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Heat and Mass Transfer Analysis on Mud Radiating Flow in Presence of Natural Convection, Porous Medium and Viscoelastic Rivlin-Ericksen Fluid through Numerical Solutions

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Abstract: *An investigation is carried out on unsteady magnetohydrodynamic (MHD) natural convection in a boundary layer flow of an electrically conducting fluid through porous medium subject to uniform transverse magnetic field over a moving infinite vertical plate in the presence of thermal radiation, heat absorption and chemical reaction. The fundamental equations for governing flow through porous medium based on viscoelastic Rivlin-Ericksen fluid model. The basic governing partial differential equations for the fluid flow, temperature and concentration profiles are reduced to a system of coupled linear partial differential equations. The derived coupled linear partial differential equations and corresponding boundary conditions are solved numerically by finite difference method. To exhibit the effects of the controlling parameters on the dimensionless velocity, temperature, concentration profiles, local skin-friction, local Nusselt and local Sherwood numbers coefficients, numerical results are presented in graphical and tabular forms.*

Keywords: *MHD; Viscoelastic Rivlin-Ericksen fluid; Thermal Radiation; Heat and Mass transfer; Finite difference method;*

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Nomenclature:

List of variables:

C'_w	Concentration of the plate ($Kg\ m^{-3}$)
y	Dimensionless displacement (m)
T'_∞	Fluid temperature away from the plate (K)
u'	Velocity component in $x'-$direction ($m\ s^{-1}$)
x'	Coordinate axis along the plate (m)
y'	Co-ordinate axis normal to the plate (m)
C'	Fluid Concentration ($Kg\ m^{-3}$)
T'	Fluid temperature (K)
T'_w	Fluid temperature at the wall (K)
B_0	Uniform magnetic field (*Tesla*)
C'_∞	Concentration of the fluid far away from the plate ($Kg\ m^{-3}$)
u	Fluid velocity ($m\ s^{-1}$)
Gc	Grashof number for mass transfer
Sh	The local Sherwood number coefficient
R	Thermal radiation parameter
g	Acceleration of gravity, 9.81 ($m\ s^{-2}$)
Gr	Grashof number for heat transfer
M	Magnetic field parameter
$\Pr$	Prandtl number

Re	Reynolds number
Sc	Schmidt number
D	Solute mass diffusivity ($m^2\ s^{-1}$)
C_p	Specific heat at constant pressure $\left(J\ Kg^{-1}K\right)$
Nu	The local Nusselt number coefficient
Cf	The local skin-friction coefficient $(N\ m^{-2})$
t	Time (*sec*)
k_e	Mean absorption coefficient
U_o	Reference velocity ($m\ s^{-1}$)
Kr	Chemical reaction parameter
Q	Heat sink parameter
K	Permeability parameter
q_r	Radiative heat flux

Greek Symbols:

ν	Kinematic viscosity ($m^2\ s^{-1}$)
ϕ	Species concentration ($Kg\ m^{-3}$)
ρ	The constant density ($Kg\ m^{-3}$)
β	Volumetric coefficient of thermal expansion (K^{-1})
β^*	Volumetric Coefficient of thermal expansion with concentration ($m^3\ Kg^{-1}$)
θ	Fluid temperature (K)
τ'_w	Shear stress $(N\ m^{-2})$
σ	Electric conductivity of the fluid $(s\ m^{-1})$
β_1	Kinematic viscoelasticity
σ_s	Stefan-Boltzmann constant
κ	Thermal conductivity of the fluid (W/mK)

Superscripts:

$/$	Dimensionless properties

Subscripts:

