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# Influence of Viscoelastic Rivlin-Ericksen Fluid On Free Convective Flow Past A Vertical Plate Filled In Porous Medium In Presence of Transverse Magnetic Field And Double Diffusion Effects

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**Abstract:** *The aim of this work is to study the combined effects of transverse magnetic field and double diffusion on unsteady boundary-layer flow of a viscous, incompressible, electrically conducting and two-dimensional heat-absorbing viscoelastic fluid flow past a semi-infinite vertical permeable plate in presence of free convection. The Rivlin-Ericksen model is employed to simulate the rheological liquids encountered in cooling of electronic devices, polymer solutions, hydrocarbons and chemical engineering processes. The plate is assumed to move with a constant velocity in the direction of fluid flow while the free stream velocity is assumed to follow the exponentially increasing small perturbation law. Time-dependent wall suction is assumed to occur at the permeable surface. The transport equations employed in the flow are governed by a coupled non-linear system of partial differential equations and include the engineering parameters. However, the exact solution is not possible for this set of partial differential equations and hence these equations solved by finite difference method. Numerical evaluation of the numerical results is performed and some graphical results for the velocity, temperature and concentration profiles within the boundary layer are discussed. Skin-friction coefficient, Nusselt numbers are also discussed with the help of numerical values presented in tabular forms. Limiting case results are obtained for the non-Newtonian fluid and compared with the literature.*

**Keywords:** *Viscoelastic Rivlin-Ericksen Fluid; Free Convection; Porous Medium; Double Diffusion; Magnetic Field; Finite Difference Method;*

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***Nomenclature:***

**List of Variables:**

| | |
|---|---|
| $O$ | Origin |
| $M$ | Hartmann number |
| $C'$ | Concentration of fluid near the plate ( $mol\ \ m^{-3}$ ) |
| $D$ | Chemical molecular diffusivity ( $m^2\ \ s^{-1}$ ) |
| $g$ | Acceleration of gravity, 9.81 ($m/s^2$) |
| $C_p$ | Specific heat at constant pressure (*J-K/Kg*) |
| $B_o$ | Magnetic field component along $y' -$ axis (*Tesla*) |
| $x', y'$ | Coordinate system (*m*) |
| $\mathrm{Re}_x$ | Reynold's number |
| $U_o$ | Reference velocity (*m/s*) |
| $\Pr$ | Prandtl number |
| $U_p$ | Plate Velocity (*m/s*) |
| $Nu$ | Nusselt number (or) Rate of heat transfer |
| $S$ | Heat absorption parameter |
| $Gc$ | Grashof number for mass transfer |
| $x, y$ | Dimensionless coordinates (*m*) |

| | |
|---|---|
| $Q_o$ | Dimensional Heat absorption parameter |
| $C'_\infty$ | Concentration of the fluid at infinity ( $mol\ \ m^{-3}$ ) |
| $u,\ v$ | Components of velocities along and perpendicular to the plate respectively, $x'-$direction (*m/s*) |
| $Gr$ | Grashof number for heat transfer |
| $C'_w$ | Concentration of the fluid far away of the fluid from the plate ( $mol\ \ m^{-3}$ ) |
| $Sc$ | Schmidt number |
| $Sh$ | Sherwood number (or) Rate of mass transfer |
| $V_o$ | Suction velocity (*m/s*) |
| $U_\infty$ | Free stream velocity (*m/s*) |
| $u'$ | Velocity component in $x'-$direction (*m/s*) |
| $t$ | Time (*second*) |
| $K$ | The permeability parameter ($m^2$) |
| $K'$ | The permeability of medium ($m^2$) |
| $T'_w$ | Temperature of the fluid far away of the fluid from the plate (*K*) |
| $T'_\infty$ | Temperature of the fluid at infinity (*K*) |
| $T'$ | Temperature of fluid near the plate (*K*) |
| $u'_p$ | Dimensional Plate Velocity (*m/s*) |
| $n'$ | Dimensional exponential index |
| $n$ | An exponential index |
| $y$ | Dimensionless coordinate (*m*) |

**Greek symbols**

| | |
|---|---|
| $\kappa$ | Thermal conductivity of the fluid (*W/mK*) |
| $\tau$ | Skin-friction ( $N/m^2$ ) |
| $nt$ | Phase angle (*degrees*) |
| $\theta$ | Non-dimensional temperature (*K*) |
| $\lambda$ | Viscoelastic fluid parameter |
| $\nu$ | Kinematic viscosity $\left(m^2 s^{-1}\right)$ |
| $\sigma$ | Electrical conductivity of the fluid $\left(\Omega^{-1} m^{-1}\right)$ |
| $\rho$ | Density of the fluid $\left(kg/m^{-3}\right)$ |
| $\phi$ | Concentration of the fluid ( $mol\ \ m^{-3}$ ) |
| $\beta^*$ | Coefficient of volume expansion for mass transfer ( $m^3\ \ Kg^{-1}$ ) |
| $\beta$ | Coefficient of volume expansion for heat transfer $\left(K^{-1}\right)$ |
| $\beta_1$ | Kinematic viscoelasticity |
| $\varepsilon$ | A positive constant |

**Superscripts**

| | |
|---|---|
| $/$ | Dimensionless properties |

**Subscripts**

| | |
|---|---|
| $w$ | Wall condition |
| $p$ | Plate |
| $\infty$ | Free stream condition |

## I. Introduction

The convection problem in a porous medium has important applications in geothermal reservoirs and geothermal extractions. The process of heat and mass transfer is encountered in aeronautics, fluid fuel nuclear rector, chemical process industries and many engineering applications in which the fluid is the working medium. The wide range of technological and industrial applications has stimulated considerable amount of interest in the study of heat and mass transfer in convection flows. MHD free convection flows occur frequently in nature. The applications of hydromagnetic incompressible viscous flow in science and engineering involving heat transfer under the influence of chemical reaction are of great importance to many areas of science and engineering. This frequently occurs in petro-chemical industry, power and cooling systems, chemical vapor deposition on surface, cooling of nuclear reactors, heat exchanger design, forest fire dynamics and geophysics as well as magneto-hydrodynamic power generation systems. Srinivasa Raju [1] studied unsteady MHD boundary layer flow of Casson fluid over an inclined surface embedded in a porous medium with thermal radiation and chemical reaction. Viscous dissipation impact on MHD free convection radiating fluid flow past a vertical porous plate discussed by Srinivasa Raju et al. [2]. Anand Rao et al. [3] studied MHD over a vertical plate in presence of free convection flow and hall current through EFGM solutions. Manideep et al. [4] studed MHD free convection heat transfer couette flow in rotating system. Unsteady MHD free convection flow of Casson fluid over an inclined vertical plate embedded in a porous media discussed by Manideep et al. [5]. Krishna Prasad et al. [6] studied the role of Casson fluid on MHD natural convective flow towards vertically inclined plate with hall current. Anand Rao et al. [7] studied jeffrey fluid effect on free convective over a vertically inclined plate with magnetic field. Thermal diffusion effect on MHD mixed convective flow along a vertically inclined plate: a Casson fluid flow discussed by Krishna Prasad et al. [8]. Srinivasa Raju and Ramesh [9] studied grid independence of finite element method on magnetohydrodynamic free convective casson fluid flow with slip effect. Thermal radiation influence on MHD flow of a rotating fluid with heat transfer through EFGM solutions studied by Krishna Prasad et al. [10]. Sailaja et al. [11] discussed finite element analysis of MHD Casson fluid flow past a vertical plate with the impact of angle of inclination. Analytical solutions of unsteady MHD convective heat and mass transfer past a semi-infinite vertical permeable plate with heat absorption studied by Chamkha [12]. Some of the authors ([13]-[67]) discussed convective fluid flows in presence of thermal diffusion, diffusion thermo, heat absorption, heat and mass transfer, porous medium, thermal radiation, chemical reaction, hall current, magnetic field towards a vertical plate and inclined plate using numerical results.

