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Unsteady MHD Flow of Rivlin-Ericksen Fluid Past an Infinite Vertical Porous Plate with Heat Absorption Effect

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Abstract:

This study examines the unsteady magnetohydrodynamic (MHD) convective flow of an incompressible, viscous, electrically conducting Rivlin–Ericksen fluid past a semi-infinite, perpendicular, porous moving plate, with consideration of heat absorption. The plate is assumed to move at a constant velocity in the direction of the fluid flow, while the free stream velocity is modeled to follow an exponentially increasing small perturbation law. Time-dependent wall suction is considered at the permeable surface. The dimensionless governing equations for this analysis are solved analytically using two-term harmonic and non-harmonic functions. The analytical results obtained are shown to reduce to previously published results for a special case of the problem. Numerical evaluation of these analytical results is conducted, and graphical representations of the velocity and temperature profiles within the boundary layer are provided. Additionally, the skin-friction coefficient and Nusselt numbers are discussed with the aid of graphs. Keywords: Hall effects, MHD flows, Rivlin-Ericksen fluid, porous medium and unsteady flows

1. Introduction:

In this study, we examine the unsteady magnetohydrodynamic (MHD) convective flow of an incompressible, viscous, electrically conducting Rivlin–Ericksen fluid past a semi-infinite vertical porous plate, considering heat absorption. The plate is assumed to move at a constant speed in the fluid flow direction, while the free stream velocity is modeled to follow an exponentially increasing small perturbation pattern. Time-dependent suction is considered at the permeable surface. The dimensionless governing equations for this study are analytically solved 1 using two-term harmonic and non-harmonic functions. The analytical results obtained are consistent with previously published findings for a specific case of the problem. Numerical evaluations of these analytical results are conducted, and graphical representations of the velocity and temperature profiles within the boundary layer are provided. Additionally, the skin- friction coefficient and Nusselt numbers are discussed with the aid of graphs. [4] conducted a numerical investigation into the interaction of free and forced convection with mass transfer as fluid flows past a vertical porous plate within a porous medium, considering heat generation and thermal diffusion. Hossain et al. [5] examined how radiation affects the free convection flow of a fluid with variable viscosity from a vertical porous plate. MHD free convection flows are commonly observed in nature. The study of hydro magnetic incompressible viscous flow, particularly in relation to heat transfer influenced by chemical reactions, is crucial in various scientific and engineering fields. This phenomenon is often seen in the petrochemical industry, power and cooling systems, chemical vapor deposition on surfaces, nuclear reactor cooling, heat exchanger design, forest fire dynamics, geophysics, and magneto-hydrodynamic power generation systems. Seethmahalakshmi et al. [6] explored the unsteady effects of thermal radiation on MHD free convection flow past a vertical porous plate. Sahin et al. [7] investigated the combined heat and mass transfer in mixed convection MHD flow along a porous plate with chemical reactions, considering the presence of a heat source. Chaudhaury et al. [8] analyzed the effects of combined heat and mass transfer on MHD free convection flow past an oscillating plate embedded in a porous medium. Ravikumar et al. [9] investigated the MHD double diffusive and chemically reactive flow within a porous medium confined by two vertical plates. Ravikumar et al. [10,11] explored the effects of heat and mass transfer on MHD flow of a viscous fluid through a non-homogeneous porous medium, considering a heat source dependent on temperature. Singh et al. [12] examined the fluctuating heat and mass transfer in unsteady MHD free convection flow of a radiating and reacting fluid past a vertical porous plate in a slip-flow regime. Seethamahalakshmi et al. [13] analyzed MHD free convective mass transfer flow past an infinite vertical porous plate with variable suction and the Soret effect. Rajesh et al. [14] focused on the radiation and mass transfer effects on MHD free convection flow past an exponentially accelerated vertical plate with varying temperature. Israel-Cookey et al. [15] investigated the impact of viscous dissipation on unsteady MHD free convection flow past an infinite heated vertical plate in a porous medium with time-dependent suction. Raju et al. [16] studied unsteady MHD free convective oscillatory Couette flow through a porous medium with periodic wall temperature. The Rivlin–Ericksen elastic-viscous fluid is significant in geophysical fluid dynamics, chemical technology, and industry. Daleep et al. [17] examined bounds for complex growth rates in thermosolutal convection in Rivlin–Ericksen viscoelastic fluid within a porous medium. Noushima et al. [18] discussed hydromagnetic free convective Rivlin–Ericksen flow through a porous medium with variable permeability. Rana [19] addressed the thermal instability of compressible Rivlin–Ericksen rotating fluid permeated with suspended dust particles in a porous medium. Sharma et al. [20] explored the Hall effects on the thermal instability of Rivlin–Ericksen fluid. Gupta et al. [21] discussed Rivlin–Ericksen elastico-viscous fluid heated and solution from below in the presence of compressibility, rotation, and Hall currents. Uwanta et al.[22] examined the influence of mass transfer on hydro magnetic free convective Rivlin–Ericksen flow through a porous medium with time-varying suction. Varshney et al. [23] explored the impact of rotator Rivlin–Ericksen fluid on MHD free convective and mass transfer flow through a porous medium, maintaining constant heat and mass flux across a moving plate. Ravikumar et al. [24] analyzed the effects of a magnetic field on transient free convection flow through a porous medium past a suddenly started vertical plate with varying temperature and mass diffusion. Seth et al. [25] investigated MHD natural convection flow with radiative heat transfer past an impulsively moving plate with a ramped wall temperature. Alam et al. [26] studied the effects of variable suction and thermophoresis on steady MHD combined free-forced convective heat and mass transfer flow over a semi-infinite permeable inclined plate in the presence of thermal radiation. Rajasekhar [27], Linga [28], Muthucumaraswamy [29], and others examined various heat transfer effects in different geometries. Raju et al. [30] considered MHD convective flow through a porous medium in a horizontal channel with an insulated and impermeable bottom wall, accounting for viscous dissipation and Joule heating. Satya Narayana et al. [31] studied the effects of Hall current and radiation absorption on MHD micropolar fluid in a rotating system. Mahgoub [32] investigated forced convection heat transfer over a flat plate in a porous medium. Swati [33] considered slip effects on MHD boundary layer flow over an exponentially stretching sheet with suction/blowing and thermal radiation. Sivaraj and Rushi Kumar [34] explored chemically reacting dusty viscoelastic fluid flow in an irregular channel with a convective boundary. Most of the previous studies mentioned here assumed that the semi-infinite plate remains stationary. Additionally, the fluid considered in these studies was Newtonian. Inspired by the numerous studies, this paper addresses the unsteady MHD convective flow of an incompressible, viscous, electrically conducting Rivlin–Ericksen fluid past a semi-infinite, perpendicular, porous moving plate, considering heat absorption. This specific scenario has not been previously explored. Consequently, this paper examines the unsteady MHD convective flow of an incompressible, viscous, electrically conducting Rivlin–Ericksen fluid past a semi- 3 infinite, perpendicular, porous moving plate, with heat absorption taken into account. Additionally, the free stream is assumed to have a mean velocity and temperature, which change exponentially over time.

