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Exploring the Impact of Variable Temperature and Concentration on Radiative Chemically Reactive Magnetohydrodynamic Viscoelastic Fluid Flow Across a Moving Porous Plate.

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Abstract

This study explores the dynamics of a magnetohydrodynamic viscoelastic fluid flowing past a vertically moving porous plate, accounting for variable temperature, radiation effects, chemical reactions, and concentration. The governing mathematical formulation is rigorously examined through perturbation analysis. The primary objective of this research is to investigate the impact of various parameters and dimensionless numbers on the fluid flow, thermal boundary, and concentration profiles. An increase in the magnetic parameter leads to a reduction in the velocity profile due to the opposing Lorentz force. Elevated thermal radiation results in an increased temperature profile, while a stronger chemical reaction and higher Schmidt number lead to a decrease in the concentration distribution. The Schmidt number, which characterizes molecular momentum and mass transfer, plays a pivotal role in multiphase flows by influencing boundary layers and diffusion.

Introduction

Convection holds paramount significance across an array of engineering, industrial, and environmental contexts, including electronic device cooling, air conditioning systems, atmospheric dynamics, and energy system security. The interplay of thermal and mass transfer within porous media finds application in various industrial sectors, from filtration processes to power engineering equipment like electronic device cooling, microelectronic chips, printed circuit boards, and photovoltaic sheets [1]. It also plays a pivotal role in diverse engineering and geophysical challenges. Non-Newtonian fluids are indispensable in numerous engineering and technological applications, exemplified by substances like shampoos, mayonnaise, blood, paints, alcoholic beverages, yogurt, cosmetics, and syrups. Mathematical modeling of these fluids presents challenges, as conventional Navier-Stokes equations fall short in capturing their unique characteristics [2]. These fluids are categorized into differential, rate, and integral types. Among them, viscoelastic fluids stand out as a subclass with memory effects, displaying partial elastic recovery upon stress removal. The boundary layer analysis of idealized viscoelastic fluids was pioneered by Beard and Walters [3]. Singh et al. [4] introduced natural convection flow between parallel vertical plates, while Sajid et al. [3] explored fully mixed convection flow between permeable vertical walls in viscoelastic media. Numerous authors have examined the significance of viscoelastic fluid flow under the influence of various parameters [5]. Suneetha et al. [6] derived a radiative dissipative magnetohydrodynamic (MHD) natural convection flow with heat sources and sinks. In summary, the intricate dynamics of convection and viscoelastic fluids find extensive exploration in a broad range of scientific and engineering inquiries [7].

Building upon the insights gleaned from the aforementioned studies, the present inquiry aims to elucidate the impact of heat generation or absorption and first-order chemical reaction phenomena on the laminar boundary layer flow through a porous medium [8]. This investigation extends to encompass the interplay of thermal radiation, variable temperature, and concentration. Through the application of perturbation technique, the dimensionless equations are analytically solved.

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Consequently, the study delves into the influence of various parameters on the characteristics of physical quantities, offering a deeper understanding of their behaviors [9].

Mathematical formulation

We examine a scenario involving the unsteady two-dimensional magnetohydrodynamic (MHD) flow of an incompressible electrically conducting fluid [10]. This fluid flows over a semi-infinite vertical permeable moving plate that also serves as a permeable stretching surface. The presence of thermal radiation is taken into account [11]. The coordinate system is structured such that the x-axis aligns with the sheet's length, while the y-axis stands orthogonal to it, as illustrated in Figure 1 [12]. The influence of the induced magnetic field is considered negligible compared to the applied magnetic field. In this context, the fluid flow is governed by the viscoelastic model proposed by Babu et al. [13]. The equations governing the conservation of mass, momentum, energy, and species are formulated without accounting for the pressure gradient. They are presented below [14]:

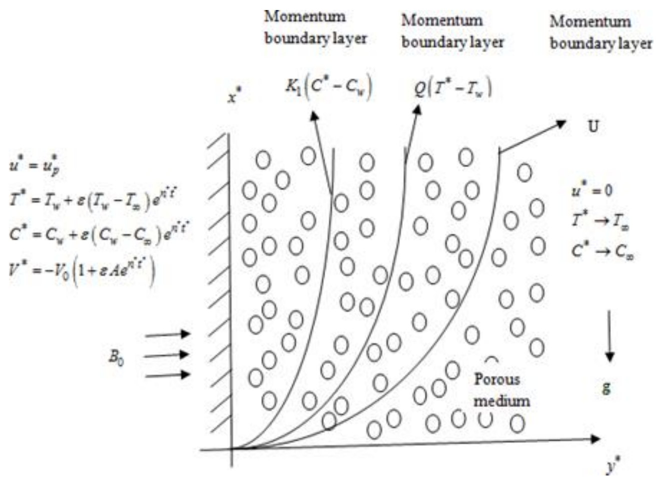

Figure 1: Physical model of the problem

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

$$\frac{\partial u^*}{\partial y^*} + v^* \frac{\partial u^*}{\partial y^*} = \upsilon \frac{\partial^2 u^*}{\partial y^{*2}} - \left(\frac{\sigma B_0^2}{\rho} + \frac{\upsilon}{K^*} \right) u^* + g\beta_T (T^* - T_\infty)$$
$$+ g\beta_C (C^* - C_\infty) - k_0 \left(\frac{\partial^3 u^*}{\partial t^* \partial y^{*2}} + v^* \frac{\partial^3 u^*}{\partial y^{*3}} \right) \qquad (2)$$

$$\frac{\partial T^*}{\partial t^*} + v^* \frac{\partial T^*}{\partial y^*} = \frac{k}{\rho C_p} \frac{\partial^2 T^*}{\partial y^{*2}} - \frac{1}{\rho C_p} \frac{\partial q_r^*}{\partial y^*} - \frac{Q_0}{\rho C_p} \left(T^* - T_\infty \right) \qquad (3)$$

$$\frac{\partial C^*}{\partial t^*} + v^* \frac{\partial C^*}{\partial y^*} = D \frac{\partial^2 C^*}{\partial y^{*2}} - k_1 \left(C^* - C_\infty \right) \qquad (4)$$

The boundary conditions for the above model[15].

$$u^* = u_{p^*}, \; T^* = T_w + \varepsilon \left(T_w - T_\infty \right) e^{n^* t^*}, \qquad (5)$$

$$v^* = -V_0 (1 + \varepsilon A e^{n^* t^*}) \qquad (6)$$

$$u = \frac{u^*}{V_0}, \; u = \frac{v^*}{V_0}, \; y = \frac{V_0 y^*}{\upsilon}, \; t = \frac{V_0^2 y^*}{\upsilon}, \; u_p = \frac{u_p^*}{V_0},$$
$$n = \frac{n^* \upsilon}{V_0^2}, \; \theta = \frac{T^* - T_\infty}{T_w - T_\infty}, \; C = \frac{C^* - C_\infty}{C_w - C_\infty} \qquad (7)$$

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$$\frac{\partial u}{\partial t}-\left(1+\varepsilon Ae^{nt}\right)\frac{\partial u}{\partial y}=\frac{\partial^2 u}{\partial y^2}-\left(M+\frac{1}{K}\right)u+Gr\theta+GmC - E\left[\frac{\partial^3 u}{\partial t\partial y^2}-\left(1+\varepsilon Ae^{nt}\right)\frac{\partial^3 u}{\partial y^3}\right] \quad (8)$$

$$\frac{\partial \theta}{\partial t}-\left(1+\varepsilon Ae^{nt}\right)\frac{\partial \theta}{\partial y}=\frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2}-\left(Q+R\right)\theta \quad (9)$$

$$\frac{\partial C}{\partial t}-\left(1+\varepsilon Ae^{nt}\right)\frac{\partial C}{\partial y}=\frac{1}{Sc}\frac{\partial^2 C}{\partial y^2}-KrC \quad (10)$$