∞	Free stream conditions
p	Plate
w	Conditions on the wall

I. Introduction

The study of heat and mass transfer with chemical reactions is of great practical importance to engineers and scientists because of its almost universal occurrence in many branches of science and engineering. The flow of a fluid past a wedge is of fundamental importance since it constitutes a general and wide class of flows in which the free stream velocity is proportional to the power of the length coordinate measured from the stagnation point. All industrial chemical processes are designed to transform cheaper raw materials to high value products (usually via chemical reactions). A “reactor”, in which such chemical transformations take place, has to carry out several functions like bringing reactants into intimate contacts, providing an appropriate environment (temperature and concentration fields) at adequate time, and allowing for the removal of products. Fluid dynamics plays a pivotal role in establishing the relationship between the reactor hardware and the reactor performance. For a specific chemistry/catalyst, the reactor performance is a complex function of the underlying transport processes. The first step in any reaction engineering analysis is to formulate a mathematical framework to describe the rate (and mechanisms) by which one chemical species is converted into another in the absence of any transport limitations (chemical kinetics). Once the intrinsic kinetics is available, the production rate and composition of the products are related, in principle, to react the volume, the configuration, and the mode of operation by solving the mass, momentum, and energy balances over the reactor. This is the central task of a reaction and reactor engineering activity. The analyses of the transport processes and their interactions with chemical reactions are quite difficult. It is intimately connected to the underlying fluid dynamics. Such a combined analysis of chemical and physical processes constitutes for the core of the chemical reaction engineering. Recent advances in understanding the physics of flows and modeling the computational flow make tremendous contributions in chemical engineering. We are particularly interested in the cases in which the diffusion and the chemical reaction occur at the roughly same speed. When the diffusion is much faster than the chemical reaction, only chemical factors influence the chemical reaction rate; when the diffusion is not much faster than the reaction, the diffusion and the kinetics interact to produce very different effects. The study of heat generation or absorption effects in moving fluids is important in many physical problems, such as fluids undergoing exothermic or endothermic chemical reactions. 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. Transfer effects on an unsteady MHD free convective flow past a vertical plate with chemical reaction studied by Srinivasa Raju [2]. Influence of angle of inclination on unsteady MHD Casson fluid flow past a vertical surface filled by porous medium in presence of constant heat flux, chemical reaction and viscous dissipation discussed by Srinivasa Raju et al. [3]. Influence of chemical reaction on MHD boundary layer flow of nano fluids over a nonlinear stretching sheet with thermal radiation studied by Ramya et al. [4]. Srinivasa Raju [5] studied combined influence of thermal diffusion and diffusion thermo on unsteady hydromagnetic free convective fluid flow past an infinite vertical porous plate in presence of chemical reaction. Chemical reaction and radiation effects on MHD free convection from an impulsively started infinite vertical plate with viscous dissipation studied by Jithender Reddy et al. [6]. Galerkin finite element solutions of MHD free convection radiative flow past an infinite vertical porous plate with chemical reaction and hall current studied by Anand Rao et al. [7]. Sudhakar et al. [8] studied hall effect on an unsteady MHD flow past along a porous flat plate with thermal diffusion, diffusion thermo and chemical reaction. Chemical reaction effect on an unsteady MHD free convection flow past an infinite vertical accelerated plate with constant heat flux, thermal diffusion and diffusion thermo studied by Sudhakar et al. [9]. Unsteady MHD free convection flow near on an infinite vertical plate embedded in a porous medium with chemical reaction, hall current and thermal radiation discussed by Sarada et al. [10]. Finite element analysis of hall current and rotation effects on free convection flow past a moving vertical porous plate with chemical reaction and heat absorption investigated by Jithender Reddy et al. [11]. Dharmendar Reddy et al. [12] studied chemical reaction effect on an unsteady MHD free convective flow past a vertical porous plate with hall current. Srinivasa Raju et al. [13] studied viscous dissipation impact on MHD free convection radiating fluid flow past a vertical porous plate. Anand Rao et al. [14] studied MHD over a vertical plate in presence of free convection flow and hall current through EFGM solutions. Manideep et al. [15] studied 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 studied by Manideep et al. [16]. Srinivasa Raju et al. [17] studied finite element solutions of MHD free convective casson fluid flow past a vertically inclined plate submitted in magnetic field in presence of heat and mass transfer. Srinivasa Raju et al. [18] studied MHD Casson viscous dissipative fluid flow past a vertically inclined plate in presence of heat and mass transfer using finite element technique. Numerical solutions by EFGM of MHD convective fluid flow past a vertical plate filled in porous medium in presence of cross diffusion effects via Biot number and convective boundary condition discussed by Srinivasa Raju et al. [19]. Jithender Reddy et al. [20] studied unsteady MHD Couette flow of water at $4^{o}c$ in a rotating system in presence of heat transfer with ramped temperature via finite element method. Thermal diffusion and diffusion thermo effects on unsteady MHD fluid flow past a moving vertical plate embedded in porous medium in the presence of hall current and rotating system studied by Jithender Reddy et al. [21]. Srinivasa Raju et al.[22] investigated thermal diffusion and diffusion thermo effects on an unsteady heat and mass transfer MHD natural convection Couette flow using finite element method. Chemically reacting fluid flow induced by an exponentially accelerated infinite vertical plate in a magnetic field and variable temperature via Laplace transform and finite element techniques discussed by Srinivasa Raju et al. [23]. Ramya et al. [24] discussed boundary layer viscous flow of nanofluids and heat transfer over a nonlinearly isothermal stretching sheet in the presence of heat generation/absorption and slip boundary conditions. Srinivasa Raju et al. [25] studied the influence of thermal radiation on unsteady free convection flow of water near $4^{o}C$ past a moving vertical plate. Viscous dissipation impact on chemically reacting flow past an infinite vertical oscillating porous plate with magnetic field studied by Srinivasa Raju et al. [26]. Hall effect on an unsteady MHD free convective Couette flow between two permeable plates studied by Maddilety and Srinivasa Raju [27]. Srinivasa Raju et al. [28] studied application of finite element technique to free convective flow of Water near 4˚C past a vertical moving plate embedded in porous medium in presence of magnetic field. Finite element study of an unsteady MHD free convection Couette flow with viscous dissipation discussed by Anand Rao et al. [29]. Finite element analysis of unsteady MHD free convection flow past an infinite vertical plate with soret, dufour, thermal radiation and heat source studied by Anand Rao et al. [30]. Thermal radiation and rotation effect on an unsteady MHD mixed convection flow through a porous medium with Hall current and Heat absorption discussed by Venkataramana et al. [31]. Anand Rao and Srinivasa Raju [32] studied the combined effects of Hall currents, Soret and Dufour on MHD flow and heat transfer along a porous flat plate with mass transfer. Hall Effect on an unsteady MHD flow and heat transfer along a porous flat plate with mass transfer and viscous dissipation studied by Anand Rao and Srinivasa Raju [33]. Applied magnetic field on transient free convective flow of an incompressible viscous dissipative fluid in a vertical channel studied by Anand Rao and Srinivasa Raju [34]. Hall Current effect on an unsteady MHD free convection flow past a vertical porous plate with heat and mass transfer studied by Dharmendar Reddy et al. [35]. Hydromagnetic free convection heat transfer Couette flow of water at 4^oC in rotating system studied by Anand Rao et al. [36]. Some of the authors ([37]-[66]) studied heat and mass transfer problems on MHD free convective flows in presence of porous medium, thermal radiation, heat source, Soret and Dufour effects.

Motivated by the above reference work and the numerous possible industrial applications of the problem, it is of paramount interest in this study to investigate the effects thermal radiation and chemical reaction on MHD free convection flow along an infinite vertical porous plate in presence of heat absorption, viscoelastic Rivlin-Ericksen fluid, heat and mass transfer. Hence, the purpose of this paper is to extend the results of Mohamed et al. [67] to study the more general problem which includes viscoelastic Rivlin-Ericksen fluid. In this study, the effects of different flow parameters encountered in the equations are also studied. The problem is solved numerically using the finite difference scheme, which is more economical from the computational view point.

II. Mathematical formulation

In this investigation, unsteady MHD natural convective heat and mass transfer non-newtonian viscoelastic Rivlin-Ericksen fluid flow of a viscous, incompressible, gray, absorbing-emitting but non-scattering, optically-thick and electrically conducting fluid occupying a vertical porous regime with constant velocity in presence of thermal radiation, heat absorption and chemical reaction is considered. The flow configuration of the problem is presented in Fig. 1. For this investigation, let us assume that $x'-$axis is taken along the vertical infinite porous plate in the upward direction and the $y'-$axis normal to the plate. Initially, for time $t' \leq 0,$ the plate and the fluid are at some temperature T'_∞ in a stationary condition with the same species concentration C'_∞ at all points. A constant magnetic field B_o is maintained in the $y'-$direction and the plate moves uniformly along the positive $x'-$direction with velocity U_0. At time $t' > 0$ a magnetic field of uniform strength is applied in the direction of y'-axis and the induced magnetic field is neglected. The magnetic Reynolds number is so small that the induced magnetic field can be neglected. Also no applied or polarized voltages exist so the effect of polarization of fluid is negligible. All the fluid properties except the density in the buoyancy force term are constants. The temperature at the surface of the plate is raised to uniform temperature T'_w and species concentration at the surface of the plate is raised to uniform species concentration C'_w and is maintained thereafter. The viscous dissipation and Ohmic dissipation of energy are negligible. The homogeneous chemical reaction of first order with rate constant $\overline{K}$ between the diffusing species is assumed. Under the above foregoing assumptions and Boussinesq's approximation, the equations governing the flow and transport reduce to the following equations:

Momentum Equation:

$$\frac{\partial u'}{\partial t'} = \nu \frac{\partial^2 u'}{\partial y'^2} + g\beta(T' - T'_\infty) + g\beta^*(C' - C'_\infty) - \left(\frac{\sigma B_0^2}{\rho}\right)u' - \left(\frac{\nu}{K'}\right)u' - \beta_1\left(\frac{\partial^3 u'}{\partial t' \partial y'^2}\right) \tag{1}$$