2. Formulation and Solution of the Problem:

We examine the unsteady MHD convective flow of an incompressible, viscous, electrically conducting Rivlin–Ericksen fluid past a semi-infinite, perpendicular, porous moving plate, considering heat absorption (Fig.1). It is assumed that no voltage is applied, indicating the absence of an electric field. The transversely applied magnetic field and the magnetic Reynolds number are considered very small, rendering the induced magnetic field and Hall effects negligible. Due to the small magnetic Reynolds number, the Navier-Stokes equations are decoupled from Maxwell's equations. The governing equations for this study, based on the balances of mass and linear momentum, can be expressed in a Cartesian frame of reference as follows:

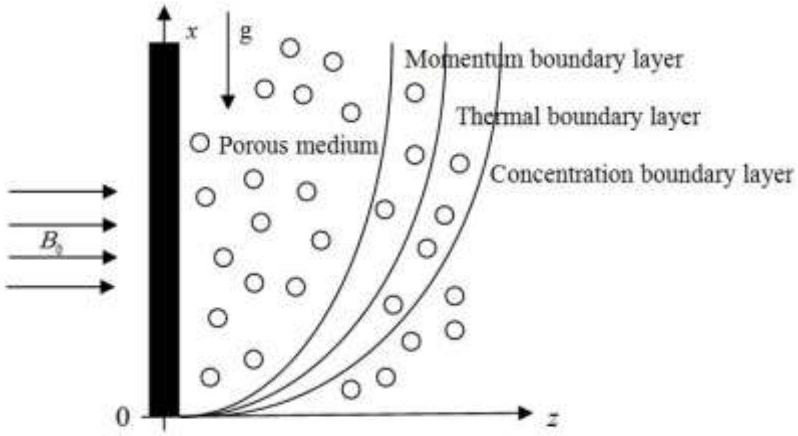

Fig. 1 Physical configuration of the Problem

$$\frac{\partial w}{\partial z} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\partial^2 u}{\partial z^2} - \beta_1\left(\frac{\partial^3 u}{\partial t \partial z^2} + v\frac{\partial^3 u}{\partial z^3}\right) - \frac{\sigma B_0^2 u}{\rho} - \frac{\nu}{k}u + \beta_T\left(T - T_\infty\right) + \beta_C\left(C - C_\infty\right) \tag{2}$$

$$\frac{\partial v}{\partial t} + w\frac{\partial v}{\partial z} = \nu\frac{\partial^2 v}{\partial z^2} - \beta_1\left(\frac{\partial^3 v}{\partial z^2 \partial t} + \frac{\partial^3 v}{\partial z^3}\right) - \frac{\sigma B_0^2 v}{\rho} - \frac{\nu}{k}v \tag{3}$$

$$\frac{\partial T}{\partial t} + w\frac{\partial T}{\partial z} = \alpha\frac{\partial^2 T}{\partial z^2} - \frac{Q_0}{\rho C_p}\left(T - T_\infty\right) \tag{4}$$

$$\frac{\partial C}{\partial t} + w\frac{\partial C}{\partial z} = D\frac{\partial^2 C}{\partial z^2}$$

(5)

In this research, magnetic and viscous dissipations are disregarded. The study presumes that the permeable plate travels at a steady speed aligned with the fluid's direction, while the free stream velocity adheres to an exponentially increasing small perturbation pattern. Furthermore, it is considered that both the wall temperature and the suction velocity change exponentially over time. Based on these assumptions, the suitable conditions for the velocity and temperature fields are established.

$$u = u_p,\ v = 0,\ T = T_w + \varepsilon\left(T_w - T_\infty\right)e^{nt}, C = C_w + \varepsilon\left(C_w - C_\infty\right)e^{nt} \quad \text{at} \quad z = 0, \tag{5}$$

$$u \to U_{\infty,} v \to 0 = u_0\left(1 + \varepsilon e^{nt}\right), T \to T_{\infty,}\ C \to C_{\infty,} \quad \text{as} \quad z \to \infty \tag{6}$$

Where u_p, T_w, are the wall dimensional velocity temperature, respectively U_∞, T_∞ are the free steam dimensional velocity, temperature respectively, u_0 and n are constants. It is clear from equation (1) that the suction velocity at the plate surface is a function of time only assuming that it takes the following exponential form

$$w = -w_0\left(1+\varepsilon A e^{nt}\right) \tag{7}$$

Combining equations (2) and (3), let, $q = u + iv$ we obtain,

$$\frac{\partial q}{\partial t} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\partial^2 q}{\partial z^2} - \beta_1\left(\frac{\partial^3 q}{\partial t\partial z^2} + v\frac{\partial^3 q}{\partial z^3}\right) - \frac{\sigma B_0^2 q}{\rho} - \frac{v}{k}q + \beta_T\left(T - T_\infty\right) + \beta_C\left(C - C_\infty\right) \tag{8}$$

Where A is a real positive constants, ε and εA are small less then unity, and w_0 is a scale of suction velocity which has non-zero positive constant outside the boundary layer equation (2) gives

$$-\frac{1}{\rho}\frac{\partial p}{\partial x} = \frac{\partial U_\infty}{\partial t} + \frac{v}{k}U_\infty + \frac{\sigma}{\rho}B_0^2 U_\infty \tag{9}$$

We introduced the following non-dimensional variables

$$u^* = \frac{u}{U_0}, v^* = \frac{v}{w_0}, z^* = \frac{w_0 z}{v}, U_\infty^* = \frac{U_\infty}{U_0}, u_p^* = \frac{u_p}{U_0}, t^1 = \frac{t w_0^2}{v}, \theta = \frac{T - T_\infty}{T_w - T_\infty}, \phi = \frac{C - C_\infty}{C_w - C_\infty}$$

Making use of non-dimensional variables the governing equations reduces to (Dropping asterisks).

$$\frac{\partial q}{\partial t} - \left(1+\varepsilon A e^{nt}\right)\frac{\partial q}{\partial z} = \frac{\partial U_\infty}{\partial t} + \frac{\partial^2 q}{\partial z^2} + \mathrm{Gr}\,\theta + \mathrm{Gm}\,\phi + \left(M^2 + \frac{1}{K}\right)\left(U_\infty - q\right) - \beta\frac{\partial^3 u}{\partial t\partial z^2}$$

$$-\left(1+\varepsilon A e^{nt}\right)\frac{\partial^3 q}{\partial z^3} \tag{10}$$

$$\frac{\partial \theta}{\partial t} - \left(1+\varepsilon A e^{nt}\right)\frac{\partial \theta}{\partial z} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial z^2} - Q\theta \tag{11}$$

$$\frac{\partial \phi}{\partial t} - \left(1+\varepsilon A e^{nt}\right)\frac{\partial \phi}{\partial z} = \frac{1}{\mathrm{Sc}}\frac{\partial^2 \phi}{\partial z^2}$$

(12)

Where, $K = \frac{k w_0}{v^2}$ is the permeability of the porous medium, $\Pr = \frac{v\rho C_p}{k}$ is the prandtl number, $M^2 = \frac{\sigma B_0^2 v}{\rho w_0^2}$ is the magnetic field parameter, $\mathrm{Gr} = \frac{v\beta_T g\left(T_w - T_\infty\right)}{w_0^3}$ is the thermal Grashof number, $\mathrm{Gm} = \frac{v\beta_C g\left(C_w - C_\infty\right)}{w_0^3}$ is the mass Grashof number, $\mathrm{Sc} = \frac{v}{D}$ is the Schmist number, $\beta = \frac{\beta_1 w_0^2}{v^2}$ is the visco-elastic parameter of the Rivlin-Ericksen Fluid.

The dimensionless form boundary conditions equations become

$$\begin{aligned} &q = u_p, \theta = 1 + \varepsilon e^{nt}, \phi = 1 + \varepsilon e^{nt}, U = 1 + \varepsilon e^{nt} \quad \text{at} \quad z = 0 \\ &q \to U_\infty, \theta = 0, \phi \to 0, U \to 0 \qquad \text{at} \quad z \to \infty \end{aligned} \tag{13}$$

Equation (10) and (11) represent a set of partial differential equations that cannot be solved in closed form however if can be reduced to a set off ordinary differential equations in dimensionless fom that can be solved analytically this can be done representing the velocity and temperature as,

$$q = q_0(z) + \varepsilon e^{nt} q_1(z) + O\left(\varepsilon^2\right) \tag{14}$$

$$\theta = \theta_0(z) + \varepsilon e^{nt}\theta_1(z) + O\left(\varepsilon^2\right) \tag{15}$$

$$\phi = \phi_0(z) + \varepsilon e^{nt}\phi_1(z) + O\left(\varepsilon^2\right) \tag{16}$$