The Rivlin-Ericksen viscoelastic fluid has relevance and importance in geophysical fluid dynamics, chemical technology and industry. Sivaraj and Rushi Kumar [68] investigated chemically reacting dusty viscoelastic fluid flow in an irregular channel with convective boundary. Slip effects on MHD boundary layer flow over an exponentially stretching sheet with suction/blowing and thermal radiation were considered by Swati [69]. Mahgoub [70] investigated forced convection heat transfer over a flat plate in a porous medium. Effects of hall current and radiation absorption on MHD micropolar fluid in a rotating system were studied by Satya Narayana et al. [71]. Raju et al. [72] considered MHD convective flow through porous medium in a horizontal channel with insulated and impermeable bottom wall in the presence of viscous dissipation and Joule heating. Effects of variable suction and thermophoresis on steady MHD combined free-forced convective heat and mass transfer flow over a semi-infinite permeable inclined plat in the presence of thermal radiation were investigated by Alam et al. [73]. Seth et al. [74] considered, MHD natural convection flow with irradiative heat transfer past an impulsively moving plat with ramped wall temperature. Magnetic field effects on transient free convection flow through porous medium past an impulsively started vertical plate with fluctuating temperature and mass diffusion was studied by Ravikumar et al. [75]. Varshney et al. [76] discussed effects of rotator Rivlin-Ericksen fluid on MHD free convective and mass transfer flow through porous medium with constants heat and mass flux across moving plate. Uwanta et al. [77] discussed effects of mass transfer on hydromagnetic free convective Rivlin-Ericksen flow through a porous medium with time dependent suction. Gupta et al. [78] discussed on Rivlin-Ericksen elastico-viscous fluid heated and solution from below in the presence of compressibility, rotation and Hall currents. Sharma et al. [79] discussed hall effects on thermal instability of Rivlin-Ericksen fluid. Rana [80] discussed thermal instability of compressible Rivlin-Ericksen rotating fluid permeated with suspended dust particles in porous medium. Noushima et al. [81] discussed hydromagnetic free convective Rivlin-Ericksen flow through a porous medium with variable permeability. Daleep et al. [82] studied bounds for complex growth rate in thermosolutal convection in Rivlin-Ericksen viscoelastic fluid in a porous medium.

Motivated by the above studies, this paper is extended the study of Chamkha [12], by considering a well known non-Newtonian fluid namely Rivlin-Ericksen fluid for the case of a semi-infinite vertical plate in a porous medium in the presence of pressure gradient and constant velocity in the flow direction when the magnetic field is imposed transverse to the plate. The results obtained here are in good agreement with the results of Chamkha [12] in the absence of non-Newtonian fluid. This research article is arranged in the following ways: Section “Mathematical modeling” deals with the physical model of a non-newtonian fluid flow over a semi-infinite vertical plate with non-dimensionalization. The next section dealt with finite difference method to solve the flow-field partial differentail equations. In the Section comparison between third-grade and Newtonian fluids are explained . Further, “Results and discussion”, the velocity, temperature and concentration profiles, wall and heat and mass transfer rate coefficients are analyzed. Finally, in Section “Concluding remarks” the important observations are made.

## II. Mathematical Formulation

Consider unsteady two-dimensional flow of a laminar, incompressible, viscous, electrically conducting fluid past a semi-infinite vertical permeable plate embedded in a uniform porous medium and subjected to a uniform transverse magnetic field in the presence of viscoelastic Rivlin-Ericksen fluid. The flow geometry along with specified variables is shown in Fig. 1. For this investigation the following assumptions are made.

i. In cartesian coordinate system, let $x'-$ axis is taken to be along the plate and the $y'-$axis normal to the plate.

ii. Since the plate is considered infinite in $x'-$ direction, hence all physical quantities will be independent of $x'-$ direction.

iii. The wall is maintained at constant temperature $(T'_w)$ and concentration $(C'_w)$ higher than the ambient temperature $(T'_\infty)$ and concentration $(C'_\infty)$ respectively.

iv. A uniform magnetic field of magnitude $B_o$ is applied normal to the plate.

v. It is assumed that there is no applied voltage which implies the absence of an electrical field.

vi. The transversely applied magnetic field and magnetic Reynolds number are assumed to be very small so that the induced magnetic field and the Hall effect are negligible.

vii. Similarly, in this work, Soret and Dufour effects are also negligible.

viii. A consequence of the small magnetic Reynolds number is the uncoupling of the Navier-Stokes equations from Maxwell’s equations.

ix. The governing equations for this investigation are based on the balances of mass, linear momentum, energy and concentration species.

x. The magnetic and viscous dissipations are neglected in this study.

xi. It is assumed that the permeable plate moves with a constant velocity in the direction of fluid flow, and the free stream velocity follows the exponentially increasing.

xii. In addition, it is assumed that the temperature and the concentration at the wall as well as the suction velocity are exponentially varying with time.

xiii. The homogeneous chemical reaction of first order with rate constant $\overline{K}$ between the diffusing species is neglected.

xiv. The fluid has constant kinematic viscosity and constant thermal conductavity, and the Boussinesq's approximation have been adopted for the flow.

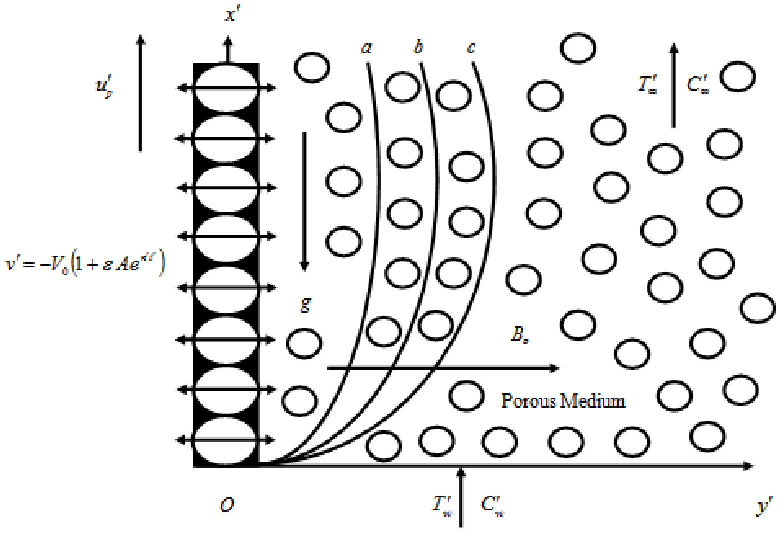


Fig. 1. Physical configuration of the problem

*a* --- Momentum boundary layer, *b* --- Thermal boundary layer, *c* --- Concentration boundary layer

Taking into consideration the assumptions made above, the flow equations can be written in Cartesian frame of reference as follows (Chamkha [12]):

*Equation of Continuity:*

$$\frac{\partial v'}{\partial y'} = 0 \tag{1}$$

*Momentum Equation:*

$$\frac{\partial u'}{\partial t'} + v'\frac{\partial u'}{\partial y'} = -\frac{1}{\rho}\frac{\partial p'}{\partial x'} + \nu\frac{\partial^2 u'}{\partial y'^2} + g\beta\left(T' - T'_\infty\right) + g\beta^*\left(C' - C'_\infty\right) - \beta_1\left[\frac{\partial^3 u'}{\partial t'\partial y'^2} + v'\left(\frac{\partial^3 u'}{\partial y'^3}\right)\right] - \nu\left(\frac{u'}{k'}\right) - \left(\frac{\sigma B_o^2}{\rho}\right)u' \tag{2}$$

