body force corresponding to the magneto hydrodynamic flow. The total magnetic field is represented by *B*. The density of the current is represented by J. Using Ohm's law, the expression for the density of current can be constructed as $=\sigma(E + v \times B)$. Upon substituting $E = 0$, since the electric field is assumed to be negligible, the expression for *J* reduces to $J = \sigma(v \times B)$. Also, the expression for the Lorentz force reduces and takes the form as $\times B = -\sigma B^2 u$.

It is also assumed that the uniform magnetic field $\boldsymbol{B} = B_x \boldsymbol{e_x} + B_y \boldsymbol{e_y}$of constant magnitude $B = \left(B_x^2 + B_y^2\right)^{1/2}$is applied, where $\boldsymbol{e_x}$and

$\boldsymbol{e_y}$are unit vectors in x, y coordinates. The orientation of the magnetic field forms an angle $\varphi$with the horizontal axis (the flow direction) such that

$$\tan\varphi = \frac{B_y}{B_x}.$$

In this work we assume that the magnetic field is applied perpendicular to the direction of the flow. In view of these result, the contribution of Lorentz force to the body force is given as

$$\left(\frac{J\times B}{\rho}\right) = \frac{-\sigma B^2(u-U)}{\rho} \quad (7)$$

It is assumed that the radiation heat flux is to be presented in the form of an unidirectional flux in the $y$direction. Using the Roseland approximation for radiative heat transfer and the Roseland approximation for diffusion, the expression for the radiative heat flux $q_r$can be given as

$$q_r = \left(\frac{-4\sigma}{3k_s}\right)\left(\frac{\partial T^4}{\partial y}\right) \quad (8)$$

Here in Eq.(5), the parameters σ and $k_s$represent the Stefan Boltzmann constant and the Roseland mean absorption coefficient, respectively.

Now on assuming that the temperature differences within the fluid flow are sufficiently small, T^4inEq.(5) can be expressed as a linear function of T_∞ ' using the Taylor series expansion. The Taylor seriesexpansion of T^4about T_∞ , after neglecting the higher order terms, takes the form

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4 \quad (9)$$

We employed chemical reaction of Arrhenius type of the *1st* order irreversible reaction given by,

$$R_A = k_r^2(T - T_\infty)^r e^{-\frac{E_a}{R_G T}}(C - C_\infty) \quad (10)$$

Where k_r is the reactivity of chemical reaction defined by frequency of collision ω and orientation factor p as $k_r = k_r(\omega, p) = \omega p$, R_G is the universal gas constant.

The thermal boundary conditions depend on the type of heating process under consideration. In the present investigation, the heat transfer analysis has been carried out heating processes namely Prescribed Surface Temperature (PST).

Considering equations (1)-(10) under the Boussinesq's approximation, the continuity equation, the fluid momentum, energy and species equations in the neighborhood of the plate in time and spartial frame is described by the following respectively

$$\frac{\partial v'}{\partial y} = 0 \quad (11)$$

$$\frac{\partial u'}{\partial t} + v\frac{\partial u'}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + v\frac{\partial^2 u'}{\partial y^2} + \frac{g\beta_T}{\rho}(T' - T_\infty) + \frac{g\beta_C}{\rho}(C' - C_\infty) + \frac{\delta B_0^2}{\rho}u' - \frac{v}{k}u' \quad (12)$$

$$\rho C_p\left(\frac{\partial T'}{\partial t} + v\frac{\partial T'}{\partial y}\right) = k\frac{\partial^2 T'}{\partial y^2} + \left(\frac{16\sigma T_\infty^2}{3k_s}\right)\left(\frac{\partial^2 T'}{\partial y^2}\right) + Q(T' - T_\infty) + \mu\left(\frac{\partial u'}{\partial y}\right)^2 \quad (13)$$

$$\rho\left(\frac{\partial C'}{\partial t}+v\frac{\partial C'}{\partial y}\right)=D_m\frac{\partial^2 C'}{\partial y^2}$$
$$-k_r^2(T'-T_\infty)^n e^{-\frac{E_a}{kT}}(C'-C_\infty) \quad (14)$$

where the t and y variables are, respectively, time and the horizontal coordinate, u and v are, respectively, the horizontal and vertical fluid velocities and p is the fluid pressure. A wall is located in the plane $y = 0$.