Substituting the equations (14), (15) and (16) into equation (10), (11) and (12), equating the harmonic and non-harmonic terms, the neglecting and higher order terms of $O\left(\varepsilon^2\right)$,one obtains the following pairs of equations $\left(q_0,\theta_0,\phi_0\right)$ and $\left(q_1,\theta_1,\phi_1\right)$,

$$\beta\frac{d^3q_0}{dz^3}+\frac{d^2q_0}{dz^2}+\frac{dq_0}{dz}-\left(M^2+\frac{1}{K}\right)q_0=-\mathrm{Gr}\theta_0-\mathrm{Gm}\phi_0-\left(M^2+\frac{1}{K}\right) \tag{17}$$

$$\beta\frac{d^3q_1}{dz^3}+\left(1-n\beta\right)\frac{d^2q_1}{dz^2}+\frac{dq_1}{dz}-\left(M^2+\frac{1}{K}\right)q_1-nq_1=$$

$$-n-\mathrm{Gr}\theta_1-\mathrm{Gm}\phi_1-\left(M^2+\frac{1}{K}\right)-\beta A\frac{d^3q_0}{dz^3}-A\frac{dq_0}{dz} \tag{18}$$

$$\frac{d^2\theta_0}{d^2z}+\mathrm{Pr}\frac{d\theta_0}{dz}-Q\mathrm{Pr}\theta_0=0 \tag{19}$$

$$\frac{d^2\theta_1}{d^2z}+\mathrm{Pr}\frac{d\theta_1}{dz}-n\mathrm{Pr}\theta_1-Q\mathrm{Pr}\theta_1=-A\mathrm{Pr}\frac{d\theta_0}{dz} \tag{20}$$

$$\frac{d^2\phi_0}{d^2z}+\mathrm{Sc}\frac{d\phi_0}{dz}=0 \tag{21}$$

$$\frac{d^2\phi_1}{dz^2}+\mathrm{Sc}\frac{d\phi_1}{dz}-n\mathrm{Sc}\theta_1=-A\mathrm{Sc}\frac{d\theta_0}{dz} \tag{22}$$

The corresponding boundary conditions can be written as

$$q_0=u_p,q_1=0,\theta_0=1,\theta_1=1,\phi_0=1,\phi_1=1 \quad \text{at} \quad z=0 \tag{23}$$

$$q_0=1,\ q_1=1,\ \theta_0\to0,\ \theta_1\to0,\phi_0\to0,\ \phi_1\to0 \quad \text{at} \quad z\to\infty \tag{24}$$

Without going into detail, the solution of equation (17)-(22) subject to conditions (23) and (24) can be show to be

$$\theta_0=e^{-m_1z} \tag{25}$$

$$\theta_1=a_2e^{-m_3z}+a_1e^{-m_1z} \tag{26}$$

$$\phi_0=e^{-n_1z} \tag{27}$$

$$\phi_1=b_2e^{-n_3z}+b_1e^{-n_1z} \tag{28}$$

Equations (24) an (25) are third degree order differential equations when $\beta\neq0$ and we have two boundary conditions so we follows bears and Walter's as $q_0=q_{01}+\beta q_{02}+\mathrm{O}\left(\beta^2\right)$ (29)

$$q_1=q_{11}+\beta q_{12}+\mathrm{O}\left(\beta^2\right) \tag{30}$$

Substituting equations (29) and (30) into (17) and (18), equating different powers of β and neglecting higher order powers of β are,

$$\frac{d^2q_{01}}{dz^2}+\frac{dq_{01}}{dz}-\left(M^2+\frac{1}{K}\right)q_{01}=-\mathrm{Gr}e^{-m_1z}-\mathrm{Gm}e^{-n_1z}-\left(M^2+\frac{1}{K}\right) \tag{31}$$

$$\frac{d^3q_{01}}{\partial z^3}+\frac{d^2q_{02}}{dz^2}+\frac{dq_{02}}{dz}-\left(\frac{M^2}{1+m^2}+\frac{1}{K}\right)q_{02}=0 \tag{32}$$

$$\frac{d^2q_{11}}{dz^2}+\frac{dq_{11}}{dz}-\left(n+\left(M^2+\frac{1}{K}\right)\right)q_{11}=-n-\mathrm{Gr}\left(a_1e^{-m_1z}+a_2e^{-m_3z}\right)$$

$$-\mathrm{Gm}\left(b_1 e^{-n_1 z}+b_2 e^{-n_3 z}\right)-\left(M^2+\frac{1}{K}\right)-A\frac{dq_{01}}{dz} \quad (33)$$

$$\frac{d^3 q_{11}}{dz^3}+\frac{d^2 q_{12}}{dz^2}-n\frac{d^2 q_{11}}{dz^2}+\frac{dq_{12}}{dz}-\left(n+\left(M^2+\frac{1}{K}\right)\right)q_{12}=-A\frac{d^3 q_{01}}{dz^3}-A\frac{dq_{02}}{dz} \quad (34)$$

The corresponding boundary conditions are

$$q_{01}=u_p, q_{02}=0, q_{11}=0, q_{12}=0 \quad \text{at} \quad z=0$$

$$q_{01}=1, q_{02}=0, q_{11}=1, q_{12}=0, \quad \text{as} \quad z\to\infty \quad (35)$$

Solving the equations (30) – (34) using boundary conditions (35), it is acquired the solutions of the zeroth order and first order as,

$$q_{01}=a_4 e^{-m_6 z}+a_3 e^{-m_1 z}+b_4 e^{-m_6 z}+b_3 e^{-n_1 z}+1 \quad (36)$$

$$q_{02}=a_7 e^{-m_8 z}+a_5 e^{-m_6 z}+b_7 e^{-m_8 z}+b_5 e^{-m_6 z}+a_6 e^{-m_1 z}+b_6 e^{-n_1 z} \quad (37)$$

$$q_{11}=-a_{16} e^{-m_{10} z}+a_9 e^{-m_3 z}+a_{15} e^{-m_1 z}+b_5 e^{-n_3 z}+b_{10} e^{-n_1 z}+a_{12} e^{-m_6 z}+a_{14} \quad (38)$$

$$q_{12}=-a_{27} e^{-m_{12} z}+a_{22} e^{-m_6 z}+a_{23} e^{-m_1 z}+a_{24} e^{-m_8 z}+a_{25} e^{-m_{10} z}+a_{26} e^{-m_3 z} \quad (39)$$

In view of the above solutions, the velocity and temperature distributions in the boundary layer become

$$q(z,t)=q_0(z)+\varepsilon e^{nt} q_1(z)$$

$$=\left[\left(a_4 e^{-m_6 z}+a_3 e^{-m_1 z}+b_4 e^{-m_6 z}+b_3 e^{-n_1 z}+1\right)+\right.$$

$$\beta\left(a_7 e^{-m_8 z}+a_5 e^{-m_6 z}+b_7 e^{-m_8 z}+b_5 e^{-m_6 z}+a_6 e^{-m_1 z}+b_6 e^{-n_1 z}\right)$$

$$+\varepsilon e^{nt}\left[\left(-a_{16} e^{-m_{10} z}+a_9 e^{-m_3 z}+a_{15} e^{-m_1 z}+b_8 e^{-n_3 z}+b_{12} e^{-n_1 z}+a_{12} e^{-m_6 z}+a_{14}\right)\right.$$

$$\left.+\beta\left(-a_{27} e^{-m_{12} z}+a_{22} e^{-m_6 z}+a_{23} e^{-m_1 z}+b_{16} e^{-n_1 z}+a_{24} e^{-m_8 z}+a_{25} e^{-m_{10} z}+a_{26} e^{-m_3 z}+b_{17} e^{-n_3 z}\right)\right] \quad (40)$$

$$\theta(z,t)=\theta_0(z)+\varepsilon e^{nt}\theta_1(z)=e^{-m_1 z}+\varepsilon e^{nt}\left(a_2 e^{-m_3 z}+a_1 e^{-m_1 z}\right) \quad (41)$$

$$\phi(z,t)=\phi_0(z)+\varepsilon e^{nt}\phi_1(z)=e^{-n_1 z}+\varepsilon e^{nt}\left(b_2 e^{-n_3 z}+b_1 e^{-n_1 z}\right) \quad (42)$$

The co-efficient of skin friction, Nusselt number and Sherwood number are important physical parameters for this type of boundary layer flow. These parameters can be defined and determined as follows.

$$\tau=\left(\frac{\partial q}{\partial z}\right)_{z=0}=\left(a_{28}+\beta a_{29}\right)+\varepsilon e^{nt}\left(a_{30}+\beta a_{31}\right) \quad (43)$$

$$Nu=\left(\frac{\partial\theta}{\partial z}\right)_{z=0}=a_{32}+\varepsilon e^{nt}\left(a_{33}\right) \quad (44)$$

$$Sh=\left(\frac{\partial\phi}{\partial z}\right)_{z=0}=a_{33}+\varepsilon e^{nt}\left(a_{35}\right) \quad (45)$$

3. Results and Discussion

The unsteady MHD convective flow of an incompressible viscous electrically conducting flow of Rivlin–Ericksen fluid past a semi-infinite perpendicular porous moving plate taking heat absorption into account has been discussed. For the computational purpose, it is fixed $\varepsilon=0.01$, $n=0.5$, $A=0.5$, $\beta=0.01$, $M=0.5$, $K=0.5$, $\Pr=0.71$, $\mathrm{Gr}=5$, $\mathrm{Gm}=3$, and $Q=0.5$ and the profiles are drawn varied over the range. In ordered to acquire physical insight into this research problem, the consequences of various parameters meet in the governing equation are analyzed on velocity, temperature and concentration distributions with the aid of graphical profiles 2-13. It is also discussed the consequences of the physical constraints on coefficients of skin friction, Nusselt number and Sherwood numbers are declared in the tables 1-3.