*Energy Equation:*

$$\frac{\partial T'}{\partial t'} + v'\frac{\partial T'}{\partial y'} = \frac{1}{\rho C_p}\left[\kappa\frac{\partial^2 T'}{\partial y'^2}\right] - \frac{1}{\rho C_p}\left[Q_o\left(T' - T'_\infty\right)\right] \tag{3}$$

*Species Diffusion Equation:*

$$\frac{\partial C'}{\partial t'} + v'\frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2} \tag{4}$$

The appropriate boundary conditions for the velocity, temperature and concentration fields are (Chamkha [12])

$$\left.\begin{array}{l} t' \le 0:\ u' = 0,\ T' = T'_\infty,\ C' = C'_\infty \quad for\ all\ y' \\ t' > 0: \begin{cases} u' = u'_p,\ T' = T'_w + \varepsilon\left(T'_w - T'_\infty\right)e^{nt},\ C' = C'_w + \varepsilon\left(C'_w - C'_\infty\right)e^{nt} \ \ at\ \ y' = 0 \\ u' \to U'_\infty = U_0\left(1 + \varepsilon e^{nt}\right),\ T' \to T'_\infty,\ C' \to C'_\infty \ \ as\ y' \to \infty \end{cases} \end{array}\right\} \tag{5}$$

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 (Chamkha [12]):

$$v' = -V_0\left(1 + \varepsilon A e^{nt}\right) \tag{6}$$

Where $A$ is a real positive constant, $\varepsilon$ and $\varepsilon A$ are small less than unity, and $V_0$ is a scale of suction velocity which has non-zero positive constant. Outside the boundary layer, equation (2) gives (Chamkha [12])

$$-\frac{1}{\rho}\frac{\partial p'}{\partial x'} = \frac{\partial U'_\infty}{\partial t'} + \frac{\nu}{K'}U'_\infty + \frac{\sigma}{\rho}B_0^2 U'_\infty \tag{7}$$

It is convenient to employ the following dimensionless variables (Chamkha [12]):

$$\left.\begin{array}{l} u = \frac{u'}{U_0},\ \ v = \frac{v'}{V_0},\ y = \frac{V_0 y'}{\nu},\ U_\infty = \frac{U'_\infty}{U_0},\ U_p = \frac{u'_p}{U_0}, t = \frac{t' V_0^2}{\nu},\ \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty},\ \phi = \frac{C' - C'_\infty}{C'_w - C'_\infty},\ n = \frac{n'\nu}{V_0^2}, K = \frac{K' V_0^2}{\nu^2},\ \Pr = \frac{\nu\rho C_p}{\kappa} = \frac{\nu}{\alpha}, \\ Sc = \frac{\nu}{D}, M = \frac{\sigma B_0^2 \nu}{\rho V_0^2}, Gr = \frac{\nu\beta g\left(T'_w - T'_\infty\right)}{U_0 V_0^2},\ Gc = \frac{\nu\beta^* g\left(C'_w - C'_\infty\right)}{U_0 V_0^2}, S = \frac{\nu Q_o}{\rho C_p V_o^2}, \lambda = \frac{\beta_1 V_o^2}{\nu^2} \end{array}\right\} \tag{8}$$

In view of Eqs. (6), (7) and (8) and Eqs. (2)-(4) reduce to the following dimensionless form:

$$\frac{\partial u}{\partial t} - \left(1 + \varepsilon A e^{nt}\right)\frac{\partial u}{\partial y} = \frac{dU_\infty}{dt} + \frac{\partial^2 u}{\partial y^2} + Gr\theta + Gc\phi + N\left(U_\infty - u\right) - \lambda\left[\frac{\partial^3 u}{\partial t \partial y^2} - \left(1 + \varepsilon A e^{nt}\right)\left(\frac{\partial^3 u}{\partial y^3}\right)\right] \tag{9}$$

$$\frac{\partial \theta}{\partial t} - \left(1 + \varepsilon A e^{nt}\right)\frac{\partial \theta}{\partial y} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2} - S\theta \tag{10}$$

$$\frac{\partial \phi}{\partial t} - \left(1 + \varepsilon A e^{nt}\right)\frac{\partial \phi}{\partial y} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} \tag{11}$$

The dimensionless form of the boundary conditions (5) become (Chamkha [12])

$$u = U_p,\ \theta = 1 + \varepsilon e^{nt},\ \phi = 1 + \varepsilon e^{nt}\ \ at\ \ y = 0\ \&\ u \to U_\infty,\ \theta \to 0,\ \phi \to 0\ \ as\ \ y \to \infty \tag{12}$$

The Skin-friction, the Nusselt number (Rate of heat transfer) and the Sherwood numbers (Rate of mass transfer) coefficients are important physical parameters for this type of boundary layer flow. These parameters can be defined and determined as follows (Chamkha [12]):

$$\tau = \left( \frac{\tau'_w}{\rho U_o V_o} \right)_{y'=0} = \left( \frac{\partial u}{\partial y} \right)_{y=0} \tag{13}$$

$$Nu = x' \frac{\left.\frac{\partial T'}{\partial y'}\right|_{y'=0}}{\left(T'_w - T'_\infty\right)} \Rightarrow Nu\,\mathrm{Re}_x^{-1} = \left.\frac{\partial \theta}{\partial y}\right|_{y=0} \tag{14}$$

$$Sh = x' \frac{\left.\frac{\partial C'}{\partial y'}\right|_{y'=0}}{\left(C'_w - C'_\infty\right)} \Rightarrow Sh\,\mathrm{Re}_x^{-1} = \left.\frac{\partial \phi}{\partial y}\right|_{y=0} \tag{15}$$

Where $\mathrm{Re}_x = \frac{V_o x'}{\nu}$ is the local Reynolds number.

## III. Numerical Solutions By Finite Difference Method

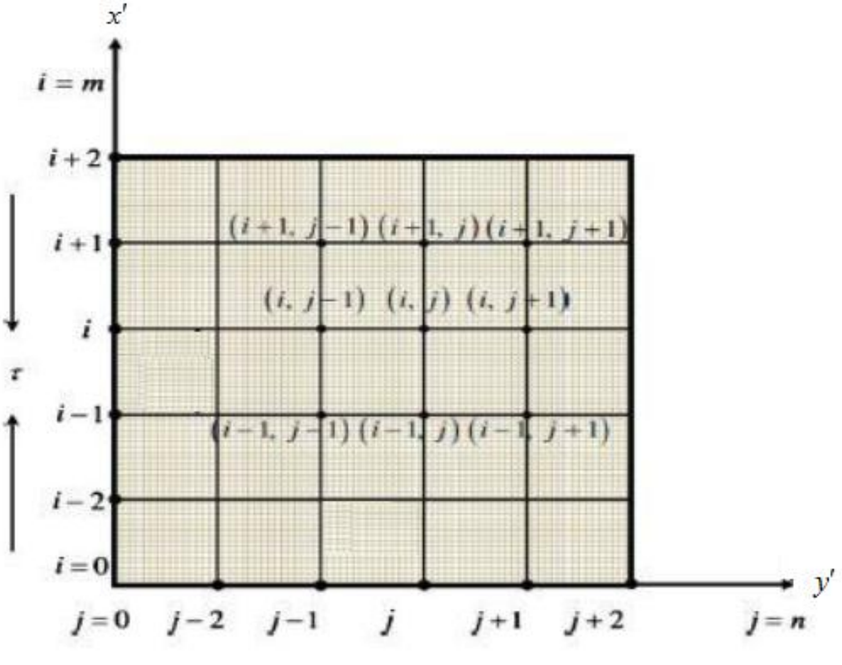


**Fig. 2.** Finite difference space grid

The non-linear momentum, energy and concentration equations given in equations (9), (10) and (11) are solved under the appropriate initial and boundary conditions (12) by the implicit finite difference method. The transport equations (9), (10) and (11) at the grid point ($i$, $j$) are expressed in difference form using Taylor's expansion.