Energy Equation:

$$\rho C_p \frac{\partial T'}{\partial t'} = \kappa \frac{\partial^2 T'}{\partial y'^2} - Q_o(T' - T'_\infty) - \frac{\partial q_r}{\partial y'} \tag{2}$$

Species Diffusion Equation:

$$\frac{\partial C'}{\partial t'} = D \frac{\partial^2 C'}{\partial y'^2} - k'_r(C' - C'_\infty) \tag{3}$$

together with initial and boundary conditions

$$\left.\begin{array}{l} t'\le 0: u'=0,\ T'=T'_\infty,\ C'=C'_\infty \quad for\ \ all\ \ y' \\ t'>0: \begin{cases} u'=U_o,\ T'=T'_w,\ C'=C'_w \ \ at\ \ y'=0 \\ u'=0,\ T'=T'_\infty,\ C'=C'_\infty \ \ as\ \ y'\to\infty \end{cases} \end{array}\right\} \tag{4}$$

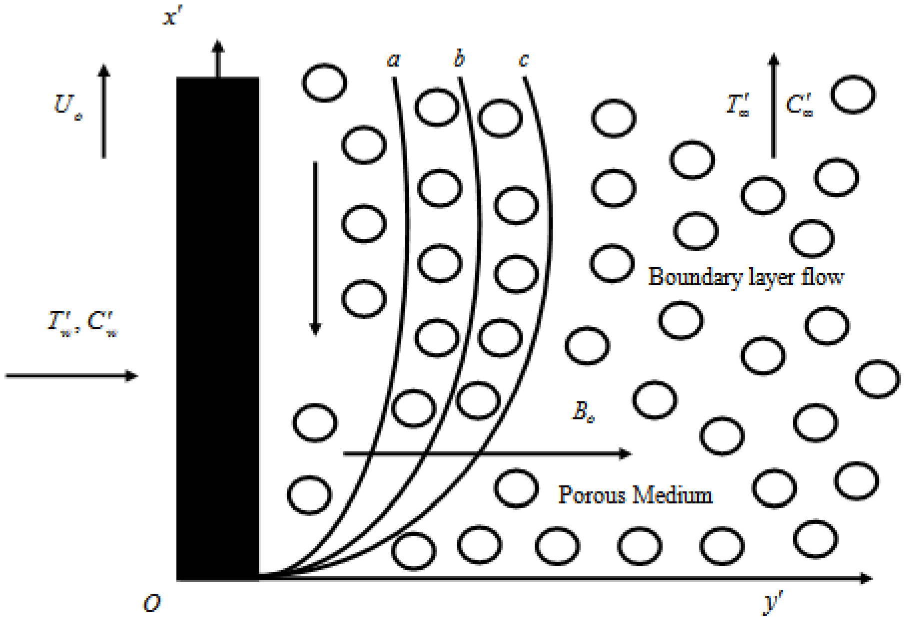

Fig. 1. Physical configuration of the problem

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

For an optically thick fluid, in addition to emission there is also self absorption and usually the absorption co-efficient is wavelength dependent and large so we can adopt the Rosseland approximation for the radiative heat flux vector . Thermal radiation is assumed to be present in the form of a unidirectional flux in the $y'-$direction i.e., q_r (Transverse to the vertical surface). By using the Rosseland approximation [68] the radiative heat flux q_r is given by:

$$q_r = -\left(\frac{4\sigma_s}{3k_e}\right)\frac{\partial T'^4}{\partial y'} \tag{5}$$

It should be noted that by using the Rosseland approximation, the present analysis is limited to optically thick fluids. If temperature differences within the flow are sufficiently small, then equation (5) can be linearized by expanding T'^4 in Taylor series about T'_∞ which after neglecting higher order terms takes the form:

$$T'^4 \cong T'^4_\infty + 4(T'-T'_\infty)T'^3_\infty = 4T'T'^3_\infty - 3T'^4_\infty \tag{6}$$

Using Eq. (5) and (6) in the last term of Eq. (2), we obtain

$$\frac{\partial q_r}{\partial y'} = -\frac{16\sigma_s T'^3_\infty}{3k_e}\frac{\partial^2 T'}{\partial y'^2} \tag{7}$$

Introducing (7) in the Eq. (2), the energy equation becomes

$$\frac{\partial T'}{\partial t'} = \left(\frac{\kappa}{\rho C_p}\right)\frac{\partial^2 T'}{\partial y'^2} - \frac{Q_o}{\rho C_p}(T'-T'_\infty) + \left(\frac{16\sigma_s T'^3_\infty}{3k_e \rho C_p}\right)\frac{\partial^2 T'}{\partial y'^2} \tag{8}$$

Let us introduce the following non-dimensional variables and parameters:

$$\left.\begin{array}{l} u=\dfrac{u'}{U_o},\ y=\dfrac{y'U_o}{\nu},\ \mathrm{t}=\dfrac{\mathrm{t}'\mathrm{U}_o^2}{\nu},\ \theta=\dfrac{T'-T'_\infty}{T'_w-T'_\infty},\ \phi=\dfrac{C'-C'_\infty}{C'_w-C'_\infty},\ M=\dfrac{\sigma B_o\nu}{\rho U_o^2},\ \mathrm{Re}=\dfrac{U_o x'}{\nu},\ Gr=\dfrac{g\beta\nu(T'_w-T'_\infty)}{U_o^3},\\ Gc=\dfrac{\nu g\beta^*(C'_w-C'_\infty)}{U_o^3},\ \mathrm{Pr}=\dfrac{\nu\rho C_p}{\kappa},\ Sc=\dfrac{\nu}{D},\ Q=\dfrac{Q_o\nu}{\rho C_p U_o^2},\ K=\dfrac{\nu^2}{K'U_o},\ Kr=\dfrac{k'_r\nu}{U_o^2},\ R=\dfrac{16\sigma_s T'^3_\infty}{3k_e\kappa},\ \lambda=\dfrac{\beta_1 U_o^2}{\nu^2} \end{array}\right\} \tag{9}$$

The above defined non-dimensionless variables in Eq. (9) into Eqs. (1), (3) and (8), and we get

$$\frac{\partial^2 u}{\partial y^2}-\frac{\partial u}{\partial t}-\left(M+\frac{1}{K}\right)u+Gr\theta+Gc\phi+\lambda\left(\frac{\partial^3 u}{\partial t\partial y^2}\right)=0 \tag{10}$$

$$(1+R)\frac{\partial^2\theta}{\partial y^2}-(\mathrm{Pr})\frac{\partial\theta}{\partial t}-(\mathrm{Pr})Q\theta=0 \tag{11}$$

$$\frac{\partial^2\phi}{\partial y^2}-(Sc)\frac{\partial\phi}{\partial t}-(Sc)(Kr)\phi=0 \tag{12}$$

with connected initial and boundary conditions

$$\left.\begin{array}{l} t\le 0:\ u=0,\ \theta=0,\ \phi=0\ \ for\ all\ \ y\\ t>0:\begin{cases} u=1,\ \theta=1,\ \phi=1\ \ at\ \ y=0\\ u=0,\ \theta=0,\ \phi=0\ \ as\ \ y\to\infty \end{cases} \end{array}\right\} \tag{13}$$