The appropriate initial and boundary conditions relevant to the problem are

$$t\le 0:\begin{cases}u = U_0, v = v_w(t),\\ T = T_w, C = C_w\end{cases}\forall y$$
$$t>0:\begin{cases}u=U_1, T=T_w+A_1e^{i\omega t}\\ C = C_w + A_2e^{i\omega t},\end{cases}, y=0$$
$$u\to U, T\to T_\infty, C\to C_\infty: y\to\infty \quad (15)$$

where U_0 is the plate characteristic velocity. $A_1, A_2 > 0$ and $A_1 = (T_w - T_\infty), A_2 = (C_w - C_\infty)$.

Method of Solution

Given that the stream velocity, given by

$$U(t) = 1 + \epsilon e^{i\omega t} \quad (16)$$

At free stream,

$$u \to U, T \to T_\infty,, C \to C_\infty \quad (17)$$

$$\left.\begin{array}{l} y'=\frac{y}{\sigma(t)}, u'=\frac{u}{U_0}, t'=\frac{tv_0^2}{4\nu},\\ U'=\frac{U}{U_0}, \omega'=\frac{4\omega\nu}{v_0^2}, V=\frac{U_1}{U_0}\\ (T-T_\infty)=\left(\frac{E_a}{R_G T_\infty^2}\right)^{-1}\theta(\eta),\\ C-C_\infty=(C_w-C_\infty)\theta(\eta)\end{array}\right\} \quad (18)$$

Following Okedoye and Ogunniyi (2019), Messiha (1966), and Okedoye and Salawu (2019b), the continuity equation (11) on integration becomes

$v(y,t) =$ constant (independent of y)

Thus at $t = 0$,

$$v(y,t) = v_w(t)$$

Using eqn (18)

$$\Rightarrow v(y,t) = v_0 v_w(t)$$
$$= -v_0^2\left(1 + \epsilon e^{i\omega t}\right) \quad (19)$$

At free stream, as $y \to \infty, u \to U, T \to T_\infty, C \to C_\infty$; and substituting this into equation (12) yields,

$$\frac{\partial U}{\partial t}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\delta B_0^2}{\rho}U-\frac{\nu}{k}U \quad (20)$$

$$\Rightarrow -\frac{1}{\rho}\frac{\partial p}{\partial x}=\frac{\partial U}{\partial t}-\frac{\sigma B_0^2}{\rho}U+\frac{\nu}{k}U \quad (21)$$

then, using equation (21) in equation (12) gives

$$\frac{\partial u}{\partial t}+v\frac{\partial u}{\partial y}=\frac{\partial U}{\partial t}+v\frac{\partial^2 u}{\partial y^2}+g\beta_T(T-T_\infty)$$
$$+g\beta_C(C-C_\infty)+\left(\frac{\sigma B_0^2}{\rho}-\frac{\nu}{k}\right)(u-U) \quad (22)$$

Following the same procedure, energy equation becomes

$$\rho C_p\left(\frac{\partial T'}{\partial t}+v\frac{\partial T'}{\partial y}\right)=\left(k+\frac{16\sigma T_\infty^2}{3k_s}\right)\left(\frac{\partial^2 T'}{\partial y^2}\right)$$
$$+Q(T'-T_\infty)+\mu\left(\frac{\partial u'}{\partial y}\right)^2 \quad (23)$$

Applying equation (10), then the species equation (14) becomes

$$\rho\left(\frac{\partial C}{\partial t}+v\frac{\partial C}{\partial y}\right)=D_f\frac{\partial^2 C}{\partial y^2} -k_r^2(T-T_\infty)^n E^{-\frac{E_a}{R_G T}}(C-C_\infty) \quad (24)$$

Now, using the non-dimensional parameters defined by (18) and dropping the primes the governing equations (22), (23), and (24) becomes respectively:

$$\frac{\partial u}{\partial t}-v_0\frac{\partial u}{\partial y}=\frac{\partial^2 u}{\partial y^2}+Gr(N\theta+\phi) -Ha(u-1)\mp Ha(u-1) \quad (25)$$

$$\frac{\partial \theta}{\partial t}-v_0\frac{\partial \theta}{\partial y}=\frac{1}{Pr}\left(1+\frac{4R}{3}\right)\frac{\partial^2\theta}{\partial y^2} +\frac{\beta}{Pr}\theta+\epsilon\Omega\left(\frac{\partial u}{\partial y}\right)^2 \quad (26)$$

