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FREE CONVECTIVE MHD RADIOACTIVE FLOW ACROSS A VERTICAL PLATE ENCLOSED IN A POROUS MEDIUM TAKING INTO ACCOUNT VISCOUS-DISSIPATION, THERMO-DIFFUSION AND CHEMICAL-REACTION

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The paper examines solution for a two-dimensional steady, viscous, heat dissipation, incompressible hydro-magnetic free convective flow past a uniformly moving vertical porous plate immersed in a porous material in the presence of the Soret effect, Dofour effect and Chemical reaction. A constant magnetic field is directed into the fluid area perpendicular to the plate. The MATLAB built-in bvp4c solver approach is used to solve the governing non-dimensional equations. The discussion of the current issue focuses mostly on the impacts of thermal diffusion, magnetic field, thermal radiation, Grashof number, Soret number, Dufour number, and chemical reaction. It is observed that the Soret number improves fluid temperature. In addition, the fluid's temperature, concentration, and velocity all drop as the magnetic field parameter rises. Although the heat dissipation caused by the medium's porosity is usually disregarded in convective MHD flow simulations, it is considered in this work.
Keywords: *MHD; Porous medium; Chemical reaction; Radiation; Heat dissipation; Soret effect and Dufour effect*
PACS: 44.25+g; 44.05.+e; 44.30.+v; 44.40.+a

INTRODUCTION

The combined effects of magnetic and temperature field on viscous flow are basically studied in a magneto-hydrodynamics (MHD) flow. In addition to many other domains, Magnetohydrodynamic (MHD) flow finds practical applications in diverse fields such as missile technology, plasma physics, geophysics, solar physics, astrophysics etc. Consequently, numerous scientists and engineers are keenly interested in its applications. Khan *et al.* [1] investigated the magnetohydrodynamic free convection flow around an oscillating plate within a porous medium. Fetecau *et al.* [2] explored the unsteady solution of magnetohydrodynamic natural convection flow incorporating radiative effects. Meanwhile, Seth *et al.* [3] delved into the radiative heat transfer in the context of MHD free convection flow past a plate with ramped wall temperature. MHD free convective flow involving chemical reaction over an inclined magnetic field was studied by Sheri *et al.* [4]. In an unstable MHD flow between two porous vertical plates, heat and mass transfer were investigated by Raghunath *et al.* [5]. Zeeshan *et al.* [6] investigated the MHD flow of water/ethylene glycol based nanofluids with natural convection through a porous medium. Their results were substantiated both mathematically and graphically.

Free convection is a method of heat transmission in which buoyancy induced fluid motion is all that occurs. Due to the significance of natural convections in both nature and engineering, several scholars have investigated these issues in depth over the past 20 years. Among them are Ahmed *et al.* [7], Lawal *et al.* [8] and Sedki [9]. Ahmed *et al.* [10] conducted a study on the three-dimensional mixed convective mass transfer flow adjacent to a semi-infinite vertical plate in porous medium. Rajput *et al.* [11] investigated the effects of chemical reactions and radiation on magnetohydrodynamic flow via a vertical plate with changing mass diffusion and temperature. Soret and Dufour effect on MHD micropolar fluid past over a Riga plate was studied by Borah *et al*. [12]. Ahmed [13] examined the impact of Soret and radiation effects on transient magnetohydrodynamic free convection from an impulsively started infinite vertical plate. Patel [14] investigated the thermal radiation effects on magnetohydrodynamic (MHD) flow involving heat and mass transfer of a micropolar fluid between two vertical walls. Reddy *et al.* [15] explored the influence of chemical reactions on magnetohydrodynamic natural flow through a porous medium past an exponentially stretching sheet, considering the presence of heat source/sink and viscous dissipation. Jha *et al.* [16] examined how a heat source or sink affected magnetohydrodynamic free convective flow in a nanofluid-filled channel. The effect of viscous dissipation on magnetohydrodynamic free convection flow around a semi-infinite moving vertical porous plate with chemical reaction and heat sink was investigated by Matta *et al*. [17]. Borah *et al.* [18] investigated the influence of Arrhenius activation energy in magnetohydrodynamic micropolar nanofluid flow along a porous stretching sheet, considering viscous dissipation and heat source. In a recent study, Akhtar *et al.* [19] explored the impacts of radiation and heat dissipation on magnetohydrodynamic convective flow in the presence of a heat sink.

Chemical reactions have a significant impact on studies of thermal and solutal convection in the fields of science and engineering technology. The existence of multi-component species in a system causes the chemical reaction.