For the design of chemical engineering systems and practical engineering applications, the local skin-friction, Nusselt number and Sherwood number important physical parameters for this type of boundary layer flow. The Skin-friction at the plate, which in the non-dimensional form is given by

$$Cf=\left(\frac{\tau'_w}{\rho U_o\nu}\right)_{y'=0}=\left(\frac{\partial u}{\partial y}\right)_{y=0} \tag{14}$$

The rate of heat transfer coefficient, which in the non-dimensional form in terms of the Nusselt number is given by

$$Nu=-x'\frac{\left(\dfrac{\partial T'}{\partial y'}\right)_{y'=0}}{T'_w-T'_\infty}\ \ \Rightarrow Nu\,\mathrm{Re}^{-1}=-\left(\frac{\partial\theta}{\partial y}\right)_{y=0} \tag{15}$$

The rate of mass transfer coefficient, which in the non-dimensional form in terms of the Sherwood number, is given by

$$Sh=-x'\frac{\left(\dfrac{\partial C'}{\partial y'}\right)_{y'=0}}{C'_w-C'_\infty}\ \ \Rightarrow Sh\,\mathrm{Re}^{-1}=-\left(\frac{\partial\phi}{\partial y}\right)_{y=0} \tag{16}$$

III. Numerical Solutions by Finite Difference Method

The non-linear momentum, energy and concentration equations given in equations (10), (11) and (12) are solved under the appropriate initial and boundary conditions (13) by the implicit finite difference method. The transport equations (10), (11) and (12) at the grid point (*i*, *j*) are expressed in difference form using Taylor's expansion.

$$\left(\frac{u_{i+1}^j-2u_i^j+u_{i-1}^j}{(\Delta y)^2}\right)-\left(\frac{u_i^{j+1}-u_i^j}{\Delta t}\right)-\left(M+\frac{1}{K}\right)u_i^j+(Gr)\theta_i^j+(Gc)\phi_i^j+\lambda\left(\frac{u_{i+1}^{j+1}-2u_i^{j+1}+u_{i-1}^{j+1}-u_{i+1}^j+2u_i^j-u_{i-1}^j}{\Delta t(\Delta y)^2}\right)=0 \tag{17}$$

$$(1+R)\left(\frac{\theta_{i+1}^j-2\theta_i^j+\theta_{i-1}^j}{(\Delta y)^2}\right)-(\mathrm{Pr})\left(\frac{\theta_i^{j+1}-\theta_i^j}{\Delta t}\right)-(\mathrm{Pr})Q\theta_i^j=0 \tag{18}$$

$$\left(\frac{\phi_{i+1}^{j}-2\phi_{i}^{j}+\phi_{i-1}^{j}}{(\Delta y)^{2}}\right)-(Sc)\left(\frac{\phi_{i}^{j+1}-\phi_{i}^{j}}{\Delta t}\right)-(Sc)(Kr)\phi_{i}^{j}=0 \quad (19)$$

Where the indices i and j refer to y and t respectively. The initial and boundary conditions (13) yield.

$$\left.\begin{array}{l} u_i^0=0,\ \theta_i^0=0,\ \phi_i^0=0\ for\ all\ i, \\ u_i^j=1,\ \theta_i^j=1,\ \phi_i^j=1\ at\ i=0 \\ u_M^j\to 0,\ \theta_M^j\to 0,\ \phi_M^j\to 0 \end{array}\right\} \quad (20)$$

Thus the values of u, θ and ϕ 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 $i=1, 2, \ldots\ldots, N-1$. 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, θ and ϕ is gained at convergence criteria.

$$abs\left|(u,\ \theta,\ \phi)_{exact}-(u,\ \theta,\ \phi)_{numerical}\right|<10^{-3} \quad (21)$$

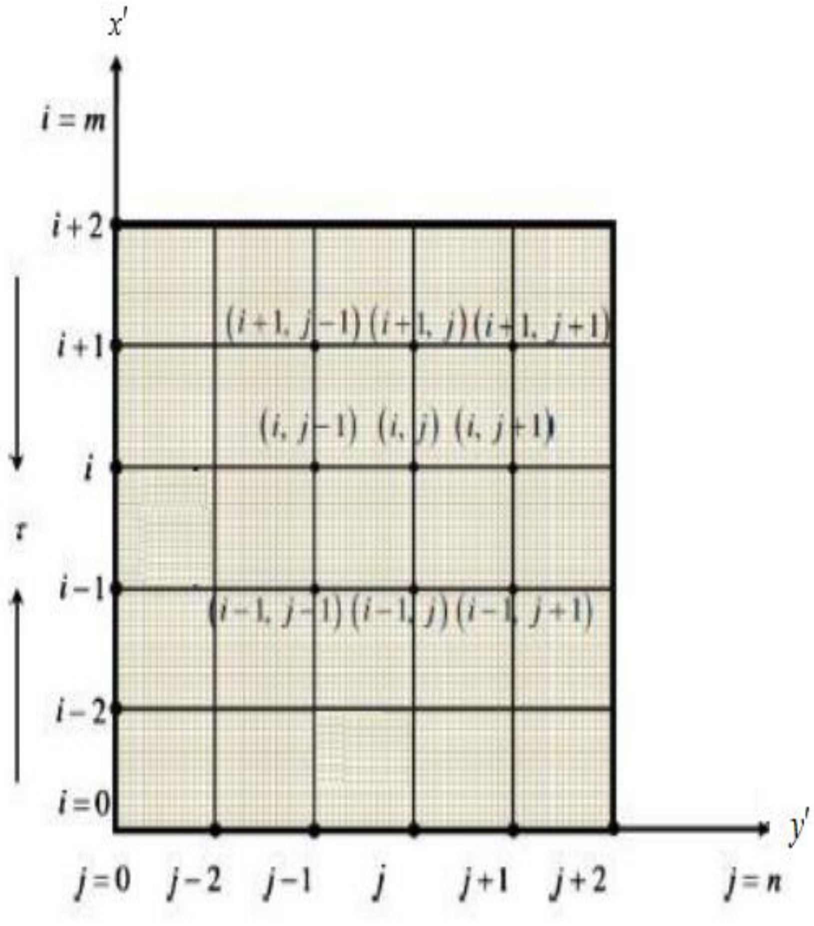

Fig. 2. Finite difference space grid

IV. Validation of Code

For code validation purpose, the author compared present numerical results with the exisistance analytical results of Mohamed et al. [67] in Fig. 3 in the absence of non-newtonian viscoelastic Rivlin-Ericksen fluid. From this figure, it is observed that the relevant results obtained agree quantitatively with earlier results of Mohamed et al. [67].