$$\left( \frac{u_i^{j+1} - u_i^j}{\Delta t} \right) - \left(1 + \varepsilon A e^{nt}\right) \left( \frac{u_{i+1}^j - u_i^j}{\Delta y} \right) = \frac{dU_\infty}{dt} + \left( \frac{u_{i+1}^j - 2u_i^j + u_{i-1}^j}{(\Delta y)^2} \right) + (Gr)\theta_i^j + (Gc)\phi_i^j + N\left(U_\infty - u_i^j\right)$$
$$- \lambda \left[ \left( \frac{u_{i+1}^{j+1} - 2u_i^{j+1} + u_{i-1}^{j+1} - u_{i+1}^j + 2u_i^j - u_{i-1}^j}{\Delta t (\Delta y)^2} \right) - \left(1 + \varepsilon A e^{nt}\right) \left( \frac{u_{i+1}^j - 3u_{i-1}^j + 3u_{i-2}^j - u_{i-3}^j}{(\Delta y)^3} \right) \right] \tag{16}$$

$$(\mathrm{Pr}) \left( \frac{\theta_i^{j+1} - \theta_i^j}{\Delta t} \right) - \left(1 + \varepsilon A e^{nt}\right)(\mathrm{Pr}) \left( \frac{\theta_{i+1}^j - \theta_i^j}{\Delta y} \right) = \left( \frac{\theta_{i+1}^j - 2\theta_i^j + \theta_{i-1}^j}{(\Delta y)^2} \right) - (\mathrm{Pr}) S \theta_i^j \tag{17}$$

$$(Sc)\left(\frac{\phi_i^{j+1}-\phi_i^j}{\Delta t}\right)-\left(1+\varepsilon Ae^{nt}\right)(Sc)\left(\frac{\phi_{i+1}^j-\phi_i^j}{\Delta y}\right)=\left(\frac{\phi_{i+1}^j-2\phi_i^j+\phi_{i-1}^j}{(\Delta y)^2}\right) \tag{18}$$

Where the indices $i$ and $j$ refer to $y$ and $t$ respectively. The initial and boundary conditions (12) yield.

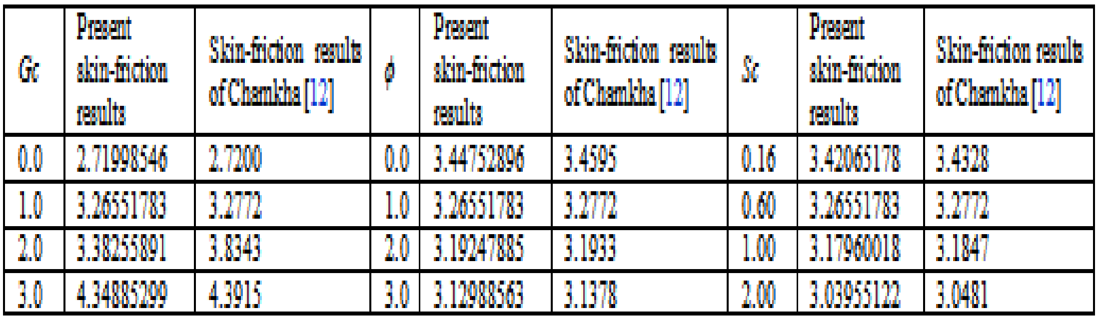
$$\left.\begin{aligned}&u_i^0=0,\ \theta_i^0=0,\ \phi_i^0=0\,for\ all\ i,\\&u_i^j=U_p,\ \theta_i^j=1+\varepsilon e^{nj},\ \phi_i^j=1+\varepsilon e^{nj}\ \ at\ i=0\\&u_M^j\to U_\infty,\ \theta_M^j\to 0,\ \phi_M^j\to 0\end{aligned}\right\} \tag{19}$$

Thus the values of $u$, $\theta$ and $\phi$ at grid point $t$ = 0 are known; hence the temperature field has been solved at time $t_{i+1}=t_i+\Delta t$ using the known values of the previous time $t=t_i$ for all $i=1,\,2,\,........,N-1$. Then the velocity field is evaluated using the already known values of temperature and concentration fields obtained at $t_{i+1}=t_i+\Delta t$. These processes are repeated till the required solution of $u$, $\theta$ and $\phi$ is gained at convergence criteria.

$$abs\left|(u,\ \theta,\ \phi)_{exact}-(u,\ \theta,\ \phi)_{numerical}\right|<10^{-3} \tag{20}$$

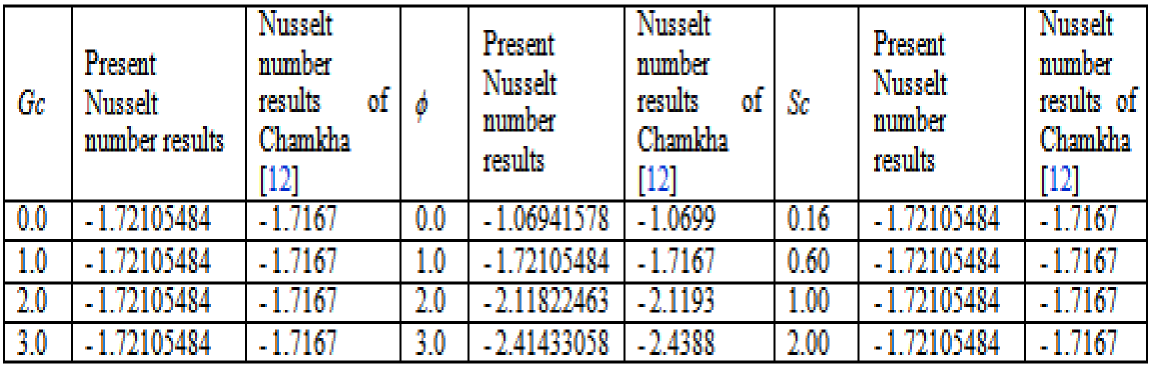
## IV. Code Validation Of Programme

**Table-1:** Comparison of present skin-friction results with the skin-friction results of Chamkha [12] for different values of Grashof number for mass transfer, Heat absorption and Schmidt number



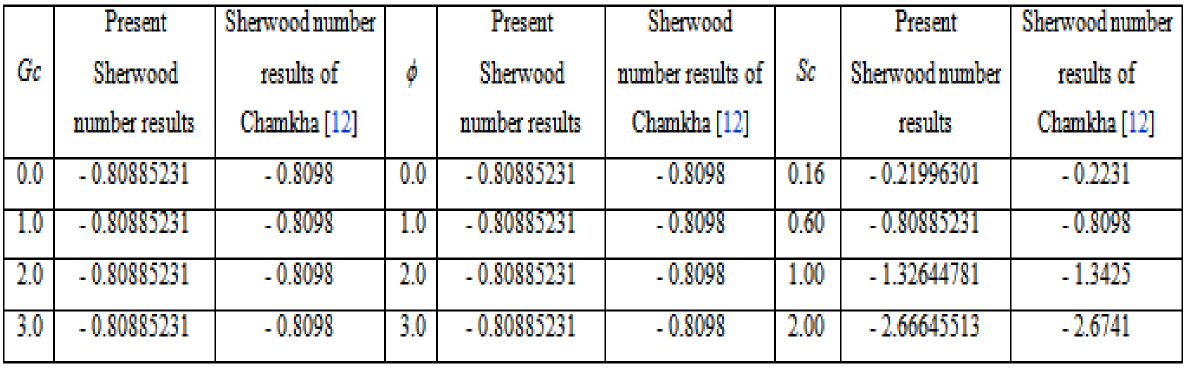
| $Gc$ | Present skin-friction results | Skin-friction results of Chamkha [12] | $\phi$ | Present skin-friction results | Skin-friction results of Chamkha [12] | $Sc$ | Present skin-friction results | Skin-friction results of Chamkha [12] |
|---|---|---|---|---|---|---|---|---|
| 0.0 | 2.71998546 | 2.7200 | 0.0 | 3.44752896 | 3.4595 | 0.16 | 3.42065178 | 3.4328 |
| 1.0 | 3.26551783 | 3.2772 | 1.0 | 3.26551783 | 3.2772 | 0.60 | 3.26551783 | 3.2772 |
| 2.0 | 3.38255891 | 3.8343 | 2.0 | 3.19247885 | 3.1933 | 1.00 | 3.17960018 | 3.1847 |
| 3.0 | 4.34885299 | 4.3915 | 3.0 | 3.12988563 | 3.1378 | 2.00 | 3.03955122 | 3.0481 |