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Senapati *et al.* [20] conducted a study on the magnetic effects on mass and heat transfer in a hydromagnetic flow past over a vertical oscillating plate in presence of a chemical reaction. Mondal *et al.* [21] examined how radiation and chemical reactions affect the free convection flow of magnetohydrodynamic via a vertical plate in a porous material. Sinha [22] conducted a study on the unsteady MHD free convective flow, considering the effects of a chemical reaction past a permeable plate under sloping temperature conditions. The results showed that the reaction rate increased as the chemical reaction parameter increased. Suresh *et al.* [23] investigated the influence of chemical reaction and radiation on magnetohydrodynamic flow along a moving vertical porous plate with heat source and suction.

Bordoloi *et al.* [24] investigated the analytical solution for a steady, viscous, incompressible hydromagnetic free convective flow in two dimensions that passes in front of a vertical porous plate that is uniformly moving and embedded in a porous material. Their study included the consideration of the Soret effect and chemical reaction. The current research extends this work by incorporating heat dissipation due to the porosity of the medium. Through the use of a vertical plate that is always moving, always experiencing a heat flux, immersed in a porous media, and always under continual suction, the study seeks to understand how chemical reactions and thermal radiation affect natural convective flow. These combined effects, which are not typically examined simultaneously, have wide range of effects on engineering processes such as paper production, plastic sheet extrusion, glass blowing, and more.

BASIC EQUATIONS

The following equations described the continuous convective flow across a porous medium of an electrically conducting, viscous, incompressible fluid while being affected by a magnetic field:

$$\vec{\nabla}.\vec{q} = 0 \tag{1}$$

$$\vec{\nabla}.\vec{B} = 0 \tag{2}$$

$$\vec{J} = \sigma\left(\vec{E} + \vec{q} \times \vec{B}\right) \tag{3}$$

$$\rho(\vec{q}.\vec{\nabla})\vec{q} = \rho\vec{g} - \vec{\nabla}p + \vec{J} \times \vec{B} + \mu\nabla^2\vec{q} - \frac{\mu\vec{q}}{K'} \tag{4}$$

$$\rho C_p(\vec{q}.\vec{\nabla})T = k\nabla^2 T + \varphi + \frac{\vec{J^2}}{\sigma} + Q'(T_\infty - T) - \vec{\nabla}.\overrightarrow{q_r} - \frac{\mu}{K'}\overrightarrow{q_r}^2 \tag{5}$$

$$(\vec{q}.\vec{\nabla})C = D_M\nabla^2 C + \frac{D_M K_T}{T_m}\nabla^2 T + \overline{K_c}(C_\infty - C) \tag{6}$$

$$\rho_\infty = \rho\left[1 + \beta(T - T_\infty) + \overline{\beta}(C_\infty - C)\right] \tag{7}$$

Radiation heat flux as per Rosseland approximation,

$$\overrightarrow{q_r} = -\frac{4\sigma^*}{3k^*}\vec{\nabla}T^4 \tag{8}$$

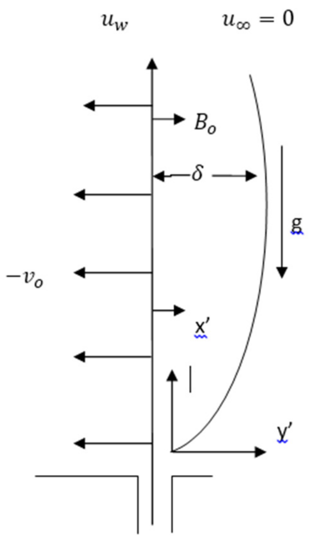

Figure 1. Physical representation of the problem.

MATHEMATICAL FORMULATION

It is considered that a viscous, incompressible, radiating fluid that conducts electricity will pass through a vertical plate embedded in a porous medium with uniform suction when a constant magnetic field is present and directed perpendicularly to the flow. The investigation is guided by the following presumptions:

I. With the exception of density in the term for the buoyant force, all fluid parameters are constant.

II. There is very little induced magnetic field.

III. The plate has no electrical conductivity.

IV. It receives no external electric field.

Let, $\vec{B}$ and $\vec{q}$ be the applied magnetic field and the flow velocity respectively at the point (x', y', z').