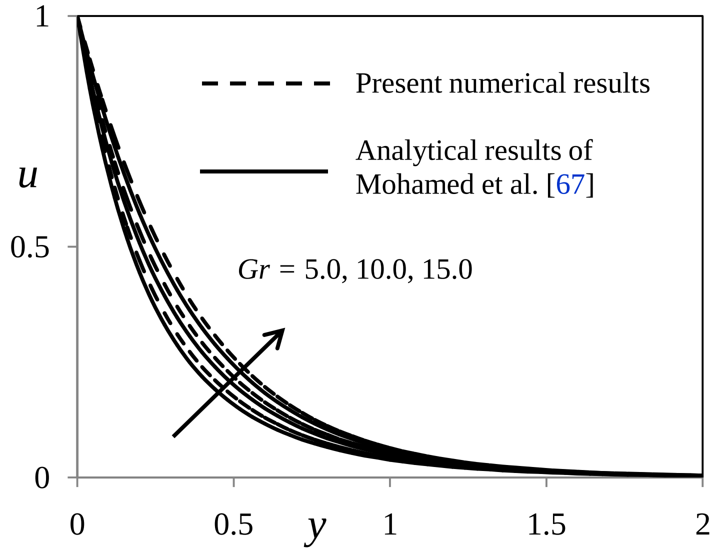

Fig. 3. Comparison between present numerical results with the analytical results of Mohamed et al. [67] for different values of *Gr* in absence of viscoelastic Rivlin-Ericksen fluid.

V. Results and Discussions

In order to point out the effects of various 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*), Thermal radiation parameter (*R*), Heat absorption parameter (*Q*), Chemical reaction parameter (*Kr*) and viscoelastic Rivlin-Ericksen fluid parameter (λ) are discussed in the following lines. on flow characteristic, the following discussion is set out. The effect of these pertinent parameters is shown in the graphs. In the present study, the following default parameter values are adopted for computations: $Gr = 2.0$, $Gc = 2.0$, $K = 0.5$, $M = 0.5$, $Q = 0.5$, $R = 0.5$, $Kr = 0.5$ and $\lambda = 0.5$. All graphs therefore correspond to these values unless specifically indicated in the appropriate graph. The velocity profiles for different values of Grashof number for heat transfer *Gr* are described in Fig. 4. It is observed that an increase in *Gr* leads to a rise in the values of velocity. Here the Grashof number for heat transfer represent the effect of free convection currents. Physically, $Gr > 0$ means heating of the fluid of cooling of the boundary surface, $Gr < 0$ means cooling of the fluid of heating of the boundary surface and $Gr = 0$ corresponds the absence of free convection current. The velocity profiles for different values of Grashof number for mass transfer *Gc* are described in Fig. 5. It is observed that an increase in *Gc* leads to a rise in the values of velocity.