**Table-2:** Comparison of present Nusselt number results with the Nusselt number results of Chamkha [12] for different values of Grashof number for mass transfer, Heat absorption and Schmidt number



| $Gc$ | Present Nusselt number results | Nusselt number results of Chamkha [12] | $\phi$ | Present Nusselt number results | Nusselt number results of Chamkha [12] | $Sc$ | Present Nusselt number results | Nusselt number results of Chamkha [12] |
|---|---|---|---|---|---|---|---|---|
| 0.0 | -1.72105484 | -1.7167 | 0.0 | -1.06941578 | -1.0699 | 0.16 | -1.72105484 | -1.7167 |
| 1.0 | -1.72105484 | -1.7167 | 1.0 | -1.72105484 | -1.7167 | 0.60 | -1.72105484 | -1.7167 |
| 2.0 | -1.72105484 | -1.7167 | 2.0 | -2.11822463 | -2.1193 | 1.00 | -1.72105484 | -1.7167 |
| 3.0 | -1.72105484 | -1.7167 | 3.0 | -2.41433058 | -2.4388 | 2.00 | -1.72105484 | -1.7167 |

**Table-3:** Comparison of present Sherwood number results with the Sherwood number results of Chamkha [12] for different values of Grashof number for mass transfer, Heat absorption and Schmidt number



| $Gc$ | Present Sherwood number results | Sherwood number results of Chamkha [12] | $\phi$ | Present Sherwood number results | Sherwood number results of Chamkha [12] | $Sc$ | Present Sherwood number results | Sherwood number results of Chamkha [12] |
|---|---|---|---|---|---|---|---|---|
| 0.0 | - 0.80885231 | - 0.8098 | 0.0 | - 0.80885231 | - 0.8098 | 0.16 | - 0.21996301 | - 0.2231 |
| 1.0 | - 0.80885231 | - 0.8098 | 1.0 | - 0.80885231 | - 0.8098 | 0.60 | - 0.80885231 | - 0.8098 |
| 2.0 | - 0.80885231 | - 0.8098 | 2.0 | - 0.80885231 | - 0.8098 | 1.00 | - 1.32644781 | - 1.3425 |
| 3.0 | - 0.80885231 | - 0.8098 | 3.0 | - 0.80885231 | - 0.8098 | 2.00 | - 2.66645513 | - 2.6741 |

Tables 1, 2 and 3 present the comparison of skin-friction, rate of heat and mass transfer coefficients for the various values of Grashof number for mass transfer, Heat absorption and Schmidt number with previous published results of Chamkha [12] in absence of Rivlin-Ericksen fluid. From these tables, It is observed that our present results are in good agreement with the published results of Chamkha [12].

## V. Results And Discussions

The non-zero coupled Eqs. (9)-(11) subject to boundary conditions (12), which describe heat absorbing Rivlin-Ericksen flow past a semi-infinite vertical porous plate under the influence of magnetic field and double diffusion are solved numerically by finite difference method. In order to get physical insight into the problem, the effects of various parameters encountered in the equations of the problem are analyzed on velocity and temperature fields with the help of figures. These results show the influence of the various physical parameters such as Grashof number for heat transfer ($Gr$), Grashof number for mass transfer ($Gc$), Magnetic field parameter ($M$), Permeability parameter ($K$), Prandtl number (Pr), Schmidt number ($Sc$), Heat absorption parameter ($S$) and Viscoelastic Rivlin-Ericksen fluid parameter ($\lambda$) on velocity, temperature and concentration distributions which are displayed graphically in Figs. 3 to 13. In the present study following default parameter values are adopted for computations: $\Pr = 0.7$, $M = 0.5$, $Gr = 1.0$, $Gc = 1.0$, $\lambda = 0.5$, $K = 0.5$, $Sc = 0.22$, $S = 0.5$, $n = 0.1$, $t = 1.0$, $A = 0.5$, $\varepsilon = 0.001$ and $U_p = 0.5$. All graphs therefore correspond to these values unless specifically indicated on the appropriate graph. To find solution of this problem, the author placed an infinite vertical plate in a finite length in the flow. Hence, the author solved the entire problem in a finite boundary. However, in the graphs, the $y$ values vary from 0 to 10, and the velocity, temperature, and concentration profiles tend to zero as $y$ tend to 10. This is true for any value of $y$. Thus, the author has considered finite length. Fig. 3 reveals that the velocity profiles increases when Grashof number for heat transfer $Gr$ increases. In fact, higher values of $Gr$ lead to an increase in the temperature gradient and enhances the buoyancy force. Therefore, it accelerates the fluid velocity profiles throughout the boundary layer region. For various values of Grashof number for mass transfer $Gc$, the velocity profiles are plotted in Fig. 4. The Grashof number for mass transfer $Gc$ defines the ratio of the species buoyancy force to the viscous hydrodynamic force. As expected, the fluid velocity increases and the peak value is more distinctive due to increase in the species buoyancy force. The velocity distribution attains a distinctive maximum value in the vicinity of the plate and then decreases properly to approach the free stream value. It is noticed that the velocity increases with increasing values of the Grashof number for mass transfer $Gc$.