Since $|T - T_\infty|$ is the very small, T^4 can be expressed as:

$$T^4 = \{T_\infty + (T - T_\infty)\}^4 = 4T_\infty^3 T - 3T_\infty^4. \tag{9}$$

Therefore, equation (8) gives,

$$\overrightarrow{q_r} = -\frac{16\sigma^* T_\infty^3}{3k^*}\vec{\nabla}T \tag{10}$$

Equation (10) gives,

$$\vec{\nabla}.\overrightarrow{q_r} = -\frac{16\sigma^* T_\infty^3}{3k^*}\nabla^2 T \tag{11}$$

Equation (11) can be used to simplify the energy equation as follows:

$$\rho C_p v' \frac{\partial T}{\partial y'} = k\frac{\partial^2 T}{\partial y'^2} + \mu\left(\frac{\partial u'}{\partial y'}\right) + \sigma {B_o}^2 u'^2 + \frac{16\,\sigma^*}{3K^*} {T_\infty}^3 \frac{\partial^2 T}{\partial y'^2} - \bar{Q}(T_\infty - T) \tag{12}$$

The equation of state (7) yields the following governing equations, which are standard boundary layer approximations.

$$\frac{\partial v'}{\partial y'} = 0, \tag{13}$$

$$v' \frac{\partial u'}{\partial y'} = g\beta(T - T_\infty) + g\bar{\beta}(C - C_\infty) + \vartheta\frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma {B_o}^2 u'}{\rho} - \frac{\vartheta u'}{K'}, \tag{14}$$

$$\rho C_p v' \frac{\partial T}{\partial y'} = k\frac{\partial^2 T}{\partial y'^2} + \mu\left(\frac{\partial u'}{\partial y'}\right) + \sigma {B_o}^2 u'^2 + \frac{16\,\sigma^*}{3K^*} {T_\infty}^3 \frac{\partial^2 T}{\partial y'^2} - \bar{Q}(T_\infty - T) - \frac{\mu}{k'} u'^2 + \frac{D_M K_T}{C_P C_S}, \tag{15}$$

$$v' \frac{\partial C}{\partial y'} = D_M \frac{\partial^2 C}{\partial y'^2} + \frac{D_M K_T}{T_m}\frac{\partial^2 T}{\partial y'^2} + \overline{K_c}(C_\infty - C), \tag{16}$$

The appropriate boundary conditions for the velocity, temperature and concentration are,

$$\text{At } y' = 0:\ u' = U,\ \frac{\partial T}{\partial y'} = -\frac{q^*}{k},\quad C = C_w \tag{17}$$

$$\text{As } y' \to \infty:\quad u' \to 0,\quad T \to T_\infty,\quad C \to C_\infty \tag{18}$$

The non-dimensional quantities are introduced as,

$$y = \frac{v_o y'}{v},\quad u = \frac{u'}{U},\quad \theta = \frac{T - T_\infty}{\frac{q^* v}{k v_o}},\quad \varphi = \frac{(C - C_\infty)}{C_w - C_\infty},\quad G_r = \frac{v g\beta \frac{q^* v}{k v_o}}{U {v_o}^2},\quad E = \frac{U^2}{C_P(T_w - T_\infty)},$$

$$P_r = \frac{\mu C_p}{k},\ K_c = \frac{\overline{K_c}\vartheta}{{v_o}^2}, G_m = \frac{g\bar{\beta}\,\vartheta}{U {v_o}^2}(C_w - C_\infty),\ S_c = \frac{\vartheta}{D_M},\ M = \frac{\sigma {B^2}_o \vartheta}{\rho {v_o}^2}, R = \frac{4\vartheta I}{\rho C_p {v_o}^2 q^*},\ Q = \frac{\bar{Q}\vartheta}{\rho {v_o}^2 C_p}, \mathrm{K} = \frac{K' {v_o}^2}{\vartheta^2},$$

$$S_r = \frac{D_M K_T \frac{q^* v}{k v_o}}{\vartheta T_m (C_w - C_\infty)}, D_u = \frac{D_M K_T (C_w - C_\infty)}{C_p C_S (T_w - T_\infty)}, N = \frac{k k^*}{4\sigma^* {T_\infty}^3}$$

Equation (13) gives,

$$v' = -v_o(v_o > 0) \tag{19}$$

The form of governing equations in dimensionless are as follows:

$$\frac{d^2 u}{dy^2} + \frac{du}{dy} - \left(M + \frac{1}{K}\right) u = -G_r\theta - G_m\varphi \tag{20}$$

$$\frac{d^2\theta}{dy^2} + \Lambda_1 \frac{d\theta}{dy} - Q_1\theta = -\Lambda_1 E\left(\frac{du}{dy}\right)^2 - \left(M + \frac{1}{K}\right)\Lambda_1 E u^2 - D_u \Lambda_1 \frac{d^2\varphi}{dy^2} \tag{21}$$

$$\frac{d^2\varphi}{dy^2} + S_c\frac{d\varphi}{dy} - K_c\,\varphi = -S_c S_r \frac{d^2\theta}{dy^2} \tag{22}$$