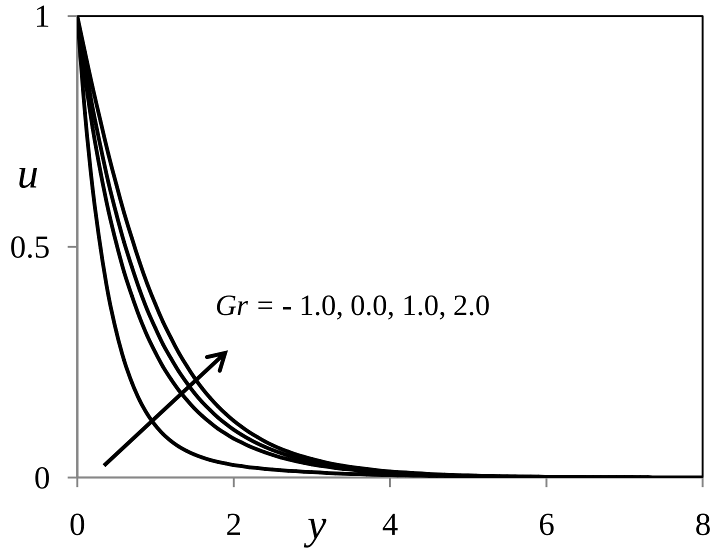

Fig. 4. *Gr* influence on velocity profiles

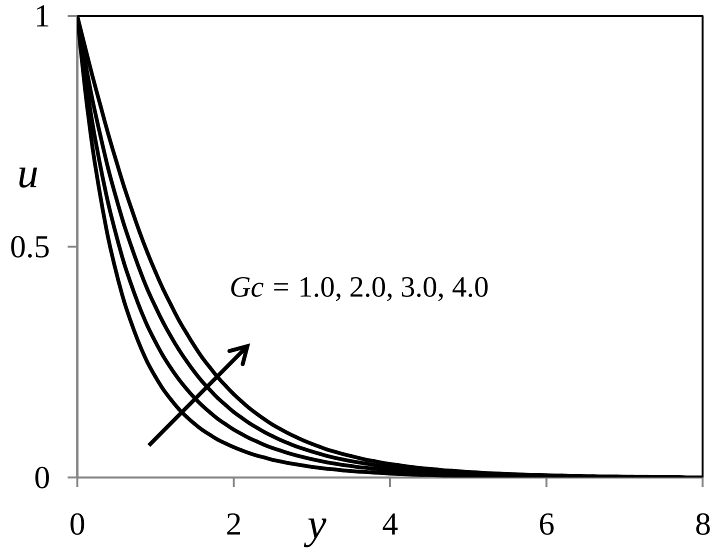

Fig. 5. *Gc* influence on velocity profiles

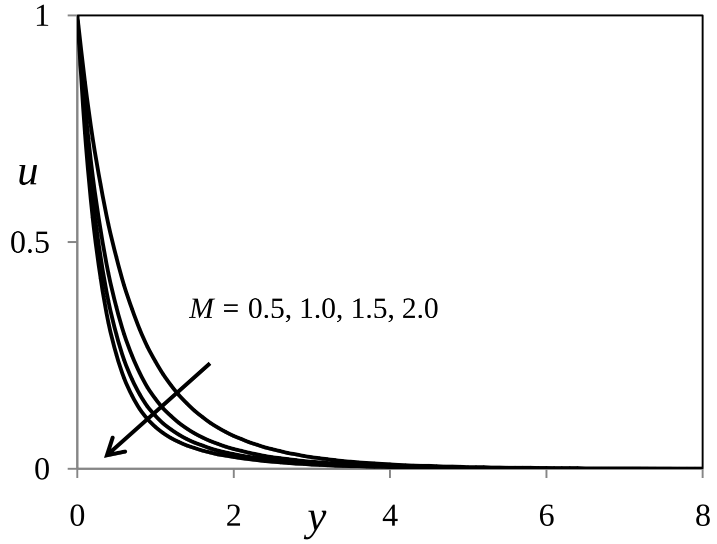

Fig. 6. *M* influence on velocity profiles

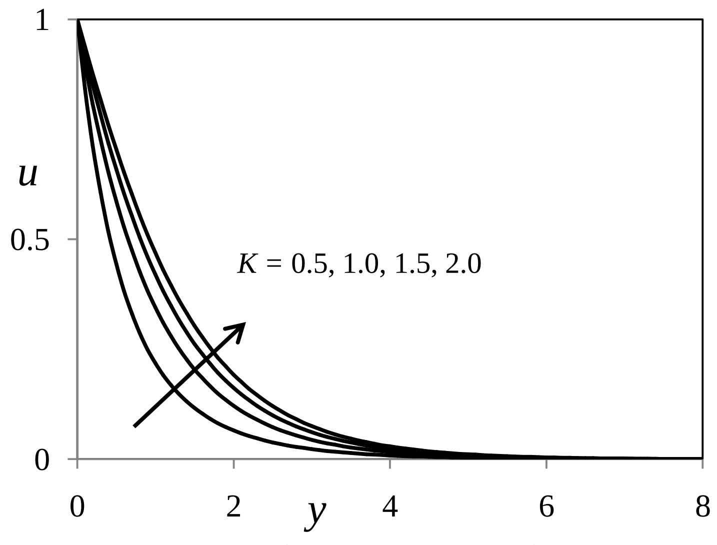

Fig. 7. *K* influence on velocity profiles

Fig. 6 shows the effect of magnetic parameter M on the velocity. From this figure it is observed that velocity decreases, in both the cases of air and water, as the value of M is increased. This is due to the application of a magnetic field to an electrically conducting fluid produces a dragline force which causes reduction in the fluid velocity. Fig. 7 depicts the velocity profiles for various values of K. From this figure it is observed that fluid velocity increases as K increases and reaches its maximum over a very short distance from the plate and then gradually reaches to zero for both water and air. Physically, an increase in the permeability of porous medium leads the rise in the flow of fluid through it. When the holes of the porous medium become large, the resistance of the medium may be neglected. Figs. 8 and 9 illustrate the velocity and temperature profiles for different values of Prandtl number. The numerical results show that the increasing values of Prandtl number, leads to velocity decreasing.

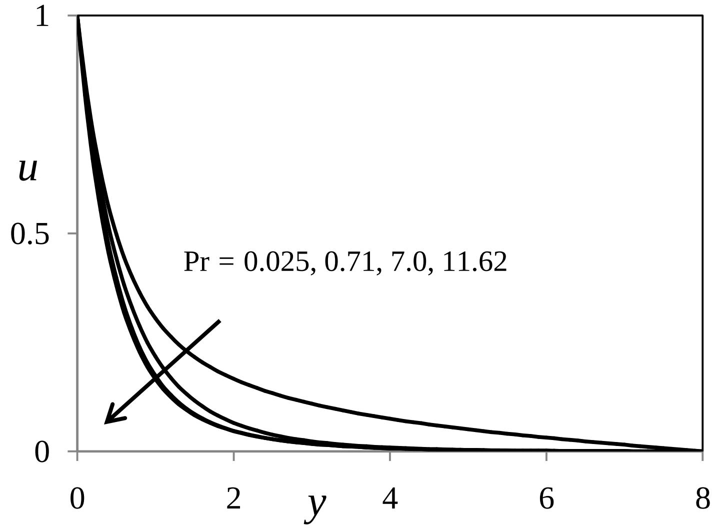

Fig. 8. Pr influence on velocity profiles

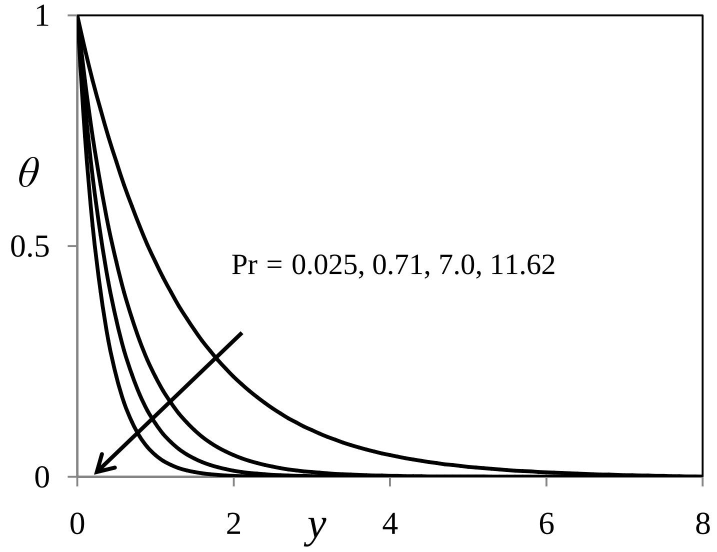

Fig. 9. Pr influence on temperature profiles

From Fig. 9, the numerical results show that, the increasing values of Prandtl number leads to a decrease in the thermal boundary layer, and in general, lower average temperature within the boundary layer. The reason is that smaller values of Pr are equivalent to increasing the thermal conductivity of the fluid and therefore heat is able to diffuse away from the heated surface more rapidly for higher values of Pr. Hence, in the case of smaller Prandtl number, the thermal boundary layer is thicker and the rate of heat transfer is reduced. For various values of the Schmidt number Sc, the velocity and concentration are plotted in Figs. 10 and 11. As the Schmidt number increases, the concentration decreases. This causes the concentration buoyancy effects decrease, yielding a reduction in the fluid velocity. Reductions in the velocity and concentration profiles are accompanied by simultaneous reductions in the velocity and concentration boundary layers. These behaviours are evident from Figs. 10 and 11.