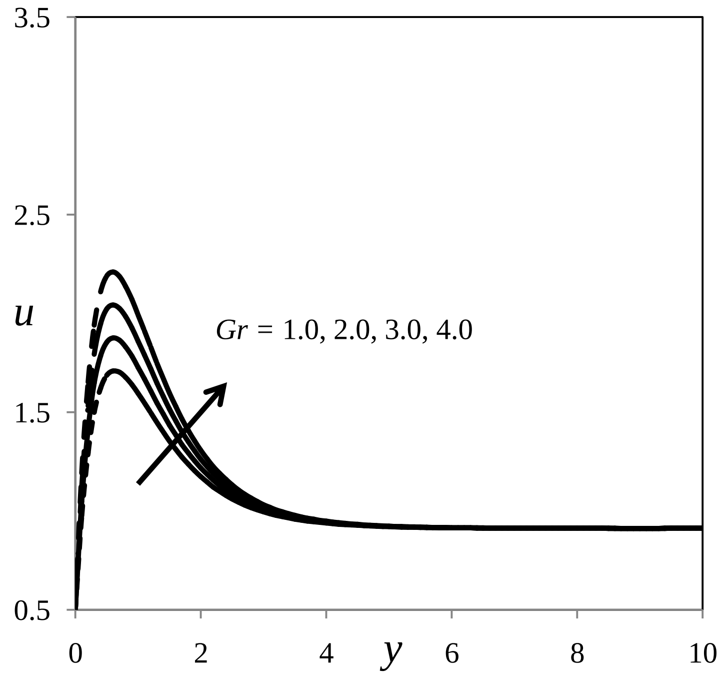


**Fig. 3.** Effect of *Gr* on velocity profiles

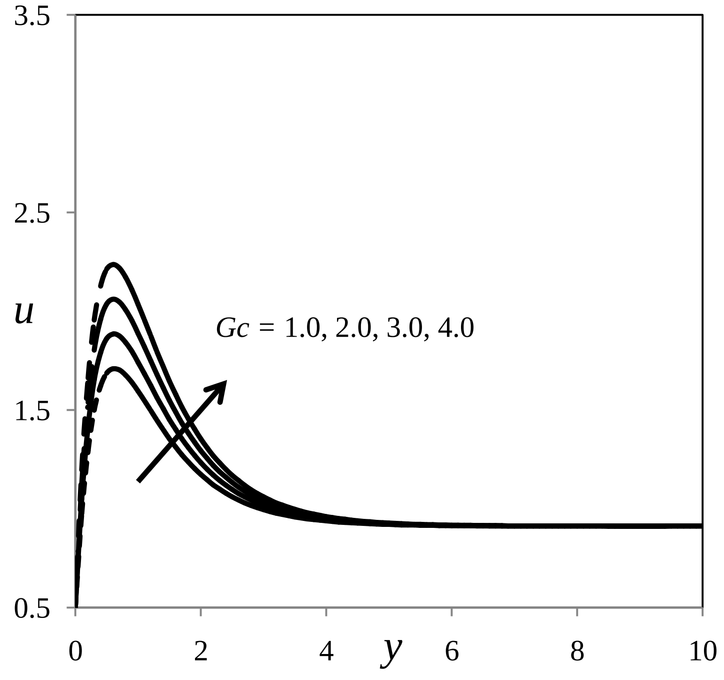


**Fig. 4.** Effect of *Gc* on velocity profiles

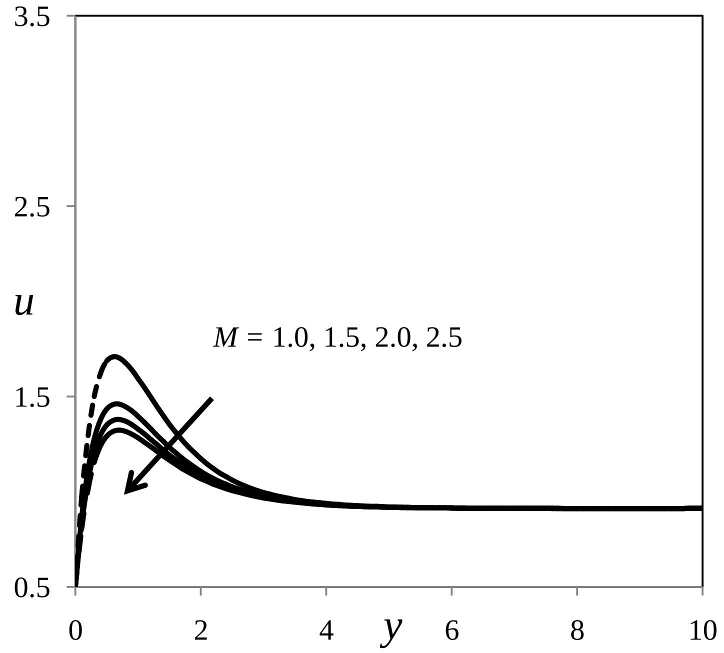


**Fig. 5.** Effect of *M* on velocity profiles

The effects of magnetic field or Hartmann number *M* on the velocity components are illustrated in Fig 5. This figure indicates that an increase in the values of *M* tends to reduce the velocity components monotonically due to the Lorentz force, which is similar to the drag force that acts as an agent to retard the fluid flow. Therefore, when we increase the magnetic parameter, the Lorentz force is technically increased and more resistance is given to the motion of the fluid thus decelerating the velocity profiles. From Fig. 6, it is noted that an increase in the permeability parameter of the porous medium *K* enhances the velocity profiles due to the less friction force, which yields the reverse effect of the magnetic parameter. In fact, higher values of *K* reduce the resistance of the porous medium, which in turn increase the momentum development of the regime and thus accelerate the fluid flow in velocity profiles. Lower values of velocity profiles are seen with the increase of Prandtl number, Pr as presented in Fig. 7. Prandtl number is defined as the ratio between momentum diffusivity and thermal diffusivity and hence controls the relative thickness of the momentum and thermal boundary layers. This means that, an increase in the Prandtl number leads to an increase in the viscosity of the fluid which makes the fluid become thick, and consequently decreases the fluid flow.

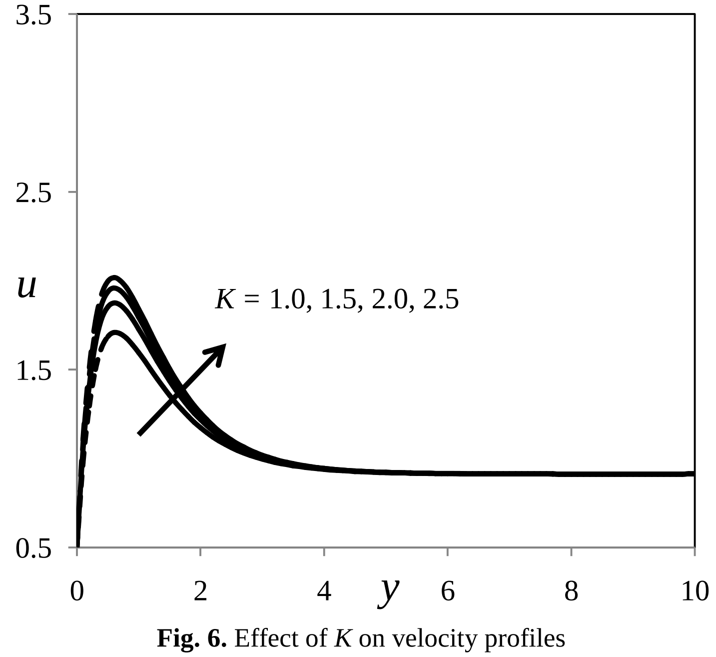


**Fig. 6.** Effect of *K* on velocity profiles

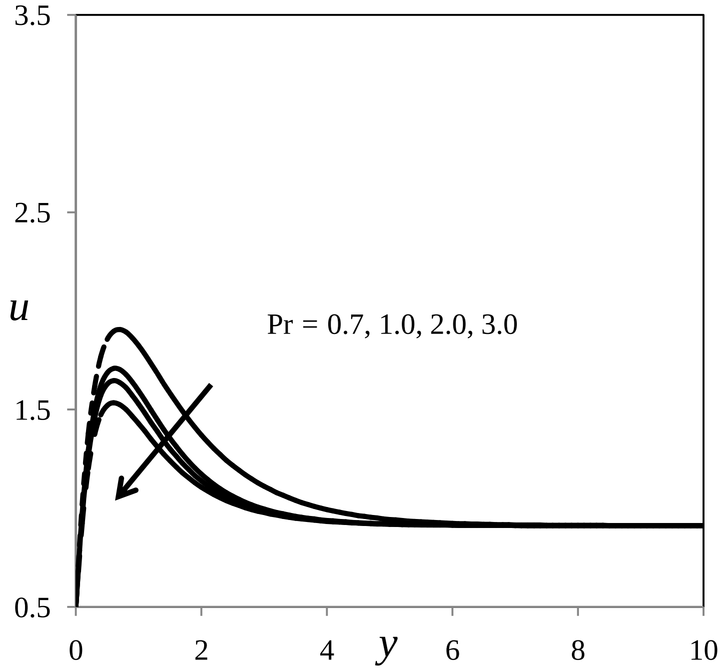


**Fig. 7.** Effect of Pr on velocity profiles

Besides that, Fig. 8 exhibits the characteristics of the Prandtl number Pr on temperature distribution. It is noticed that a higher Prandtl number leads to a fall in temperature profiles due to the fact that lower Pr values have more uniform temperature distribution across the thermal boundary layer as compared to higher Pr. In this case, lower values of Pr, fluids possess high thermal conductivity which causes the heat to diffuse away from the heated surface more rapidly and faster compare to higher values of Pr. Thus, it increases the boundary layer thickness and consequently decreases the temperature distribution. Figs. 9 and 10 display the effects of the Schmidt number *Sc* on the velocity and concentration profiles at $t = 1$, respectively. As the Schmidt number increases, the concentration decreases. This causes the concentration buoyancy effects to decrease yielding a reduction in the fluid velocity. The reductions in the velocity and concentration profiles are accompanied by simultaneous reductions in the velocity and concentration boundary layers. These behaviors are clearly shown in Figs. 9 and 10.