Where,

$$\Lambda = 1 + \frac{4}{3N}, \frac{Q}{\Lambda} = Q_1, \text{ and } \Lambda_1 = \frac{P_r}{\Lambda}$$

Corresponding boundary conditions (17)-(18) reduces to

$$\text{At } y = 0:\ u = 1, \frac{\partial\theta}{\partial y} = -1,\ \varphi = 1 \tag{23}$$

$$\text{As } y \to \infty:\ u \to 0,\ \theta \to 0,\ \varphi \to 0 \tag{24}$$

METHOD OF SOLUTION

The ordinary differential equations (20)-(22) with the boundary conditions (23) and (24) are solved by the use of numerical method 'MATLAB built-in bvp4c solver technique'. The boundary ordinary differential equations are converted into the first order differential equations are as follows:

Let,

$$u = y(1),\quad u' = y(2),\quad \theta = y(3),\quad \theta' = y(4),\quad \varphi = y(5),\quad \varphi' = y(6).$$

Now, we have the following set of first order differential equations:

$$y'(2) = -y(2) - \left(M + \frac{1}{K}\right) - G_r y(3) - G_m\, y(5) \tag{25}$$

$$y'(4) = -\frac{\Pr}{\left(1+\dfrac{4}{3N}\right)} y(4) + \frac{Q}{\left(1+\dfrac{4}{3N}\right)} y(3) - \frac{\Pr}{\left(1+\dfrac{4}{3N}\right)} E\, y(2) y(2) - \left(M + \frac{1}{K}\right) \frac{\Pr}{\left(1+\dfrac{4}{3N}\right)} E\, y(1) y(1) - Du \frac{\Pr}{\left(1+\dfrac{4}{3N}\right)} y'(6) \tag{26}$$

$$y'(6) = -Sc\, y(6) + Kc\, y(5) - Sc\, Sr\, y'(4) \tag{27}$$

The boundary conditions of the resulting ordinary differential equations can be expressed as,

$$y0(1)-1,\ \ y0(4)+1,\ \ y0(5)-1,\ \ \ y1(1)-0,\ \ y1(3)-0,\ \ y1(5)-0 \tag{28}$$

RESULT AND DISCUSSION

In this study, the effects of various non-dimensional physical parameters such as magnetic parameter (M), radiation parameter (N), thermal diffusion ratio (K_T), heat sink (Q), thermal Grashof number (G_r), solutal Grashof number (G_m), chemical reaction (K_c), Soret number (S_r), Schmidt Number (S_c), Prandlt number (P_r), Dufour number (D_u) and porosity parameter (K) on velocity field (u), temperature field (θ) and concentration field (φ) of the flow system have been studied and their variations with respect to the parameters are shown by graphs. The Variations of fluid velocity, temperature and concentration field are shown in figures 2-20 graphically.

Velocity variation: The velocity profiles are shown in figures 2-9. Figure-2 represents that the fluid velocity u decreases with the increasing values of magnetic parameter (M). This happens as a result of the fluid's velocity decreasing due to the magnetic field's generation of an opposing Lorentz force. Therefore, the increasing value of magnetic field results in the decrease of fluid velocity. Figure-3 shows the effect of the radiation parameter on the velocity profile. It is evident that as the radiation parameter increases, the velocity of fluid particles increases.

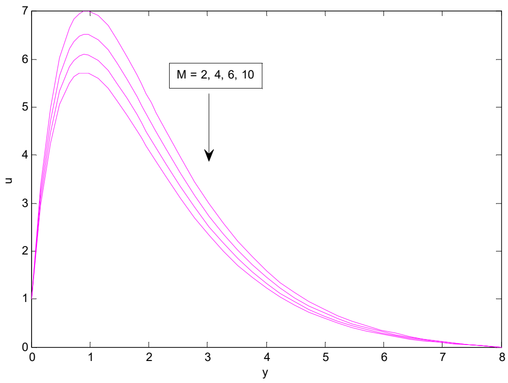

Figure 2. Variation of the velocity with M

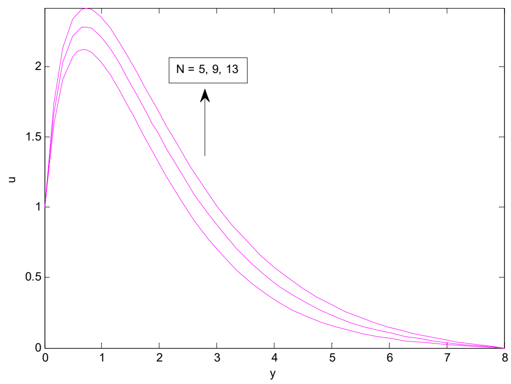

Figure 3. Variation of the velocity with N

Figure-4 shows the impact of chemical reaction parameter K_c on velocity profile. It is observed that fluid velocity (u) decreases with the increase of chemical reaction parameter K_c. Figure-5 shows how fluid velocity changes with thermal Grashof number G_r. It is noted that velocity increases along with the thermal Grashof number.