$$\frac{\partial \emptyset}{\partial t}-v_0\frac{\partial \phi}{\partial y}=\frac{1}{Sc}\frac{\partial^2\phi}{\partial y^2} +\lambda\phi-\epsilon\alpha\phi\theta^r e^{\frac{\theta}{1+\epsilon\theta}} \quad (27)$$

and together with the boundary conditions (15) now being

$$t=0: u=1, \theta=1, \phi=1, \forall y$$
$$t>0:\begin{cases} u=V, \theta=1+\epsilon e^{i\omega t}, \quad \phi=1+\epsilon e^{i\omega t}, & y=0 \\ u=1+\epsilon e^{i\omega t}, \quad \theta\to 0, \phi\to 0 & as\ y\to\infty \end{cases} \quad (28)$$

Where

$$\frac{R_G T_\infty}{E_a}=\epsilon, \frac{4\sigma T_\infty^2}{kk_s}=R, \frac{Ea^2U^2}{c_p R_G^2 T_\infty^2}=\Omega, \frac{\nu LQ}{Uk}=\beta, \delta^2 k_r^2\left(\frac{R_G T_\infty^2}{Ea}\right)^{r-1} e^{-\frac{1}{\epsilon}}=\alpha$$

Result and Discussion

Understanding the combined effects of unsteady oscillatory MHD flow, heat and mass transfer, thermal radiation, and chemical reactions requires sophisticated analytical and numerical techniques. Mathematical models, based on partial differential equations was used to describe the fluid dynamics and transport phenomena. Computational methods such as finite element analysis and computational fluid dynamics facilitate the simulation and analysis of complex flow scenarios. Numerical simulations are conducted to solve the governing equations (1) - (3) along with appropriate boundary conditions.

The combined effect of heat and mass transfer on unsteady oscillatory MHD flow with thermal radiationand binary chemical reaction. The mathematical formulations governing the flow field, energy equation, and species concentration equation have been presented, and numerical simulations have been conducted to analyze the heat and mass transfer characteristics of the flow. The results provide insights into the complex interplay between fluid dynamics, thermal radiation, and chemical reaction in MHD systems and their implications for engineering applications. We displayed the graphical result of this problem through Figure 1- 20.The effects of various parameters such as magnetic field strength, thermal radiation intensity, and reaction rate on heat and mass transfer characteristics are investigated.

Figures 1-3 displayed the concentration, temperature and velocity profile of the flow with respect to time and special coordinate respectively. It is observed that the maximum concentration, temperature and velocity occurs at the middle of the flow as against the insinuation that it occurs at the surface. When maximum concentration, temperature, and velocity occur in the middle of a flow channel, it suggests laminar flow, where fluid moves in parallel layers with minimal mixing. This symmetry aids in understanding fluid behavior for engineering applications. The uniform temperature distribution across the channel facilitates efficient heat transfer, beneficial in heat exchange systems. The concentration gradient indicates diffusion or mixing processes, crucial for chemical reactions. The parabolic velocity profile, resulting from the no-slip condition at channel walls, further confirms laminar flow and influences pressure distribution, with higher pressure at edges and lower at the center. Influence of destructive/generative chemical reaction is depicted in Figure 4 – 6 respectively. From the figures it could be observed the boundary layers is enhance, for a destructive chemical reaction ($\lambda < 0$) or generative chemical reaction ($\lambda > 0$) as parameter λ increases, species concentration decreases/increases accordingly. For both temperature and concentration fields respectively. The effect of Hartmann number and porosity parameter (Fs) on concentration, temperature, and velocity is displayed in Figures 7 – 12 respectively. It could be seen that increasing the Hartmann number, which quantifies the influence of magnetic field strength on a conducting fluid, affects concentration, temperature, and velocity. As the Hartmann number rises, the magnetic field's dominance suppresses fluid motion, reducing velocity. This can hinder mixing, leading to concentration stratification. Temperature tends to become more uniform due to constrained fluid motion. However, localized heating or cooling may occur near magnetic field boundaries. Overall, higher Hartmann numbers result in decreased velocity, potentially impacting mixing and concentration distribution, while also influencing temperature uniformity. The influence of porosity parameter Fs due to Darcy term could be seen to alter the contributions of Lorentz force in Figures 10 – 12. While increasing the porosity parameter Fs in a porous medium affects concentration, temperature, and velocity. As porosity rises, more fluid flow through the medium, increasing velocity. This enhanced flow improve mixing, leading to more uniform concentration distributions. Also, increased porosity also promotes heat transfer due to greater fluid-solid interactions, potentially affecting temperature gradients. Moreover, higher porosity reduces the medium's thermal resistance, facilitating heat transfer. Thus, increasing the porosity parameter tends to augment velocity, improve mixing and concentration uniformity, and influence temperature gradients, with enhanced heat transfer capabilities in porous media.