$$u=u_p,\ \theta=1+\varepsilon e^{nt},\ C=1+\varepsilon e^{nt} \text{ at } y=0; \quad u\to 0,\ \theta\to 0,\ C\to 0 \text{ as } y\to\infty \quad (11)$$

$$Gr=\frac{(T_w-T_\infty)\beta_T g\upsilon}{V_0^3},\ Gm=\frac{(C_w-C_\infty)\beta_C g\upsilon}{V_0^3},\ R=\frac{4\upsilon}{\rho C_p V_0^2},\ \Pr=\frac{\rho C_p \upsilon}{k},\ K=\frac{K^* V_0^2}{\upsilon^2},\ Kr=\frac{K_1\upsilon}{V_0^2},\ Sc=\frac{\upsilon}{D},\ Q=\frac{\upsilon Q_0}{\rho C_p V_0^2},\ E=\frac{k_0 V_0^2}{\upsilon^2} \quad (12)$$

Solution to the problem

$$\left.\begin{aligned} u(y,t)&=u_0(y)+\varepsilon e^{nt}u_1(y)+0(\varepsilon^2)\\ \theta(y,t)&=\theta_0(y)+\varepsilon e^{nt}\theta_1(y)+0(\varepsilon^2)\\ C(y,t)&=C_0(y)+\varepsilon e^{nt}C_1(y)+0(\varepsilon^2)\end{aligned}\right\} \quad (13)$$

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$$Eu_0''' + u_0'' + u_0' - n_1 u_0 = -Gr\theta_0 - GmC_0 \tag{14}$$

$$\theta_0'' + \Pr\theta_0' - n_3 \Pr\theta_0 = 0 \tag{15}$$

$$C_o'' + ScC_0' - ScKrC_0 = 0 \tag{16}$$

where, $n_1 = M + \frac{1}{K}$, $n_3 = Q + R$

With

$$\begin{aligned} &u_0 = u_p, \theta_0 = 1, C_0 = 1, && \text{at } y = 0 \\ &u_0 \to 0, \theta_0 \to, C_0 \to 0, && \text{as } y \to \infty \end{aligned} \tag{17}$$

And first order

$$\begin{aligned} &Eu_1''' + (1 - nE)u_1'' + u_1' - n_2 u_1 = -Gr\theta_1 - GmC_1 \\ &- AEu_0''' - Au_0' \end{aligned} \tag{18}$$

$$\theta_1'' + \Pr\theta_1' - n_4 \Pr\theta_1 = -\Pr A\theta_0' \tag{19}$$

$$C_1'' + ScC_1' - Scn_5 C_1 = -AScC_0' \tag{20}$$

where, $n_2 = \left(M + \frac{1}{K} + n\right)$, $n_4 = Q + R + n$, $n_5 = Kr + n$.

With corresponding boundary conditions

$$\begin{aligned} &u_1 = 0, \ \theta_1 = 1, \ C_1 = 1 && \text{at } y = 0 \\ &u_1 \to 0, \theta_1 \to, C_1 \to 0, && \text{as } y \to \infty \end{aligned} \tag{21}$$

Results

The results of the chosen calculations are visually represented in the provided figures, where specific values are assigned to the relevant parameters that define the fluid flow behavior. Thorough analytical computations are performed to determine the velocity, thermal, and concentration distributions. Additionally, aspects such as the friction factor, Nusselt number, and Sherwood number are analyzed for various sets of physical conditions. These investigations help illuminate the underlying flow structures and characteristics.