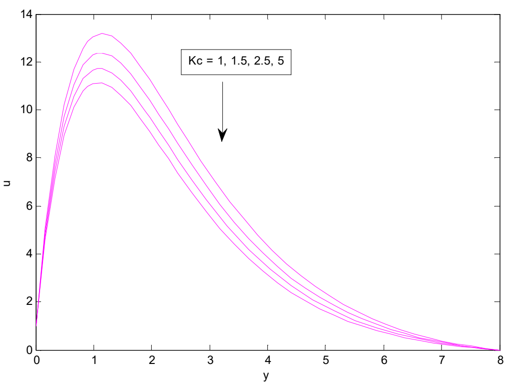

Figure 4. Variation of the velocity with K_c

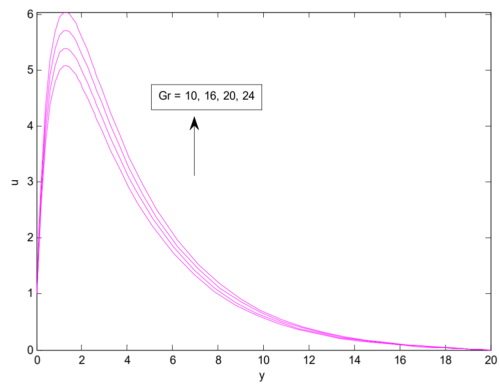

Figure 5. Variation of the velocity with G_r

This can be explained by the observation that temperature gradients rise in proportion to an increase in Grashof number, which ultimately causes the velocity distribution inside the flow to increase. Figure-6 demonstrates how the solutal Grashof number G_m affect the fluid velocity. It is noted that the fluid velocity increases with G_m. The thermal and solutal buoyancy forces cause a considerable rise in the velocity field. This results from the direct relationship between buoyant force and Grashof numbers. Figure-7 depicts the effect of Soret number (S_r) on velocity. It is seen that the fluid velocity increases due to the increase of Soret number. In figure-8, it has been noted that when the porosity parameter (K) grows, the fluid velocity increases. This happens because a fluid with a higher porosity value has more room to move. Consequently, an increase in the fluid velocity occurs. Figure-9 shows the influence of Dufour number (D_u) on fluid velocity. It is regarded that as Dufour number increases there is monotonic increase in the fluid velocity.