We noticed that, the resultant velocity reduces with increasing the intensity of the magnetic field or Hartmann number M (Figs. 2). It is obvious that the effect of increasing values of the magnetic field parameter results in a decreasing resultant velocity across the boundary layer due to Larentz force.

Figs. 3 depicts the effect of permeability of the porous medium parameter K on resultant velocity distribution profiles and it is obvious that as permeability parameter increases, the resultant velocity increases along the boundary layer thickness which is expected since when the holes of porous medium become larger, the resistive of the medium may be neglected.

Figs. 4 illustrate the variation in resultant velocity with span wise coordinate z for several values of β. We observed that, the resultant velocity decreases with increasing visco-elastic fluid parameter of the Rivlin-Ericksen fluid across the boundary layer.

Figs. 5-6 illustrate the resultant velocity profiles for different values of the thermal Grashof number Gr and mass Grashof number Gm. It can be seen that an increase in Gr and/or Gm leads to a rise in resultant velocity profiles.

We noticed that from the Figs. 6, the magnitude of the resultant velocity reduces with increasing Suction parameter A throughout the fluid region.

Fig. 8 shows the resultant velocity profiles for different values of dimensionless heat absorption coefficient Q. Clearly as Q increase the pack values of resultant velocity tends to decrease. That is, the resultant velocity reduces with increasing heat absorption coefficient Q, physically the presence of heat absorption coefficient has the tendency to reduce the fluid temperature. This causes the thermal buoyancy effects to decrease resulting in a net reduction in the fluid velocity.

We noticed that from the Figs. 9-11, the temperature reduces with increasing suction velocity A or Prandtl number Pr or heat absorption coefficient Q. The result display that an increase in the value of Q results in decrease in the temperature profiles as expected. The numerical results show that the effect of increase Q results in an decrease thermal boundary layer thickness and more uniform temperature distribution across the boundary layer.

We noticed from the Figs. 12-13, the concentration reduces with increasing in suction velocity A or Schmidt number Sc. The numerical results show that, the effect of increase value of Sc results in an decrease concentration boundary layer thickness and more uniform concentration distribution across the boundary layer.

We have also shown Table 1 of the surface skin friction coefficient against some parameters. The skin friction values are reduces with increasing the intensity of the magnetic field M, Schmidt number Sc or the suction velocity A. The reversal behaviour is observed throughout the region with increasing thermal Grashof number Gr, mass Grashof number Gm or heat absorption coefficient Q or scalar constant ε, because an increase in Gr and /or Gm influences the buoyancy that results in skin friction. The skin friction enhances with increasing permeability parameter K, where as skin friction decreases with increasing visco-elastic fluid parameter or Prandtl number Pr or frequency of oscillation n.

The rate of heat transfer Nu is shown in the Table 2 with reference to all governing parameters. The magnitude of the Nusselt number rise up throughout the fluid region with increasing scalar constant ε, suction velocity A, Prandtl number Pr, heat absorption parameter Q and the frequency of oscillation n.

The rate of mass transfer (Sh) is shown in the Table (3). The magnitude of the Sherwood number enhances throughout the fluid region with increasing scalar constant ε, suction velocity A, Schmidt number Sc, and the frequency of oscillation n.

The outcomes are attained with best agreement by the outcomes of Kumar et al. [35] in the absence of mass transfer.