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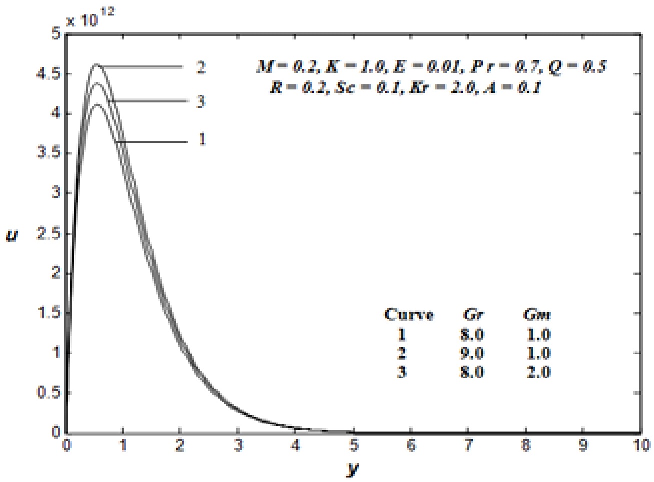

Figure 2. Distribution of u for Gr & Gm

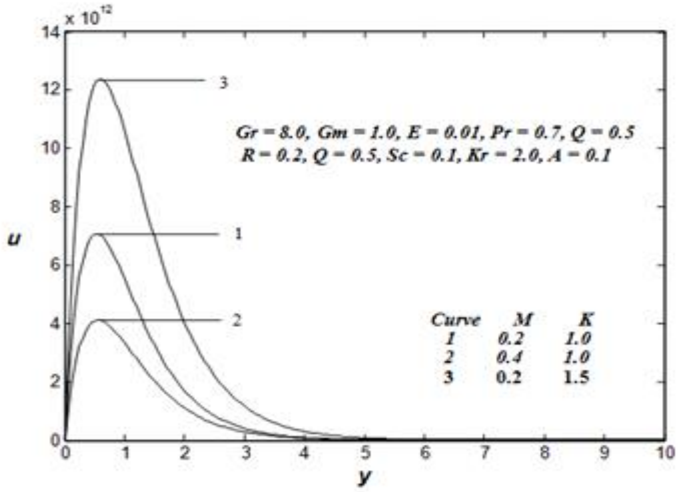

Figure 3. Distribution of u for M & K

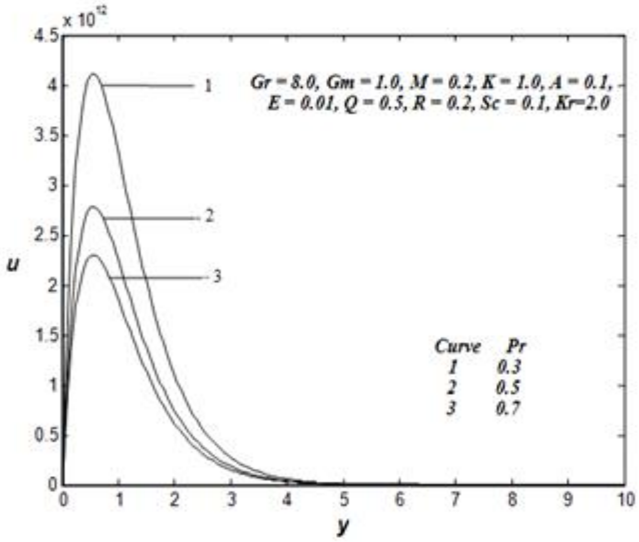

Figure 4. Distribution of u for Pr

Conclusions

This study presents the development of a mathematical model to simulate the two-dimensional unsteady magnetohydrodynamic (MHD) flow of an incompressible, electrically conducting fluid over a permeable moving plate within a porous medium. The investigation takes into account the influences of thermal radiation and chemical reaction. The governing mathematical equations are analytically addressed using perturbation technique. The obtained results yield the following conclusions:

- Fluid velocity experiences augmentation as a function of various parameters, including the Grashof number (Gr), modified Grashof number (Gm), permeability parameter (K), radiation parameter (R), viscoelastic parameter (E), and suction parameter (A).

- The distribution of thermal boundary diminishes in response to the Prandtl number (Pr) and the Q parameter, while it is enhanced by the radiation parameter (R).

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- The presence of a chemical reaction leads to an increased rate of mass transfer, a desirable outcome in the context of reacting species flow.

- The friction factor decreases as the magnetic parameter increases.

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