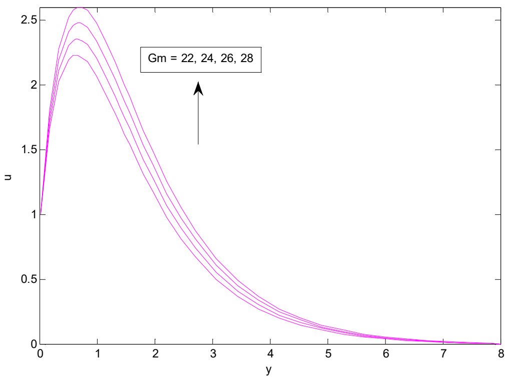

Figure 6. Variation of the velocity with G_m

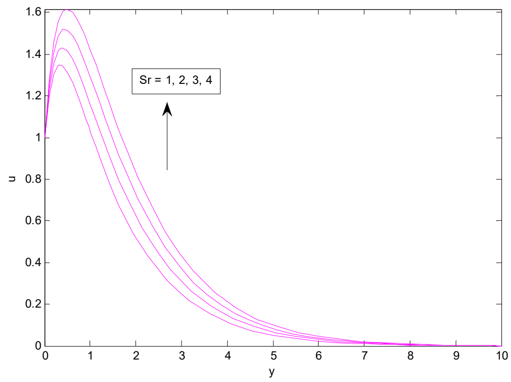

Figure 7. Variation of the velocity with S_r

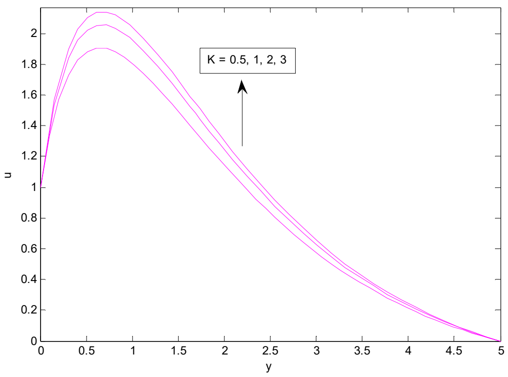

Figure 8. Variation of the velocity with K

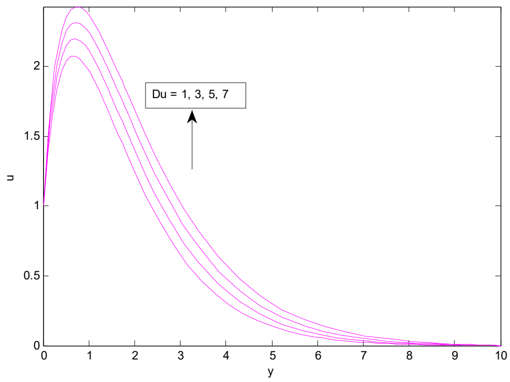

Figure 9. Variation of the velocity with D_u

<u>Temperature Variation:</u> The temperature profiles are shown in figures 10-17. Figure-10 demonstrates how temperature profile changes with heat sink (Q). It is noted that the fluid temperature decreases with the increase of Q. Figure 11 indicates that the fluid temperature decreases as the chemical reaction parameter (K_c) increases. Figure -12 shows how the radiation parameter affects the temperature profile. The observed that the fluid's temperature drops as the radiation parameter increases. Figure-13 illustrates how the fluid temperature drops as the magnetic parameter increases. The increasing values of solutal Grashof number (G_m) and thermal Grashof number($\mathrm{G_r}$) increases the fluid temperature, as shown in figures 14 and 15. Figure-16 shows a clear rise in the fluid temperature for increasing the Soret number(S_r). Figures-17 describes the effect of Dufour number ($\mathrm{D_u}$) on fluid temperature. The Dufour number signifies the contribution of the concentration gradients to the thermal energy flux in the flow. It is seen that as Dufour number (D_u) increases there is monotonic increase in temperature.