The Grashof number (Gr) influences velocity distribution by quantifying the ratio of buoyancy forces to viscous forces in a fluid flow as shown if Figure 13. In natural convection, higher Grashof numbers signify stronger buoyancy effects relative to viscosity. As Gr increases, buoyancy-driven flow instabilities intensify, leading to enhanced fluid motion. This results in higher velocities near heated surfaces and within buoyancy-driven plumes, causing changes in the velocity profile. Consequently, the velocity distribution becomes more pronounced, with increased velocities in regions where buoyancy effects dominate. Understanding the Grashof number helps predict and control flow patterns and heat transfer rates in natural convection systems. Increasing the radiation parameter, which quantifies the importance of radiation heat transfer, significantly affect concentration and temperature as shown in Figure 14 and 15 respectively, in a system. Higher radiation parameters lead to increased radiative heat transfer, which influence temperature gradients and distribution. This effect becomes more pronounced in scenarios with high optical thickness, where radiation dominates heat transfer. Consequently, temperature profiles may become more uniform or exhibit localized cooling, due to the system's geometry and boundary conditions. In addition, from Figure 16, an elevated binary chemical reaction parameter signifies stronger chemical reactions, which alter concentration gradients and further influence temperature and velocity fields due to heat release or absorption. The ohmic heating parameter, denoted as Ω, affects temperature and concentration distributions differently in fluid systems. Increasing Ω leads to more electrical energy converting into heat, raising temperatures uniformly across the system, especially in regions with significant ohmic heating (Figures 17 and 18). This results in a more uniform temperature distribution, with higher temperatures where ohmic heating is prominent. However, the influence on concentration distribution is indirect. While Ω primarily impacts temperature, temperature variations can alter reaction kinetics or solubility, affecting concentration gradients. Nonetheless, the impact on concentration distributions may be secondary to temperature changes, contingent on the fluid system's characteristics and the involved chemical processes. The effect of heat generation/absorption on temperature and concentration distribution is displayed in Figures 19 and 20. Heat generation/absorption affects temperature and concentration distributions in fluid systems. Heat generation, represented by a positive β parameter, increases thermal energy within the fluid, raising temperatures where heat is generated. This leads to a more uniform temperature distribution, with higher temperatures in regions experiencing heat generation. Conversely, heat absorption, indicated by a negative β parameter, decreases thermal energy, resulting in lower temperatures where heat is absorbed. Changes in temperature can influence reaction kinetics or solubility, indirectly affecting concentration distributions. Thus, heat generation/absorption plays a pivotal role in shaping both temperature and concentration profiles within fluid systems, impacting various chemical and physical processes.