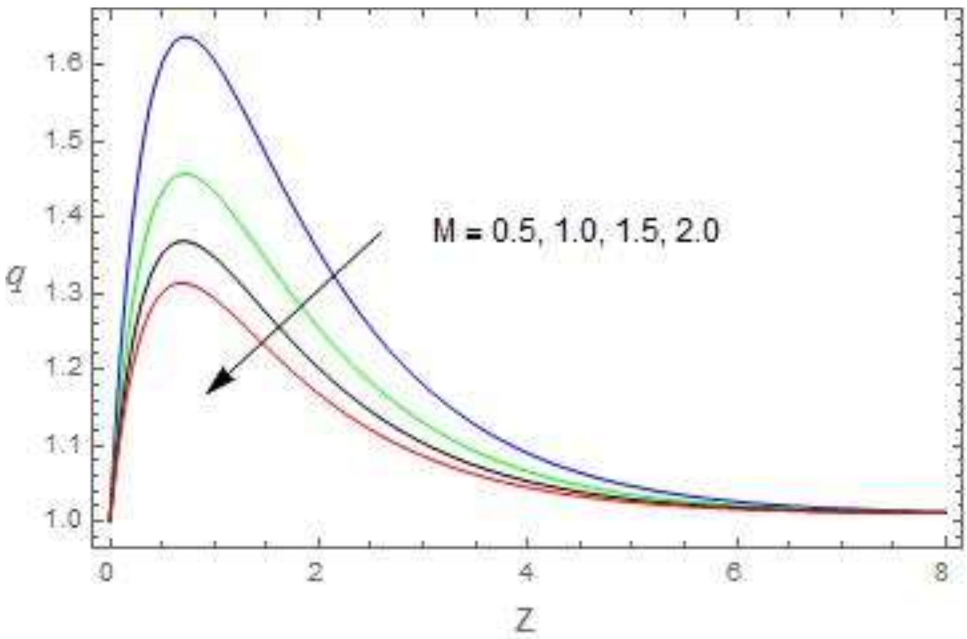

Fig 2. The velocity profiles for q against M

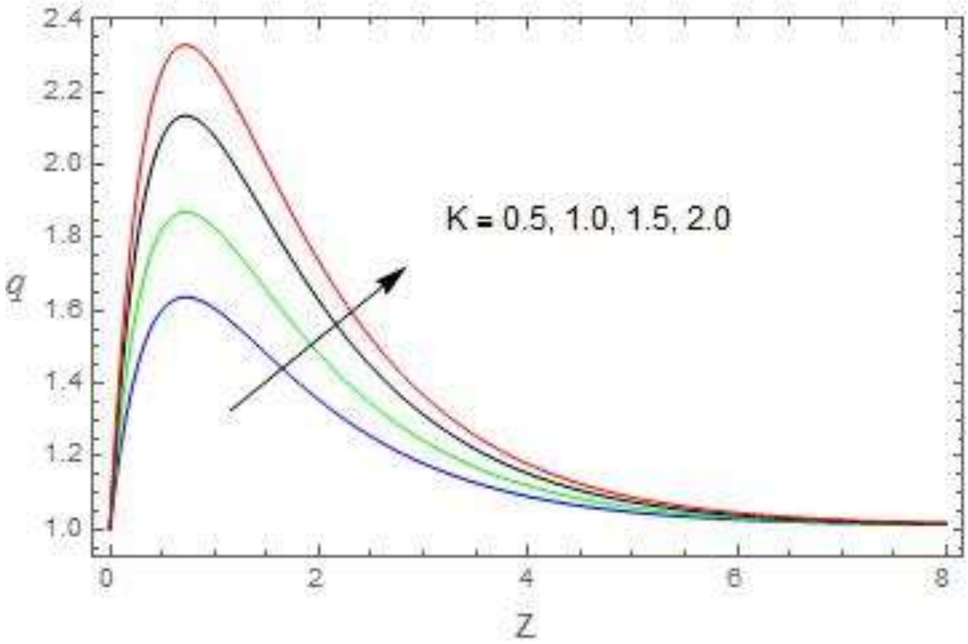

Fig 3. The velocity profiles for q against K

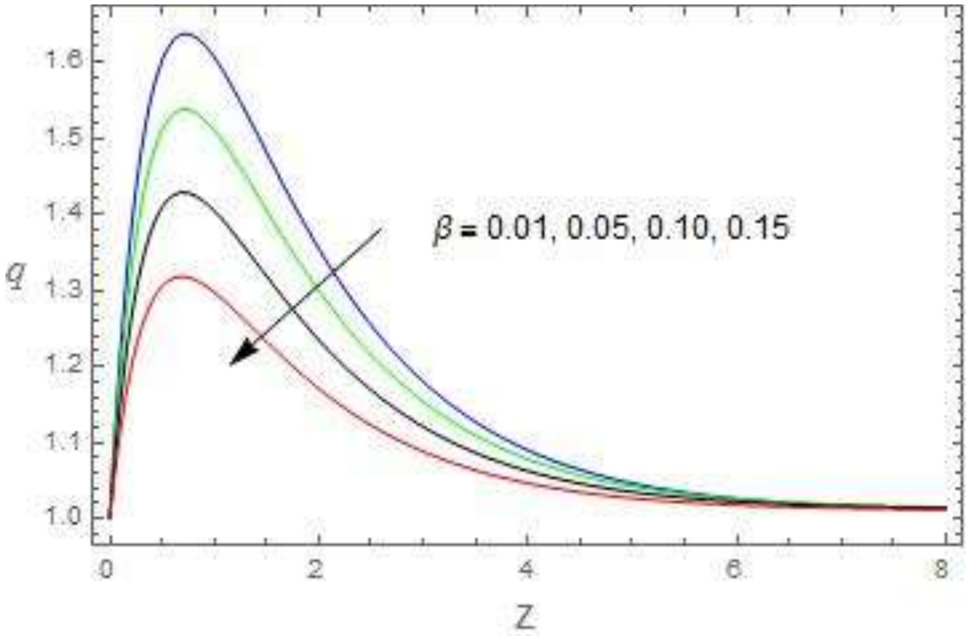

Fig 4. The velocity profiles for q against β

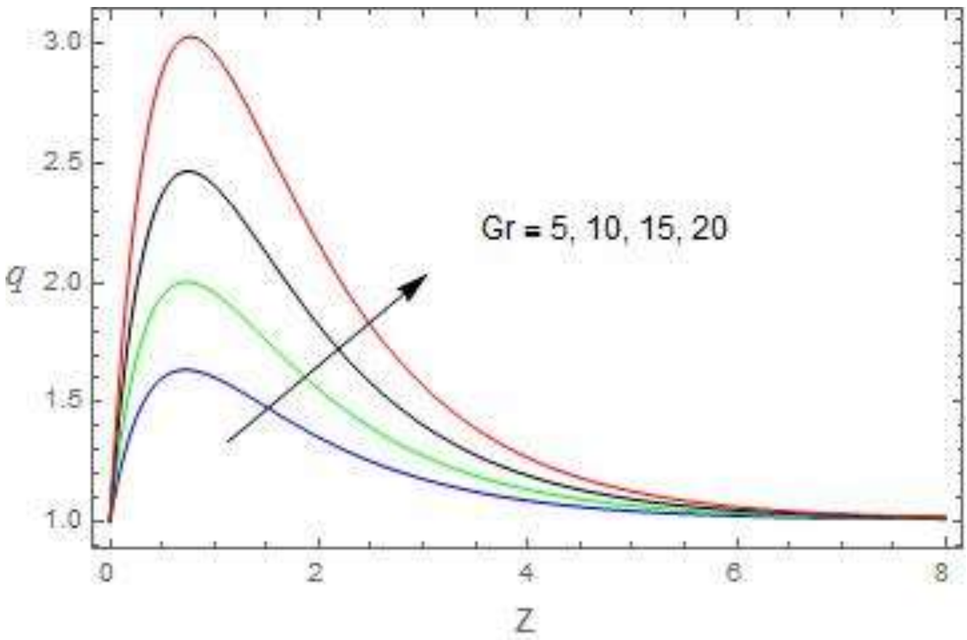

Fig 5. The velocity profiles for q against Gr

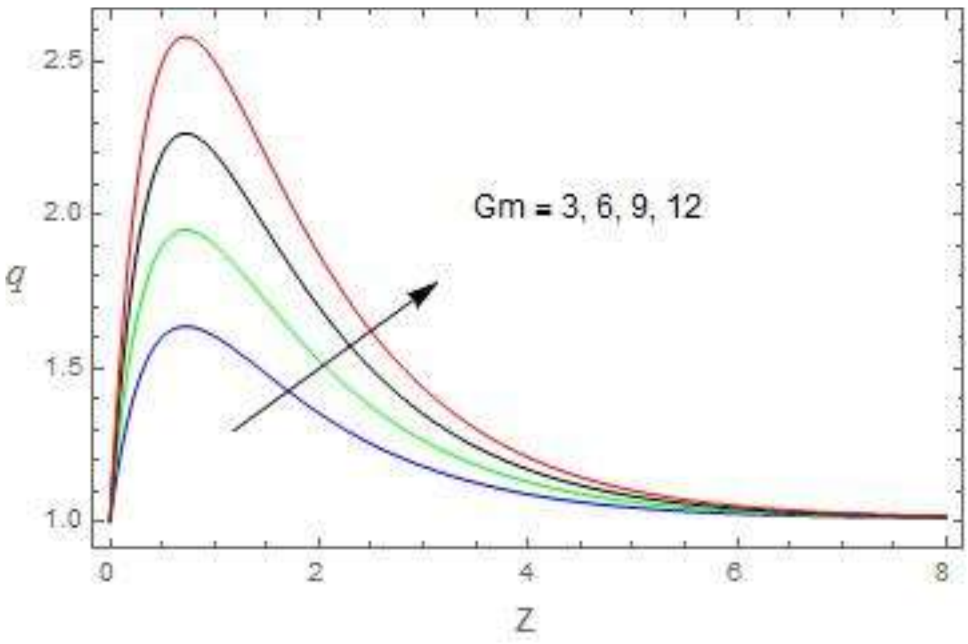

Fig 6. The velocity Profiles for *q* against Gm

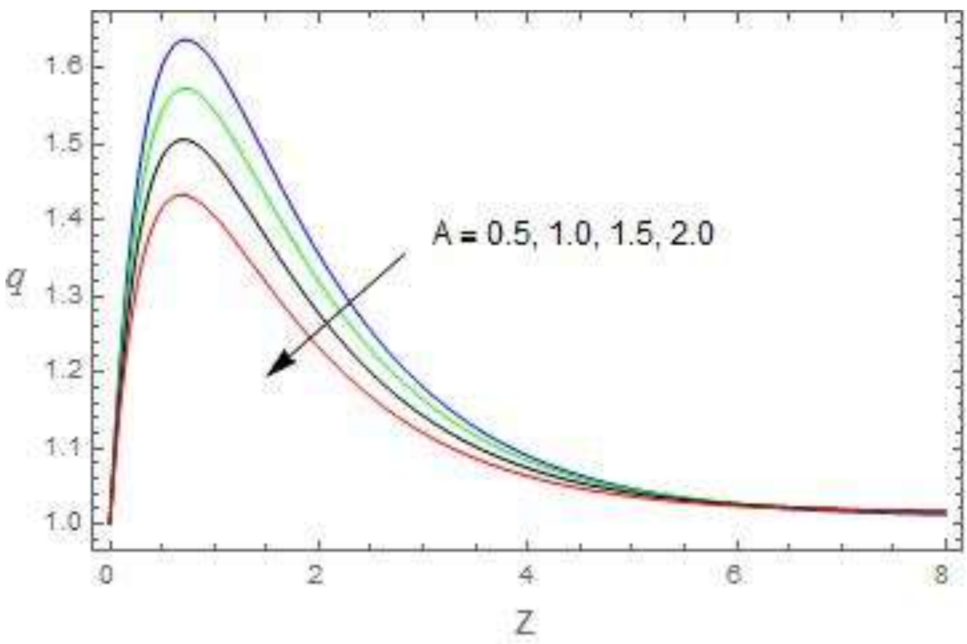

Fig 7. The velocity profiles for *q* against *A*

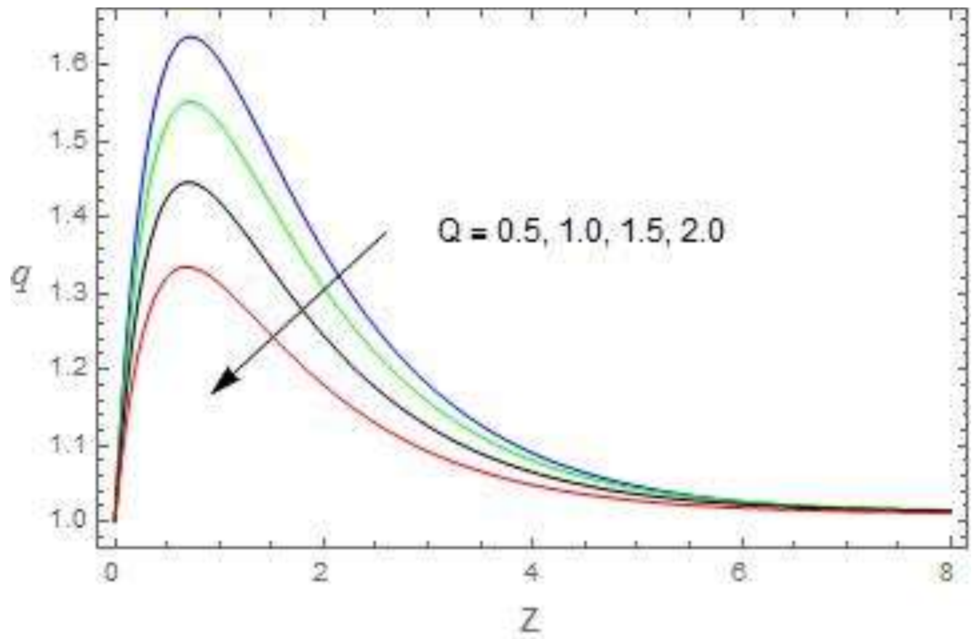

Fig 8. The velocity profiles for u and v against Q

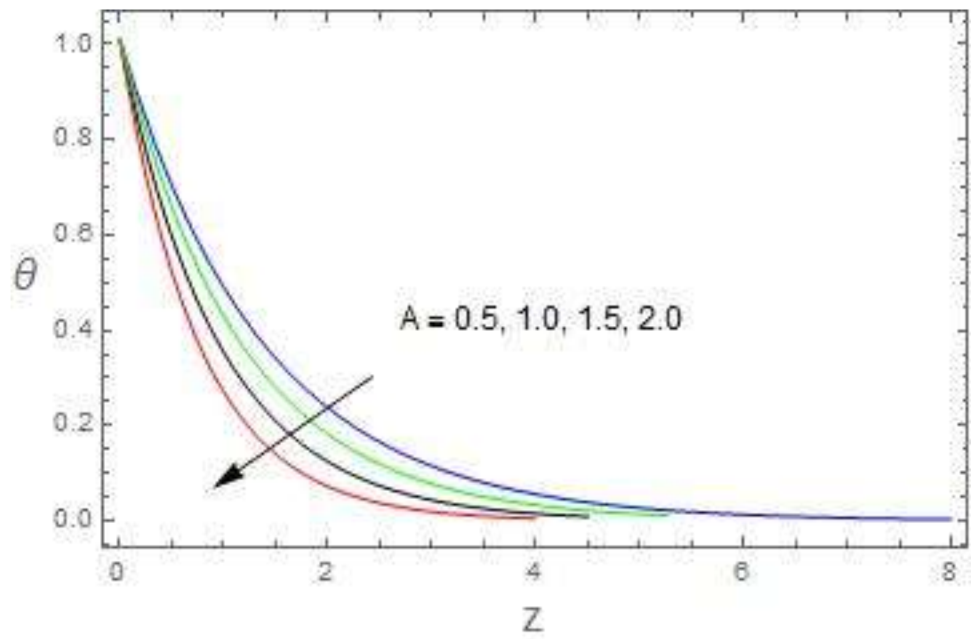

Fig 9. Temperature profiles for θ against A

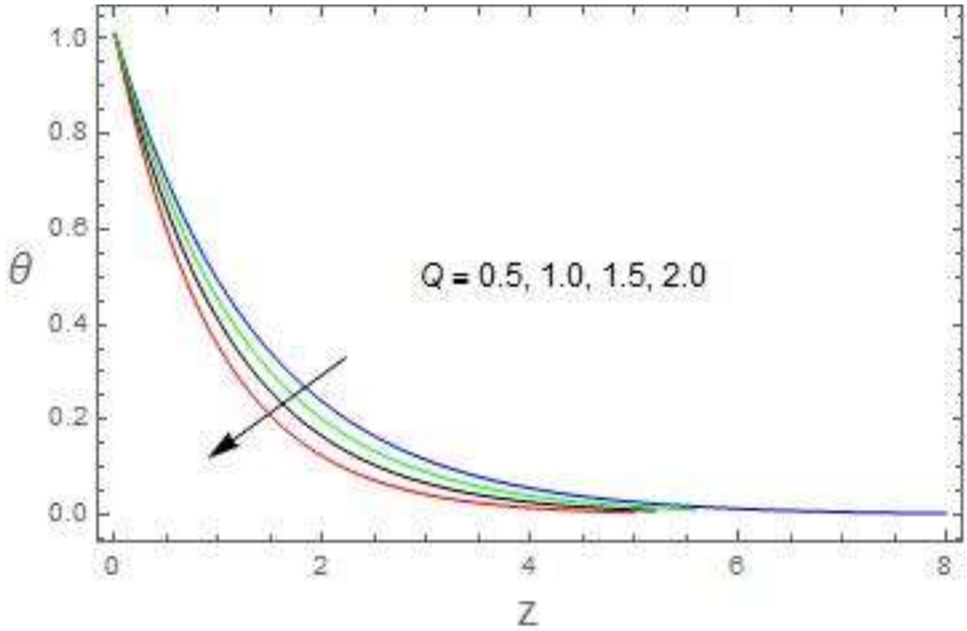

Fig 10. Temperature profiles for θ against Q

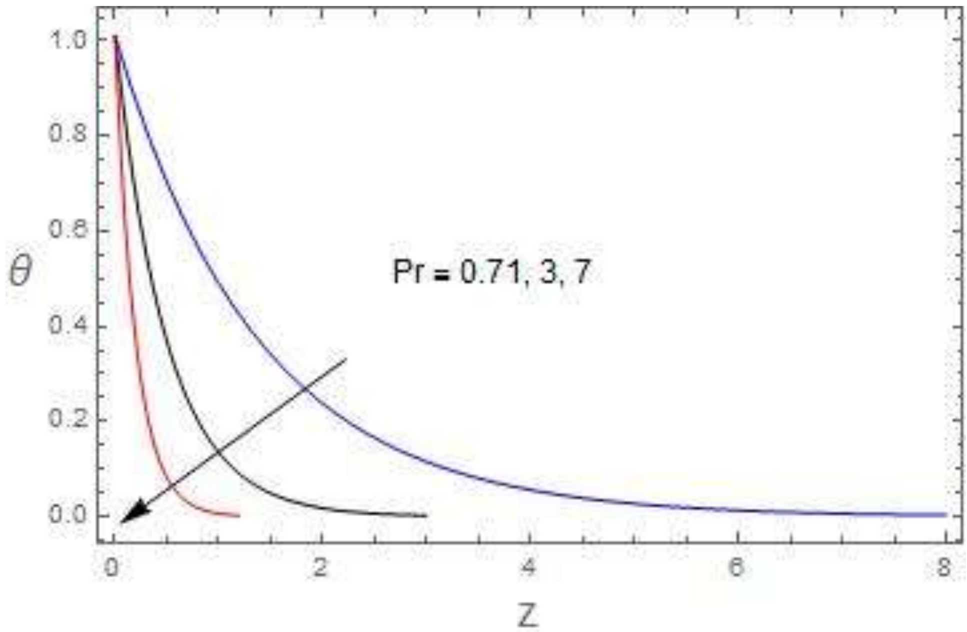

Fig 11. Temperature profiles for θ against Pr

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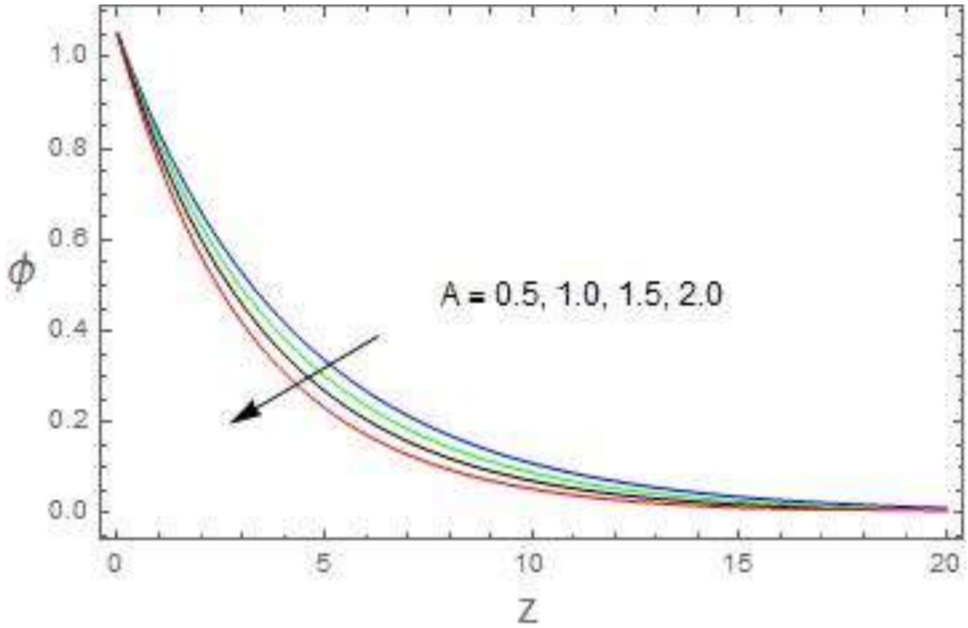

Fig 12. Concentration profile for ϕ against A

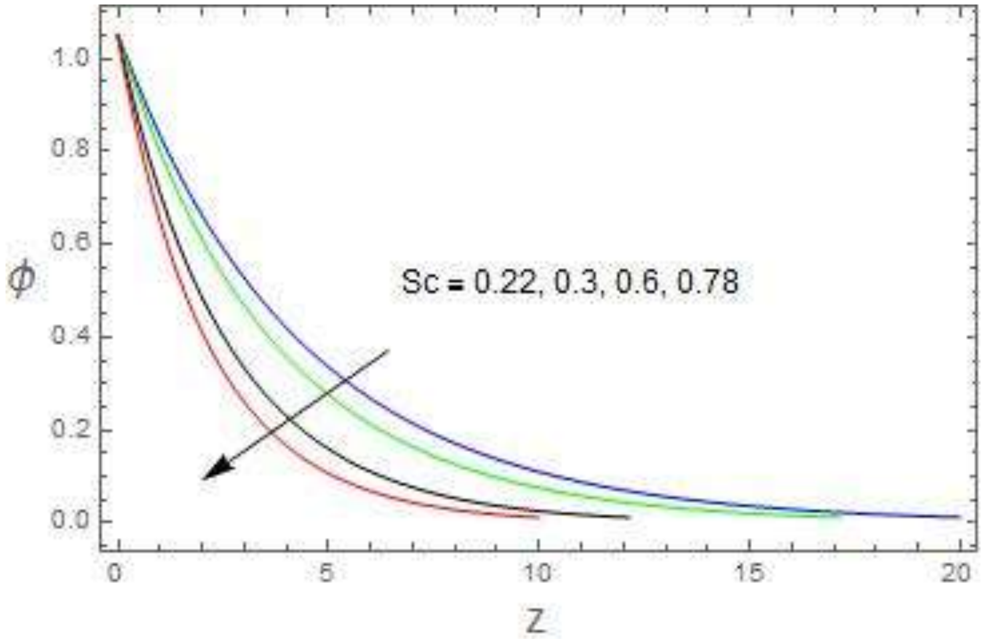

Fig 13. Concentration profiles for ϕ against Sc

Table 1: Skin friction coefficient ($\varepsilon = 0.001,\ n = 0.5,\ \mathrm{Sc} = 0.22,\ \mathrm{Pr} = 0.71$)

M	***K***	**Gr**	Gm	β	***A***	***Q***	τ
0.5	0.5	5	3	0.01	0.5	0.1	3.858564552145
1							2.911012254125
2							2.094158022410
	1						5.178119658998