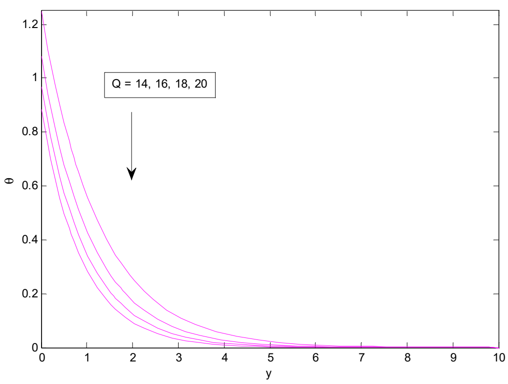

Figure 10. Variation of the temperature with Q

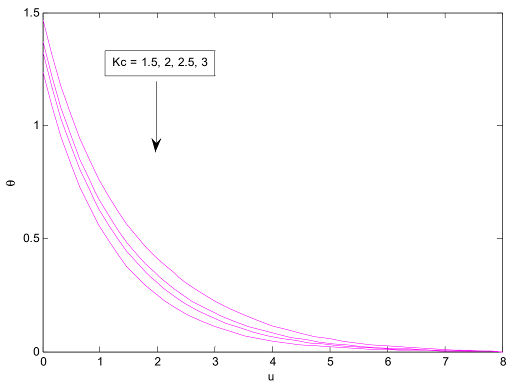

Figure 11. Variation of the temperature with K_c

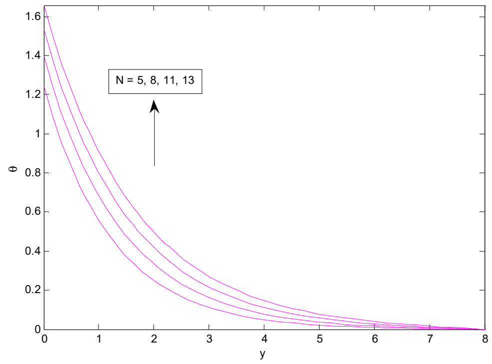

Figure 12. Variation of the temperature with N

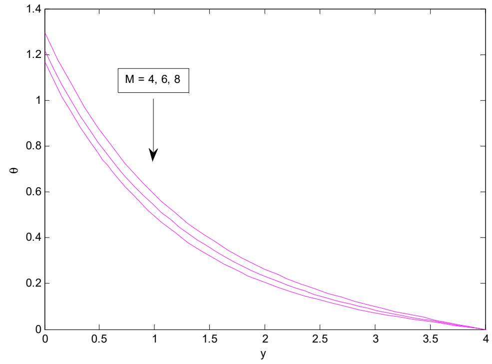

Figure 13. Variation of the temperature with M

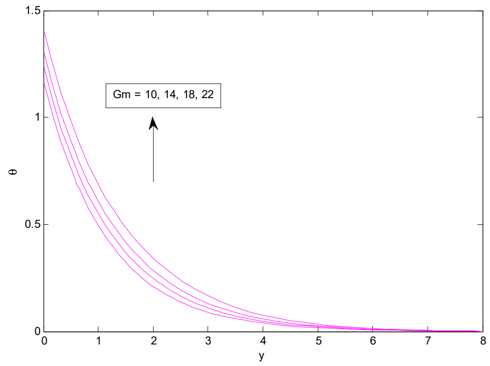

Figure 14. Variation of the temperature with G_m

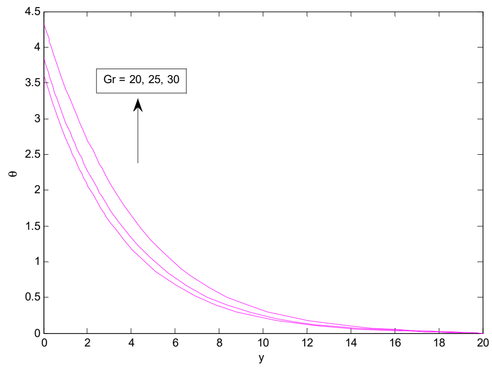

Figure 15. Variation of the temperature with G_r

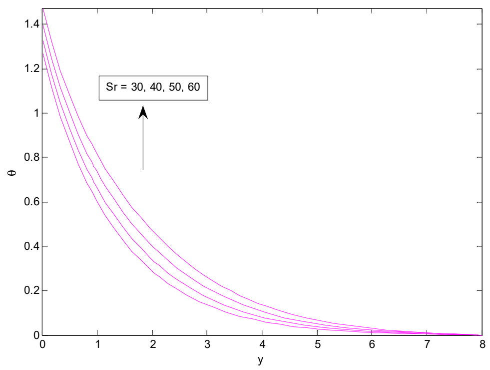

Figure 16. Variation of the temperature with S_r

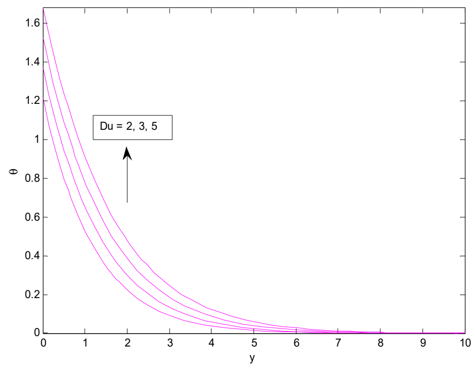

Figure 17. Variation of the temperature with D_u

Concentration Variation: The concentration profiles for the parameters $\boldsymbol{K_c}$, $\boldsymbol{S_r}$ and $\boldsymbol{D_u}$ are depicted in figures 18-20. Figure-18 illustrates that fluid concentration decreases with increasing chemical reaction parameter($\boldsymbol{K_c}$). Figure-19 shows a clear rise in the fluid concentration for increasing the Soret number ($\boldsymbol{S_r}$). Figure-20 describes the fluid concentration increases due to the increasing value of Dufour number ($\boldsymbol{D_u}$).