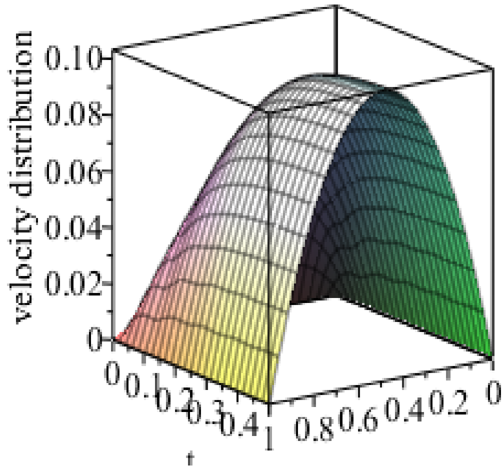

Figure 1. 3D Velocity Profile

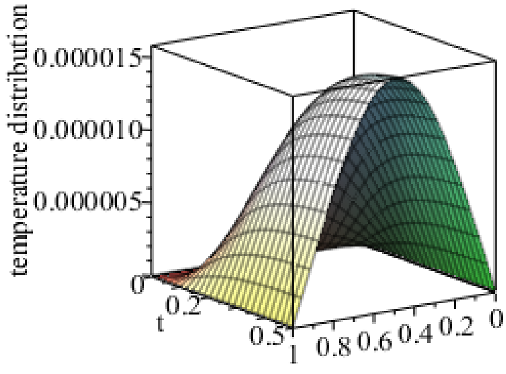

Figure 2. 3D Temperature Profile

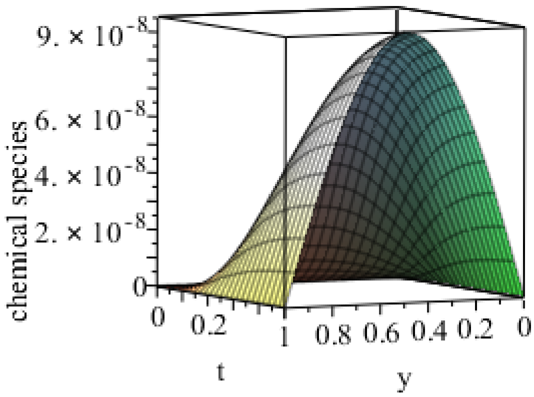

Figure 3. 3D Chemical Species Concentration Profile

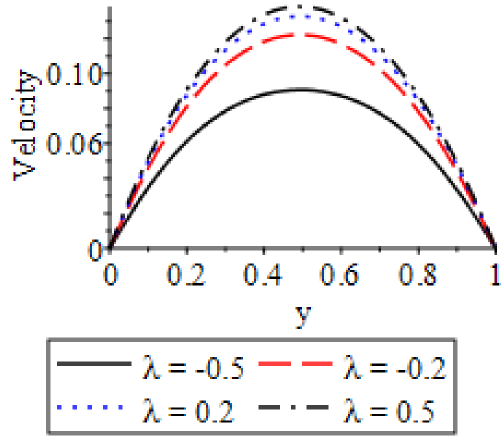

Figure 4. Effect of Reactivity Parameter on Velocity Distribution

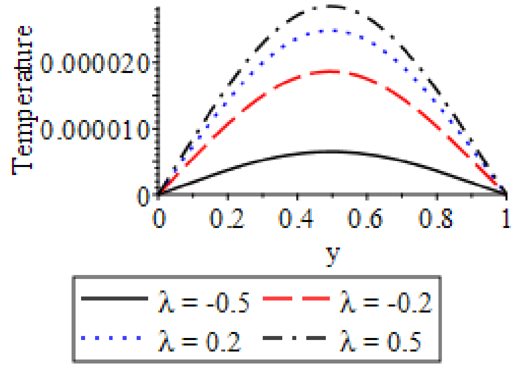

Figure 5. Effect of Reactivity Parameter on Temperature Distribution

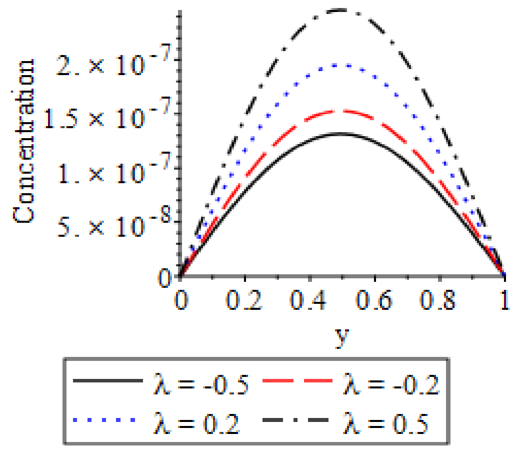

Figure 6. Effect of Reactivity Parameter on Concentration Distribution

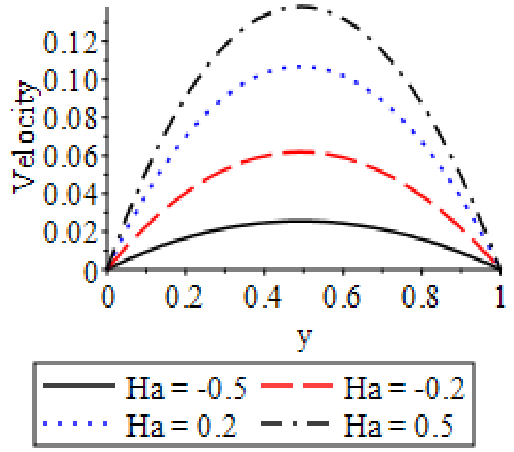

Figure 7. Effect of Lorentz Force on Velocity

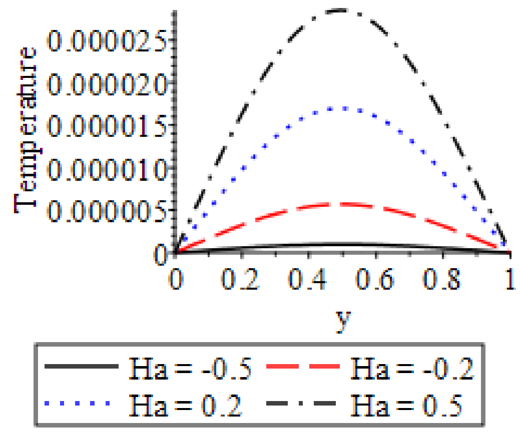

Figure 8. Effect of Lorentz Force on Temperature

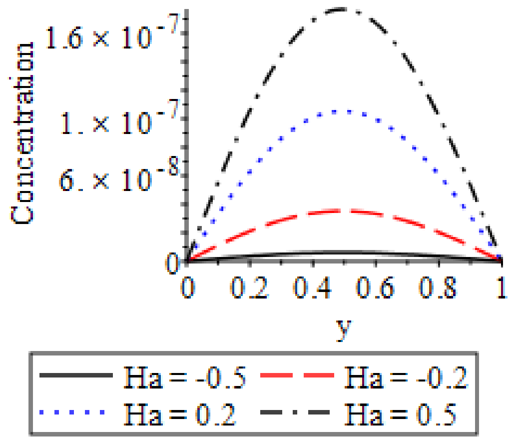

Figure 9. Effect of Lorentz Force on Concentration

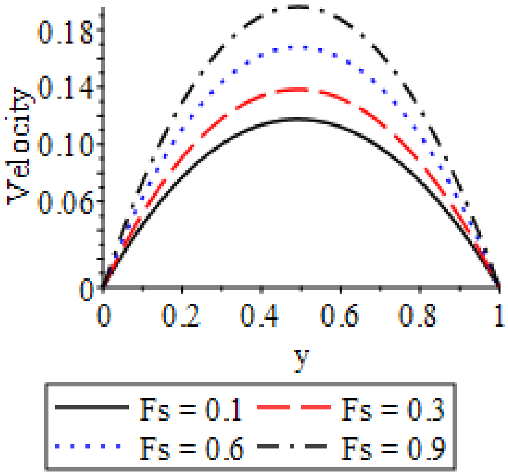

Figure 10. Impact of Porosity on Velocity Distribution

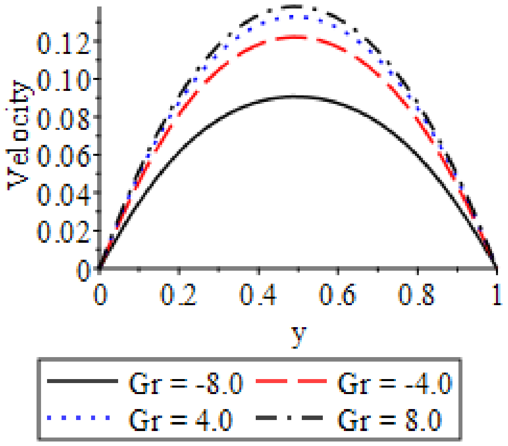

Figure 13. Effect of Grashof Number on Velocity Distribution

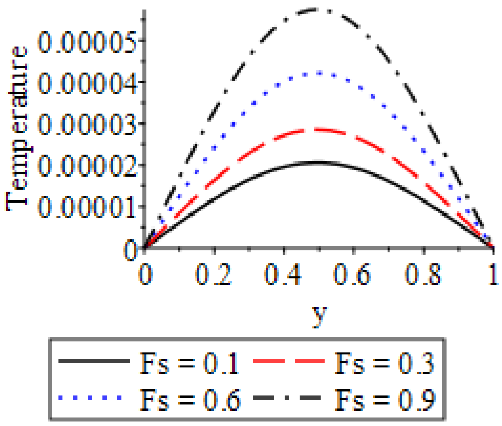

Figure 11. Impact of Porosity on Temperature Distribution

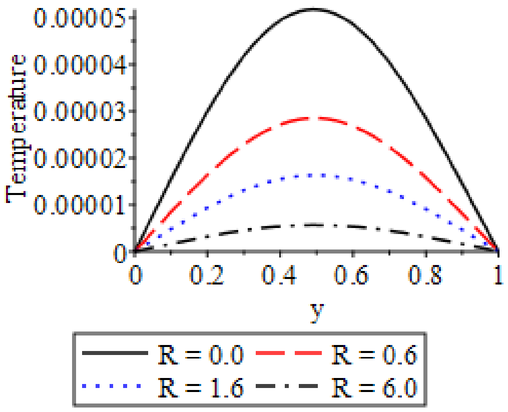

Figure 14. Influence of Radiation on Temperature Distribution

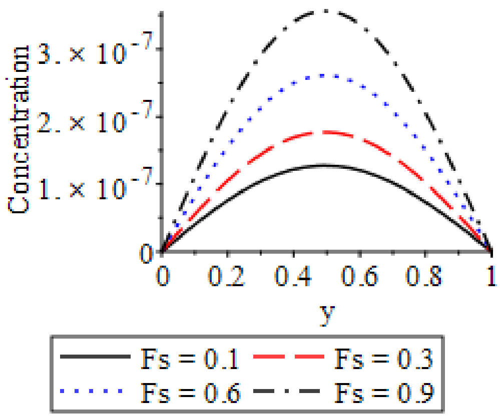

Figure 12. Impact of Porosity on Concentration Distribution

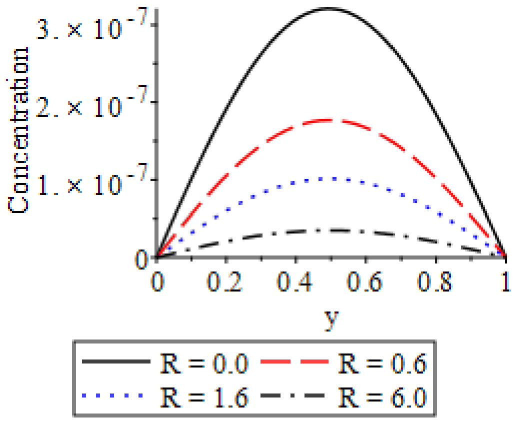

Figure 15. Influence of Radiation on Temperature Distribution