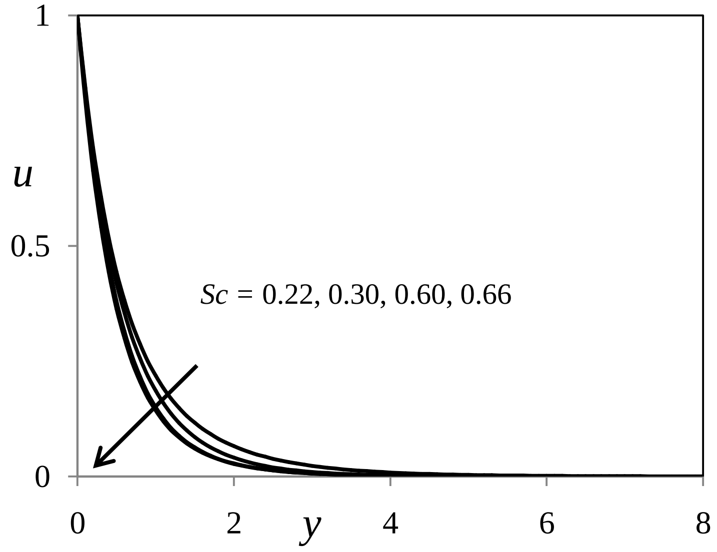

Fig. 10. *Sc* influence on velocity profiles

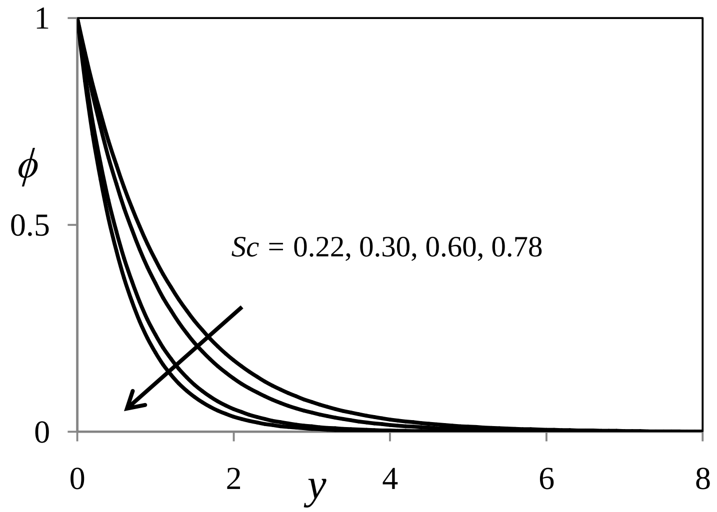

Fig. 11. *Sc* influence on concentration profiles

The effect of the thermal radiation parameter R on the velocity and temperature profiles in the boundary layer are illustrated in Figs. 12 and 13 respectively. Increasing the thermal radiation parameter R produces significant increase in the thermal condition of the fluid and its thermal boundary layer. This increase in the fluid temperature induces more flow in the boundary layer causing the velocity of the fluid there to increase. Figs. 14 and 15 has been plotted to depict the variation of velocity and temperature profiles against y for different values of heat source parameter Q by fixing other physical parameters. From this Graph we observe that velocity and temperature decrease with increase in the heat source parameter Q because when heat is absorbed, the buoyancy force decreases the temperature profiles. Fig. 16 displays the effect of the chemical reaction parameter Kr on the velocity profiles. As expected, the presence of the chemical reaction significantly affects the velocity profiles. It should be mentioned that the studied case is for a destructive chemical reaction Kr. In fact, as chemical reaction Kr increases, the considerable reduction in the velocity profiles is predicted, and the presence of the peak indicates that the maximum value of the velocity occurs in the body of the fluid close to the surface but not at the surface. Fig. 17 depicts the concentration profiles for different values of Kr, from which it is noticed that concentration decreases with an increase in chemical reaction parameter. This is due to the chemical reaction mass diffuses from higher concentration levels to lower concentration levels. The velocity profiles in the Fig. 18 shows that rate of motion is significantly reduced with increasing of viscoelastic Rivlin-Ericksen fluid parameter λ.

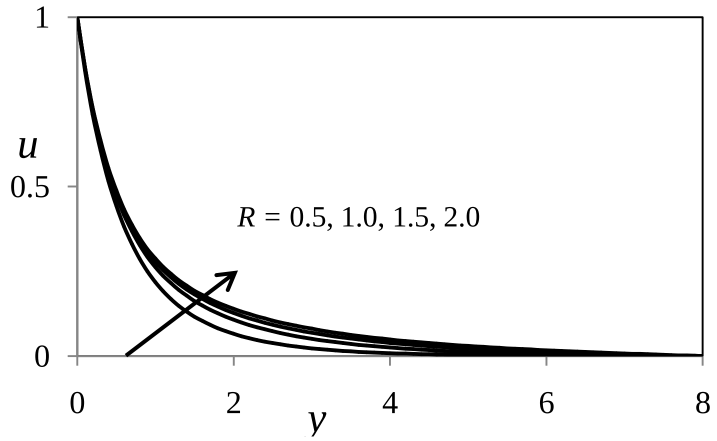

Fig. 12. *R* influence on velocity profiles

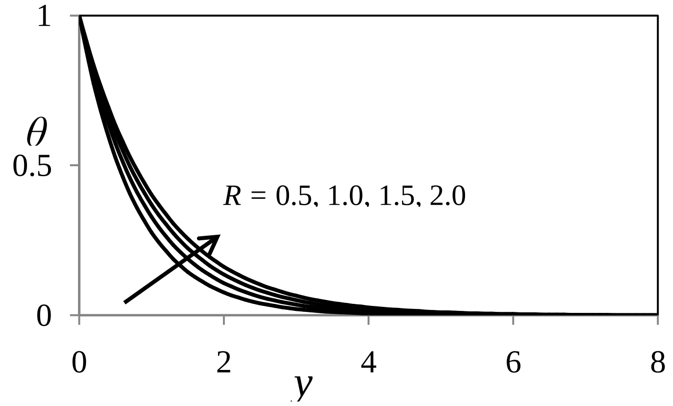

Fig. 13. *R* influence on temperature profiles

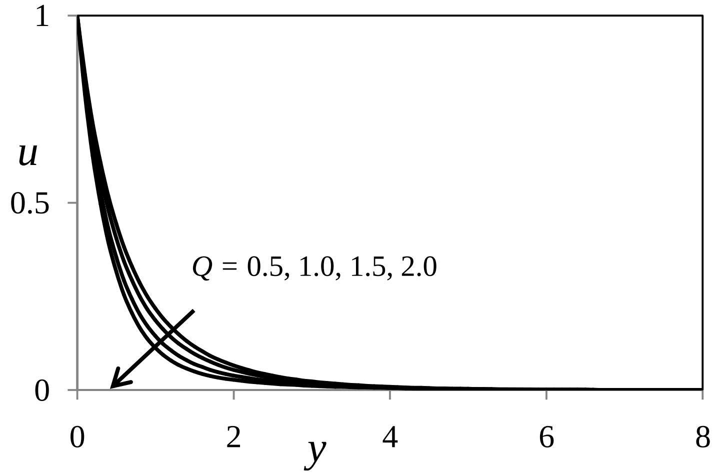

Fig. 14. *Q* influence on velocity profiles

The numerical computation of skin-friction coefficient is obtained and presented in table-1. It is observed that Magnetic field parameter, Prandtl number, Schmidt number, Chemical reaction parameter, Heat absorption parameter, viscoelastic Rivlin-Ericksen fluid parameter decreases the skin-friction coefficient whereas it increases due to increase in Grashof number for heat transfer, Grashof number for mass transfer, Permeability parameter, Thermal radiation parameter. The numerical values of Nusselt and Sherwood numbers are presented in table-2. With increase in the Thermal radiation parameter, the Nusselt number increases but for the other parameters such as Prandtl number and Heat absorption parameter it decreases. A significant decrease is remarked in case of Sherwood number when there is an increase in the value of the Schmidt number and Chemical reaction parameter.