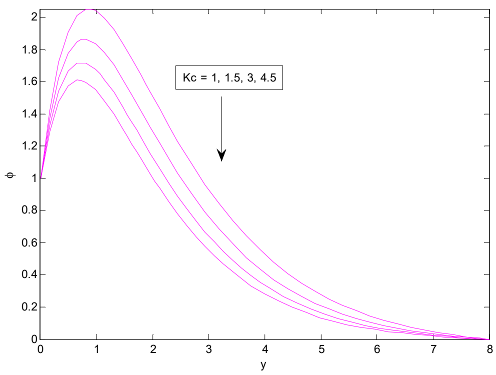

Figure 18. Variation of the concentration with $\boldsymbol{K_c}$

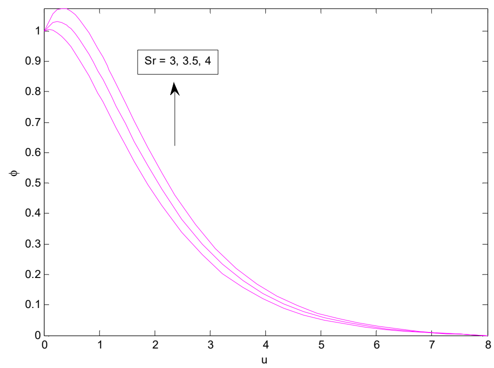

Figure 19. Variation of the concentration with $\boldsymbol{S_r}$

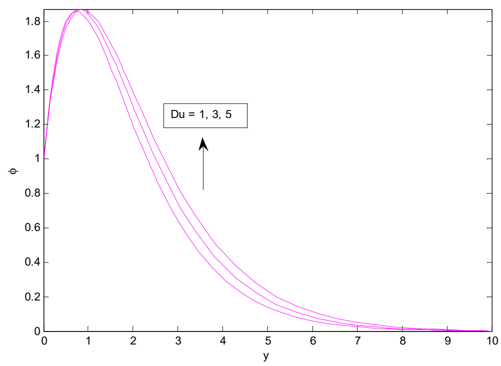

Figure 20. Variation of the concentration with $\boldsymbol{D_u}$

CONCLUSION

In this inquiry, using the 'MATLAB built-in bvp4c solver technique', free convective MHD radioactive flow across a porous vertical plate surrounded by a porous medium has been numerically simulated, accounting for viscous dissipation, thermo-diffusion, and chemical reaction. The investigation's results are noteworthy when fluid temperature rises for high radiation and high thermo-diffusion effects. The consumption of species and magnetic field characteristics is still decreased. As the buoyant force grows, the upsurge concentration rises; nevertheless, as the magnetic parameters grow, it declines. With a rise in magnetic field and intense radiation, the flow slows down. The impact of thermo-diffusion causes the flow to speed up. The application of thermal radiation and magnetic field slows the drag force at the plate. The rate of mass transfer is increased by increasing the thermo-diffusion effect.

NOMENCLATURE

- $\vec{q}$ Fluid velocity vector
- K_T Thermal diffusion ratio
- ρ Fluid density
- T Fluid temperature
- C_∞ Species concentration in free stream
- $\vec{B}$ Magnetic flux density vector
- ν Kinematic viscosity
- C Molar species concentration
- $\vec{J}$ Current density vector
- C_W Species concentration at the plate
- $\vec{J}$ Acceleration vector due to gravity
- T_m Mean fluid temperature
- P Fluid pressure
- $\vec{E}$ Electrical field
- C_p Specified heat at steady pressure
- μ Coefficient of viscosity

- U Free stream velocity
- q^* Heat flux
- σ^* Stefan-Boltzmann constant
- q_r Flux of radiation heat
- κ Thermal conductivity
- $\frac{J^2}{\sigma}$ Ohmic dissipation of energy per unit volume
- φ Viscous energy dissipation per unit volume
- K_c Chemical reaction coefficient
- σ Conductivity of electricity
- K Porosity parameter
- κ* Mean absorption coefficient
- D_M Mass diffusivity
- β Coefficient of thermal expression
- N Radiation absorption Coefficient

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ВІЛЬНИЙ КОНВЕКТИВНИЙ РАДІОАКТИВНИЙ МГД ПОТІК ЧЕРЕЗ ВЕРТИКАЛЬНУ ПЛАСТИНУ В ПОРИСТОМУ СЕРЕДОВИЩІ З УРАХУВАННЯМ В'ЯЗКОВОЇ ДИСИПАЦІЇ, ТЕРМОДИФУЗІЇ ТА ХІМІЧНОЇ РЕАКЦІЇ

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У статті розглядається рішення для двовимірного постійного, в'язкого, розсіювання тепла, нестисливого гідромагнітного вільного конвективного потоку повз рівномірно рухому вертикальну пористу пластину, занурену в пористий матеріал, за наявності ефекту Соре, ефекту Дофура та хімічної реакції. Постійне магнітне поле спрямоване в область рідини перпендикулярно до пластини. Вбудований у MATLAB розв'язувач bvp4c використовується для розв'язування керівних безвимірних рівнянь. Обговорення поточного питання зосереджено на впливі теплової дифузії, магнітного поля, теплового випромінювання, числа Грасгофа, числа Соре, числа Дюфура та хімічної реакції. Помічено, що число Соре покращує температуру рідини. Крім того, температура, концентрація та швидкість рідини падають зі збільшенням параметра магнітного поля. Хоча розсіювання тепла, викликане пористістю середовища, зазвичай не враховується при моделюванні конвективного МГД-потоку, воно розглядається в цій роботі.

Ключові слова: *МГД; пористе середовище; хімічна реакція; випромінювання; розсіювання тепла; ефект Соре і ефект Дюфура*