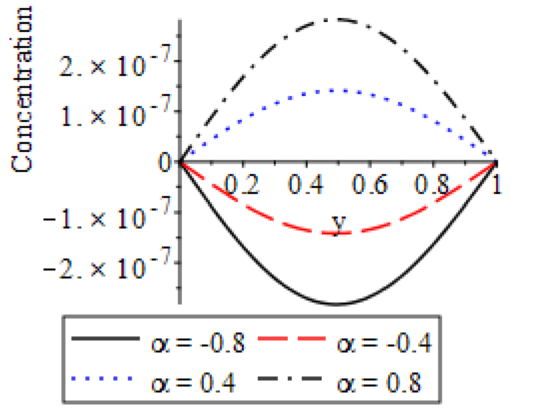

Figure 16. Effect of Reactivity Parameter on Chemical Species Distribution

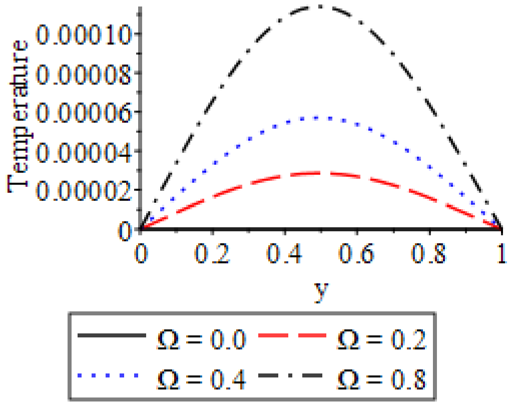

Figure 17. Effect of Ohmic Heating on Temperature

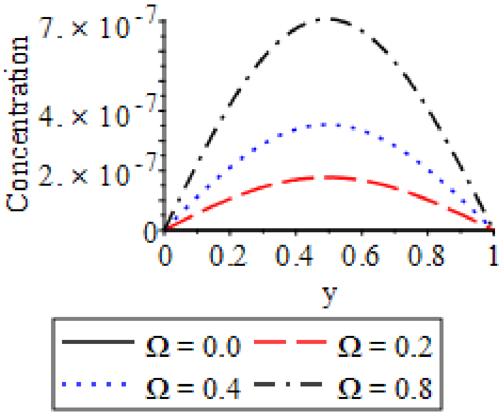

Figure 18. Effect of Ohmic Heating on Concentration

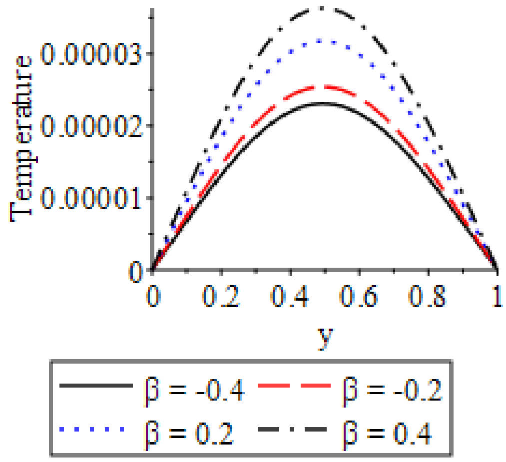

Figure 19. Influence of Heat Generation/Absorption on Temperature Distribution

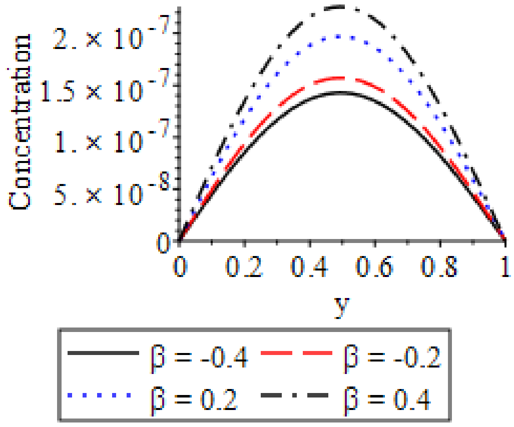

Figure 20. Influence of Heat Generation/Absorption on Chemical Species Concentration

Summary

In this paper, we have investigated the combined effects of heat and mass transfer onunsteady MHD flow with thermal radiation and binary chemical reaction. The mathematical formulations governing the flow field, energyequation, and species concentration equation have been presented, and numerical simulations have been conducted to analyze the heat and mass transfercharacteristics of the flow.

Mathematical models based on partial differential equations describe fluid dynamics and transport phenomena, with computational methods like finite element analysis and computational fluid dynamics facilitating simulation and analysis. Numerical simulations are conducted to solve the governing equations along with appropriate boundary conditions. Through graphical representations, the study investigates the impact of various parameters such as magnetic