	1.5						7.164104785112
		10					5.141103256908
		15					6.417441124542
			6				4.336589966589
			9				5.336988952010

				0.03			3.825811223245
				0.05			3.787814458779
					1		3.878450012547
					1.5		3.778419655896
						0.3	5.380200025652
						0.5	9.178151254663

Table 2: Nusselt number (Nu)

ε	***A***	**Pr**	***Q***	***n***	Nu
0.01	0.5	0.71	0.01	0.5	-0.733466022144
0.03					-0.760672125441
0.05					-0.787877023325
	1				-0.735992415528
	1.5				-0.738518445879
		3			-3.059900001455
		7			-7.123040100254
			0.03		-0.752536456636
			0.05		-0.770710225214
				1	-0.736135669859
				1.5	-0.738739002101

Table 3: Sherwood number (Sh)

ε	*A*	Sc	*n*	Sh
0.01	0.5	0.22	0.5	-0.225384221445
0.03				-0.236151445287
0.05				-0.246918996859
	1			-0.225937312232
	1.5			-0.226491001002
		0.3		-0.306780478545
		0.6		-0.611766998554
			1	-0.226992456622
			1.5	-0.228478887496

Table 4: Results comparison for the primary velocity
($\varepsilon = 0.001,\ n = 0.5,\ \mathrm{Sc} = 0,\ \mathrm{Gm} = 0,\ \mathrm{Pr} = 0.71$)

M	*K*	*Q*	Gr	Previous results Kumar et al.[35]	Present results
0.5	0.5	0.5	5	1.655214552145	1.655214550202
1.0				1.552554785528	1.552554785665
2.0				1.458879002145	1.458879003022
	1.0			1.899574885021	1.899574885622
	1.5			2.445879632210	2.445879632322
		1.0		1.366589587499	1.366589587669
		2.0		1.102254856243	1.102254856528
			10	2.135658799954	2.135658802254
			15	2.855112963369	2.855112964102

4. Conclusion

The unsteady MHD convective flow of an incompressible viscous electrically conducting flow of Rivlin–Ericksen fluid past a semi-infinite perpendicular porous moving plate taking heat absorption into account has been discussed. The conclusions are made as the following.

1. When permeability parameter increase the velocity increase, whereas when visco-elasticity parameter of the Rivlin–Ericksen fluid and heat absorption coefficient, increase the velocity decreases.
2. The resultant velocity reduces with increasing Hartmann number M and enhances with increasing thermal Grashof number.
3. Heat absorption coefficient Q increase results a decrease in temperature distribution.
4. The concentration distribution is reduced with increase in Schmidt number and suction parameter.
5. For better understanding of the thermal and concentration behavior of this work, however, it may be necessary to perform the experimental works.

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6. Funding/Conflicts of Interest

[Author to provide: funding source(s) for this research, and a statement of any conflicts of interest, or a declaration that none exist.]

7. Author Contribution

[Author to provide: a statement of each author's contribution to the manuscript, e.g. conceptualization, methodology, formal analysis, writing, supervision.]