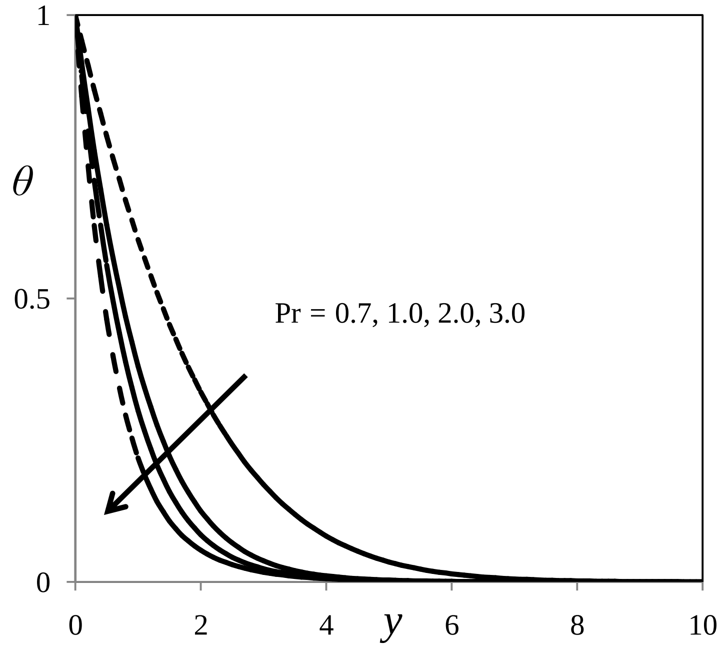


**Fig. 8.** Effect of Pr on temperature profiles

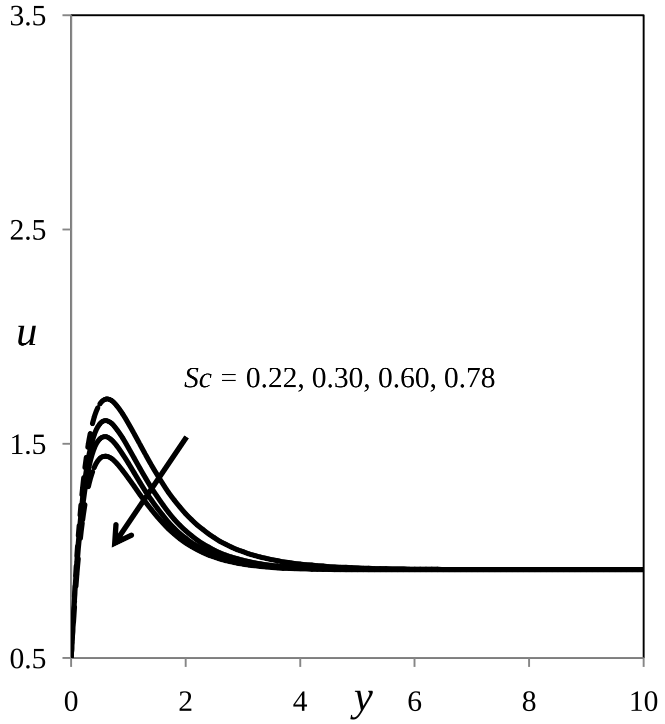


**Fig. 9.** Effect of *Sc* on velocity profiles

Figs. 11 and 12 illustrate the influence of the heat absorption coefficient *S* on the velocity and temperature profiles at $t = 1.0$, respectively. Physically speaking, the presence of heat absorption (thermal sink) effects 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. These behaviours are clearly obvious from Figs. 11 and 12 in which both the velocity and temperature distributions decrease as *S* increases. It is also observed that both the hydrodynamic (velocity) and the thermal (temperature) boundary layers decrease as the heat absorption effects increase. The behavior of material parameter of Viscoelastic Rivlin-Ericksen fluid parameter, $\lambda$ on velocity fields is portrayed in Fig. 13. It was found that an increase in $\lambda$ leads to a decrease in the velocity distribution across the boundary layer. The profiles for Skin-friction coefficient due to velocity profiles under the effects of Grashof number for heat transfer, Grashof number for mass transfer, Magnetic field parameter or Hartmann number, Permeability parameter, Prandtl number, Schmidt number, Heat absorption parameter and Viscoelastic Rivlin-Ericksen fluid parameter is presented in the table 4. It is observed from the above table 4, the Skin-friction coefficient due to velocity increases under the effects of Grashof number for heat transfer, Grashof number for mass transfer, Permeability parameter and decreases under the effects of Magnetic field parameter or Hartmann number, Prandtl number, Schmidt number, Heat absorption parameter and Viscoelastic Rivlin-Ericksen fluid parameter. The profiles for Nusselt number coefficient due to temperature profiles under the effects of Prandtl number and heat absorption parameter is presented in the table 5. From this table 5, It is observed that the Nusselt number coefficient due to temperature profiles falls under the effects of Prandtl number and heat absorption parameter. The profiles for Sherwood number coefficient due to concentration profiles under the effect of Schmidt number is presented in the table 5. From this table, It is observed that the Sherwood number coefficient due to the concentration profiles falls under the effect of Schmidt number.

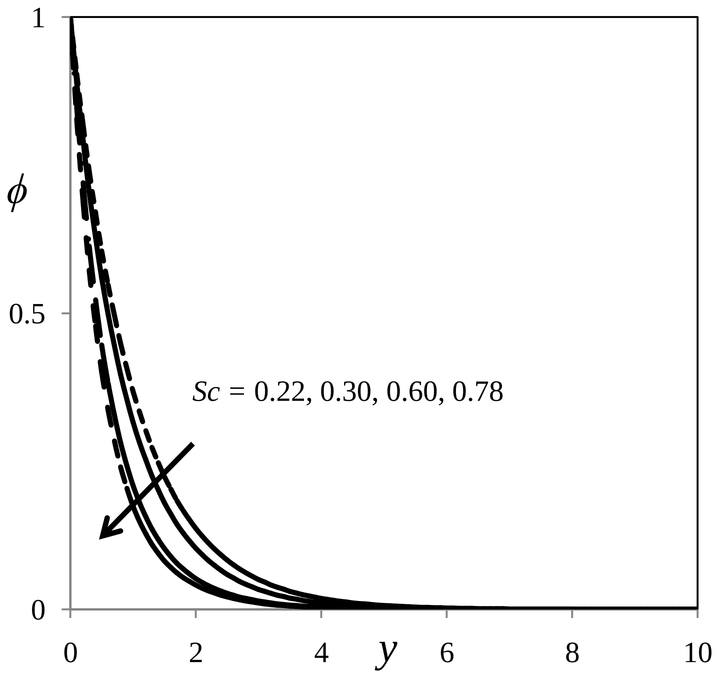


**Fig. 10.** Effect of *Sc* on concentration profiles

**Table-4:** Skin-friction coefficient ($\tau$)

| $Gr$ | $Gc$ | $M$ | $K$ | Pr | $Sc$ | $s$ | $\lambda$ | $\tau$ |
|---|---|---|---|---|---|---|---|---|
| 2.0 | 2.0 | 0.5 | 0.5 | 0.7 | 0.22 | 0.5 | 0.5 | 2.0116258925 |
| **3.0** | 2.0 | 0.5 | 0.5 | 0.7 | 0.22 | 0.5 | 0.5 | 2.2256154482 |
| 2.0 | **3.0** | 0.5 | 0.5 | 0.7 | 0.22 | 0.5 | 0.5 | 2.3015447899 |
| 2.0 | 2.0 | **1.0** | 0.5 | 0.7 | 0.22 | 0.5 | 0.5 | 1.9448511262 |
| 2.0 | 2.0 | 0.5 | **1.0** | 0.7 | 0.22 | 0.5 | 0.5 | 2.1114548517 |
| 2.0 | 2.0 | 0.5 | 0.5 | **1.0** | 0.22 | 0.5 | 0.5 | 1.9562100348 |
| 2.0 | 2.0 | 0.5 | 0.5 | 0.7 | **0.30** | 0.5 | 0.5 | 1.9622150396 |
| 2.0 | 2.0 | 0.5 | 0.5 | 0.7 | 0.22 | **1.0** | 0.5 | 1.9666654732 |
| 2.0 | 2.0 | 0.5 | 0.5 | 0.7 | 0.22 | 0.5 | **1.0** | 1.9742133356 |