field strength, thermal radiation intensity, and reaction rate on heat and mass transfer characteristics. The concentration, temperature, and velocity profiles depict laminar flow characteristics, with insights into mixing, temperature uniformity, and fluid motion provided for engineering applications.

Conclusion

The investigation underscores the complexity of fluid systems under unsteady oscillatory MHD flow, incorporating heat transfer, thermal radiation, and chemical reactions. Through numerical simulations and graphical analyses, the study elucidates the interplay of key parameters such as magnetic field strength and porosity on concentration, temperature, and velocity distributions. Understanding these dynamics is crucial for optimizing processes in diverse engineering applications, offering insights into heat transfer efficiency, fluid behavior, and concentration gradients. The findings contribute to advancing knowledge in fluid dynamics and aid in the development of more efficient and sustainable technologies. As a result of the analysis carried out in this work, the following observations were made:

1. The study provides a comprehensive analysis of the combined effects of various phenomena such as unsteady oscillatory MHD flow, heat and mass transfer, thermal radiation, and binary chemical reactions. It underscores the interdisciplinary nature of fluid dynamics, thermodynamics, and chemical kinetics.

2. Utilizing mathematical models based on partial differential equations, the research establishes a robust framework for describing and analyzing complex fluid dynamics and transport phenomena.

3. The numerical simulations offer valuable insights into the heat and mass transfer characteristics of the flow, which are essential for optimizing engineering designs and processes involving MHD systems.

4. Graphical representations and numerical simulations enable a detailed investigation of the sensitivity of various parameters such as magnetic field strength, thermal radiation intensity, and reaction rate on heat and mass transfer characteristics. This aids in understanding the dominant factors influencing fluid behavior and performance.

5. Observations regarding temperature and concentration distributions, velocity profiles, and the influence of parameters like the Grashof number and heat generation/absorption provide practical guidelines for designing efficient heat exchange systems and controlling chemical reactions in MHD flow environments.

Acknowledgement

The authours wish toexpress our sincere gratitude to the anonymous reviewers and the editorial board for their valuable expertise and suggestionsthat have been instrumental in shaping this work.

Conflict of interests

The authors declare that there are no conflicts of interest regarding the publication of this article.

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