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Appendix:

$$m_1=\frac{\mathrm{Pr}+\sqrt{\mathrm{Pr}+4\mathrm{Pr}Q}}{2},\ m_2=\frac{-\mathrm{Pr}+\sqrt{\mathrm{Pr}+4\mathrm{Pr}Q}}{2}$$

$$m_3=\frac{\mathrm{Pr}+\sqrt{\mathrm{Pr}^2+4\mathrm{Pr}(Q+n)}}{2},\ m_4=\frac{-\mathrm{Pr}+\sqrt{\mathrm{Pr}^2+4\mathrm{Pr}(Q+n)}}{2},$$

$$n_1=\frac{\mathrm{Sc}+\sqrt{\mathrm{Sc}}}{2},\ n_2=\frac{-\mathrm{Sc}+\sqrt{\mathrm{Sc}}}{2},\ n_3=\frac{\mathrm{Sc}+\sqrt{\mathrm{Sc}^2+4\mathrm{Sc}n}}{2},\ n_4=\frac{-\mathrm{Sc}+\sqrt{\mathrm{Sc}^2+4\mathrm{Sc}n}}{2},$$

$$m_5=\frac{-1+\sqrt{1+4\left(M^2+\frac{1}{K}\right)}}{2},m_6=\frac{1+\sqrt{1+4\left(M^2+\frac{1}{K}\right)}}{2},\ m_7=\frac{-1+\sqrt{1+4\left(M^2+\frac{1}{K}\right)}}{2},$$

$$m_8=\frac{1+\sqrt{1+4\left(M^2+\frac{1}{K}\right)}}{2},\ m_9=\frac{-1+\sqrt{1+4\left(\left(M^2+\frac{1}{K}\right)+n\right)}}{2}$$

$$m_{10}=\frac{1+\sqrt{1+4\left(\left(M^2+\frac{1}{K}\right)+n\right)}}{2},m_{11}=\frac{-1+\sqrt{1+4\left(\left(M^2+\frac{1}{K}\right)+n\right)}}{2},$$

$$m_{12}=\frac{1+\sqrt{1+4\left(\left(M^2+\frac{1}{K}\right)+n\right)}}{2}$$

$$a_1=\frac{Am_1\mathrm{Pr}}{m_1^2+m_1\mathrm{Pr}-\mathrm{Pr}(n+Q)},\ a_2=1-a_1,a_3=-\frac{\mathrm{Gr}}{m_1^2-m_1-\left(M^2+\frac{1}{K}\right)},\ a_4=u_p-a_3-1$$

$$b_1=\frac{An_1\mathrm{Sc}}{n_1^2+n_1\mathrm{Sc}-n\mathrm{Sc}},b_2=1-b_1,\ b_3=-\frac{\mathrm{Gm}}{n_1^2-n_1-\left(M^2+\frac{1}{K}\right)},\ b_4=u_p-b_3-1$$

$$a_5=-\frac{m_6^3a_4}{m_6^2-m_6-\left(M^2+\frac{1}{K}\right)},\ a_6=-\frac{m_1^3a_3}{m_1^2-m_1-\left(M^2+\frac{1}{K}\right)},\ ,$$

$$b_5=-\frac{m_6^3b_4}{m_6^2-m_6-\left(M^2+\frac{1}{K}\right)},\ b_6=-\frac{n_1^3b_3}{n_1^2-n_1-\left(M^2+\frac{1}{K}\right)},\ b_7=-b_5-b_6,$$

$$a_7 = -a_5 - a_6,\ a_8 = \frac{n}{\left(M^2 + \frac{1}{K}\right) + n}$$

$$a_9 = -\frac{\mathrm{Gr}\, a_2}{m_3^2 - m_3 - \left(\left(M^2 + \frac{1}{K}\right) + n\right)},\ a_{10} = -\frac{\mathrm{Gr}\, a_1}{m_1^2 - m_1 - \left(\left(M^2 + \frac{1}{K}\right) + n\right)},$$

$$b_8 = -\frac{\mathrm{Gm}\, b_2}{n_3^2 - n_3 - \left(\left(M^2 + \frac{1}{K}\right) + n\right)},\ b_9 = -\frac{\mathrm{Gm}\, b_1}{n_1^2 - n_1 - \left(\left(M^2 + \frac{1}{K}\right) + n\right)}$$

$$a_{11} = \frac{\left(M^2 + \frac{1}{K}\right)}{\left(M^2 + \frac{1}{K}\right) + n},\ a_{12} = \frac{Am_6 a_4}{m_6^2 - m_6 - \left(\left(M^2 + \frac{1}{K}\right) + n\right)},\ a_{13} = -\frac{Am_1 a_3}{m_1^2 - m_1 - \left(\left(M^2 + \frac{1}{K}\right) + n\right)}$$

$$b_{10} = \frac{Am_6 b_4}{m_6^2 - m_6 - \left(\left(M^2 + \frac{1}{K}\right) + n\right)},\ b_{11} = -\frac{An_1 b_3}{n_1^2 - n_1 - \left(\left(M^2 + \frac{1}{K}\right) + n\right)}$$

$$b_{12} = b_9 + b_{11},$$

$$a_{14} = a_8 + a_{11},\ a_{15} = a_{10} + a_{13},\ a_{16} = a_9 + a_{12} + a_{14} + a_{15}$$

$$a_{17} = Am_6^3 a_4 + Am_6 a_5 + m_6^3 a_{12} + nm_6^2 a_{12},$$

$$a_{18} = Am_1^3 a_3 + Am_1 a_6 + m_1^3 a_{15} + nm_1^2 a_{15}$$

$$b_{13} = An_1^3 b_3 + An_1 b_6 + n_1^3 b_{12} + nm_1^2 b_{12}$$

$$a_{19} = Am_8 a_7,\ a_{20} = -m_{10}^3 a_{16} - nm_{10}^2 a_{16}$$

$$b_{14} = Am_8 b_7$$

$$b_{15} = n_3^3 b_8 + nn_3^2 b_8,$$

$$a_{21} = m_3^3 a_9 + nm_3^2 a_9,$$

$$a_{22} = \frac{a_{17}}{m_6^2 - m_6 - \left(\left(M^2 + \frac{1}{K}\right) + n\right)},\ a_{23} = \frac{a_{18}}{m_1^2 - m_1 - \left(\left(M^2 + \frac{1}{K}\right) + n\right)}$$

$$b_{16} = \frac{b_{13}}{n_1^2 - n_1 - \left(\left(M^2 + \frac{1}{K}\right) + n\right)},\ b_{17} = \frac{b_{15}}{n_3^2 - n_3 - \left(\left(M^2 + \frac{1}{K}\right) + n\right)}$$

$$a_{24} = \frac{a_{19}}{m_8^2 - m_8 - \left(\left(M^2 + \frac{1}{K}\right) + n\right)},\ a_{25} = \frac{a_{20}}{m_{10}^2 - m_{10} - \left(\left(M^2 + \frac{1}{K}\right) + n\right)},$$

$$a_{26} = \frac{a_{21}}{m_3^2 - m_3 - \left(\left(M^2 + \frac{1}{K}\right) + n\right)}$$

$$a_{27} = a_{22} + a_{23} + a_{24} + a_{25} + a_{26},\ a_{28} = -m_6 a_4 - m_1 a_3 - m_6 b_4 - n_1 b_3$$

$a_{29} = -m_8 a_7 - m_6 a_5 - m_8 b_7 - m_6 b_5 - m_1 a_6 - n_1 b_6,$

$a_{30} = a_{16} m_{10} - m_3 a_9 - m_1 a_{15} - n_3 b_5 - n_1 b_{10} - m_6 a_{12},$

$a_{31} = m_{12} a_{27} - m_6 a_{22} - m_1 a_{23} - n_1 b_{16} - m_8 a_{24} - m_{10} a_{25} - m_3 a_{26} - n_3 b_{17}$

$a_{32} = -m_1,\ a_{33} = -m_3 a_2 - m_1 a_1$

$a_{34} = -n_1,\ a_{35} = -n_3 b_2 - n_1 b_1$

Nomenclature:

u, v Components of velocities along the x and z directions respectively
x, z Distances along and perpendicular to the plate, respectively
w_0 Scale of suction velocity
A suction velocity parameter
B_0 magnetic induction
C_p specific heat at constant pressure
Gr thermal Grashof number
Gm mass Grashof number
g acceleration due to gravity
k permeability of the porous medium
K permeability parameter
M magnetic field parameter
Pr Prandtl number
n dimensionless exponential index
Q_0 heat absorption coefficient
Nu Nusselt number
T temperature
C concentration
t dimensionless time
u_0 scale of free steam velocity
Q heat absorption parameter
β visco-elasticity parameter
u_p constant plate moving velocity

Greek symbol

α fluid thermal diffusivity
β_T coefficient of volumetric expansion of the working fluid
β_C coefficient of volumetric expansion of the working fluid
β_1 kinematic viscoelasticity
ε scalar constant
τ skin-friction coefficient
z dimensionless normal distance
σ electrical conductivity
ρ fluid dencity
μ fluid dynamic viscocity
ν fluid kinematic viscocity
τ Friction coefficient
θ Dimensionless temperature

ϕ Dimensionless concentration

Subscripts

p plate
w wall condition
∞ free steam condition