**Table-5:** Nusselt number (*Nu*) and Sherwood number (*Sh*) coefficients

| Pr | $s$ | $Nu$ | $Sc$ | $Sh$ |
|---|---|---|---|---|
| 0.7 | 0.5 | 4.3015201155 | 0.22 | 4.4622259158 |
| **1.0** | 0.5 | 4.2546621938 | **0.30** | 4.4033265554 |
| 0.7 | **1.0** | 4.2630155822 | **0.78** | 4.3601511187 |

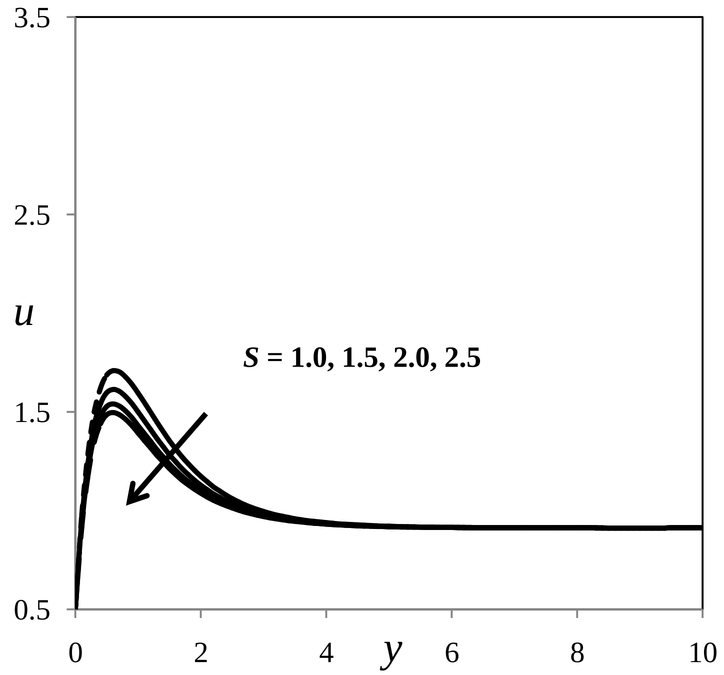


**Fig. 11.** Effect of *S* on velocity profiles

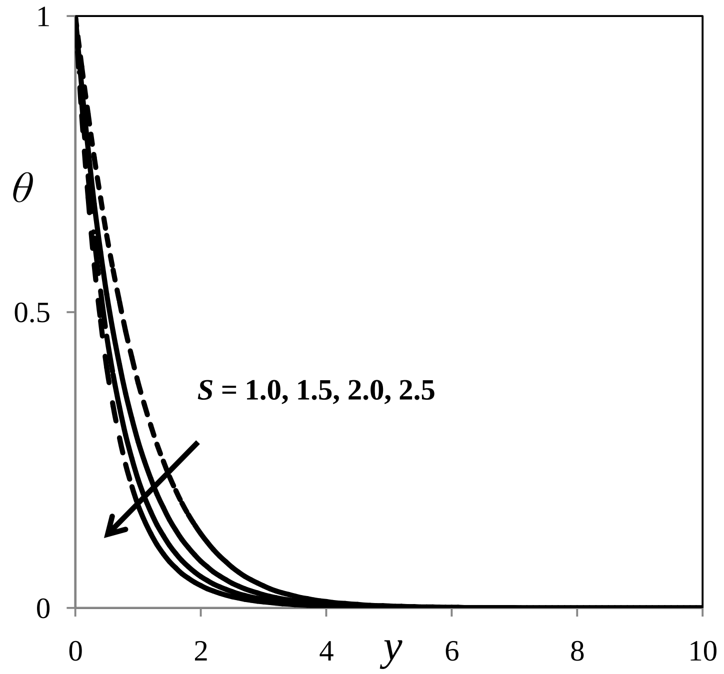


**Fig. 12.** Effect of *S* on temperature profiles

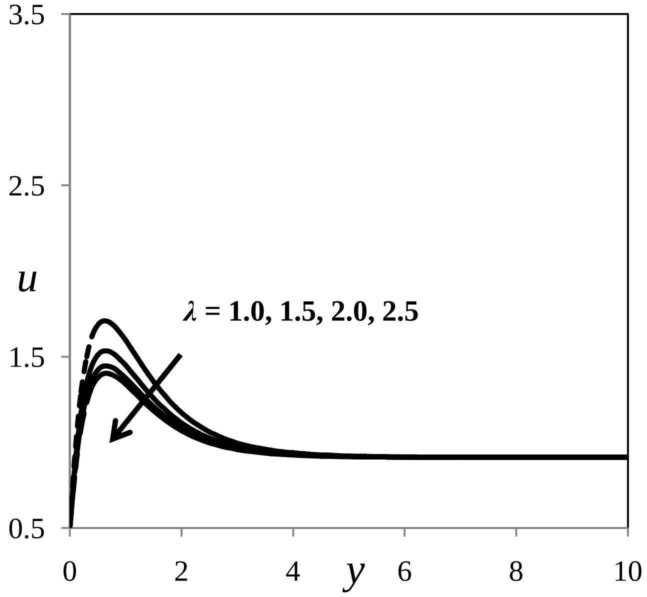


**Fig. 13.** Effect of $\lambda$ on velocity profiles

## VI. Conclusions

Generalized MHD Viscoelastic Rivlin-Eriksen fluid flow in presence of free convection past a vertical plate with heat absorption and double diffusion effects is considered. The governing equations for momentum, energy and concentration for the flow are solved in view of the boundary conditions at the clear fluid-porous interface. Velocity, temperature and concentration distributions are derived numerically which are used to finite difference method. The effects of pertinent parameters on the quantities of interest are depicted graphically and discussed. The findings are as follows.

1. Velocity profiles in the flow increases with the increase in Grashof number for heat transfer, Grashof number for mass transfer, Permeability parameter whereas it decays with the increasing values of Hartmann number, Prandtl number, Schmidt number, Heat absorption parameter and Viscoelastic Rivlin-Eriksen fluid parameter.
2. Temperature profiles falls with the increasing values of Prandtl number and Heat absorption parameter.
3. Concentration profiles decreases with rising values of Schmidt number.
4. With the increasing values of Grashof number for heat transfer, Grashof number for mass transfer and Permeability parameter, Skin-friction coefficient increases. However the trend is reversed with increasing values of Hartmann number, Prandtl number, Schmidt number, Heat absorption parameter and Viscoelastic Rivlin-Eriksen fluid parameter.
5. Variation in varying values of Prandtl number and Heat absorption parameter, Nusselt number decreases.
6. Sherwood number decays with the increasing values of Schmidt number.
7. In the absence of Viscoelastic Rivlin-Eriksen fluid parameter observation of the present study coincides with published work of Chamkha [12].

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