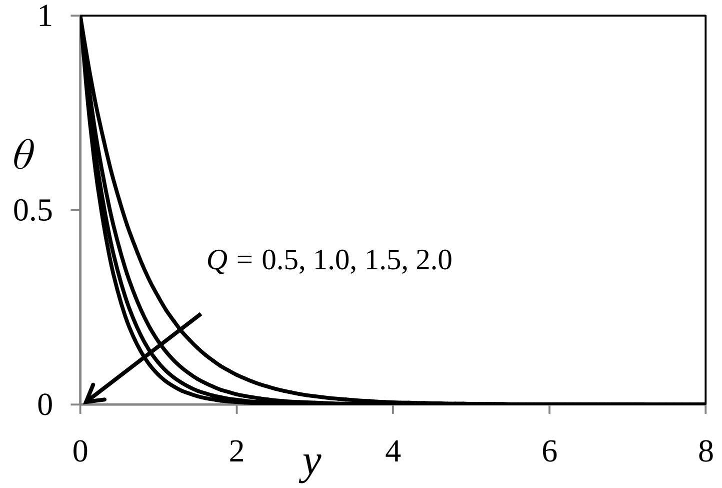

Fig. 15. *Q* influence on temperature profiles

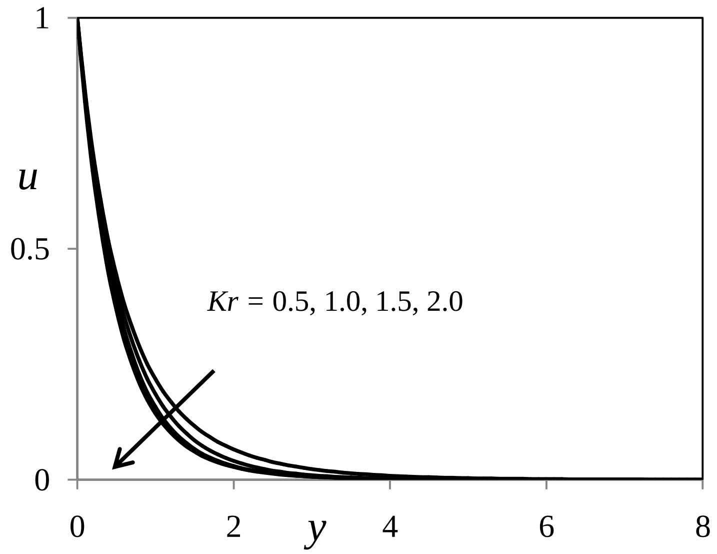

Fig. 16. *Kr* influence on velocity profiles

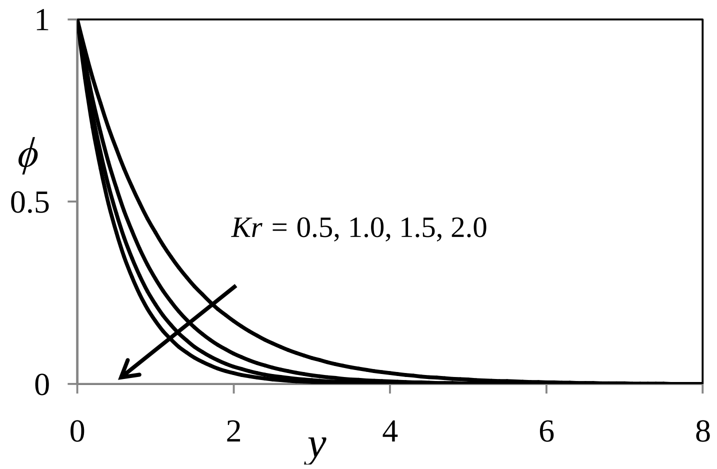

Fig. 17. *Kr* influence on concentration profiles

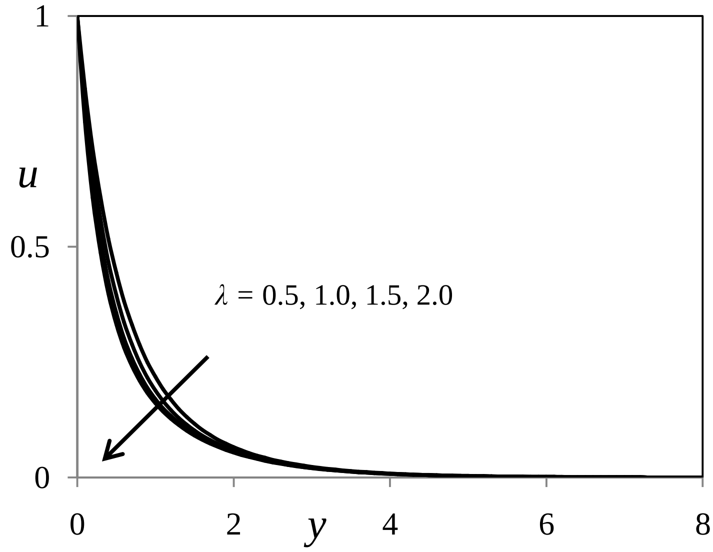

Fig. 18. λ influence on velocity profiles

Table-1: Numerical values of Skin-friction coefficient

Gr	*Gc*	*M*	*K*	Pr	*Sc*	*R*	*Q*	*Kr*	*λ*	*Cf*
2.0	2.0	0.5	0.5	0.71	0.22	0.5	0.5	0.5	0.5	- 1.2846875191
4.0	2.0	0.5	0.5	0.71	0.22	0.5	0.5	0.5	0.5	- 1.1655237675
2.0	4.0	0.5	0.5	0.71	0.22	0.5	0.5	0.5	0.5	- 1.0543143749
2.0	2.0	1.0	0.5	0.71	0.22	0.5	0.5	0.5	0.5	- 1.4110714197
2.0	2.0	0.5	1.0	0.71	0.22	0.5	0.5	0.5	0.5	- 1.2232890129
2.0	2.0	0.5	0.5	7.00	0.22	0.5	0.5	0.5	0.5	- 1.5358617306
2.0	2.0	0.5	0.5	0.71	0.30	0.5	0.5	0.5	0.5	- 1.3764232397
2.0	2.0	0.5	0.5	0.71	0.22	1.0	0.5	0.5	0.5	- 1.2459697723
2.0	2.0	0.5	0.5	0.71	0.22	0.5	1.0	0.5	0.5	- 1.3734459877
2.0	2.0	0.5	0.5	0.71	0.22	0.5	0.5	1.0	0.5	- 1.5072053671
2.0	2.0	0.5	0.5	0.71	0.22	0.5	0.5	0.5	1.0	- 1.3206881285

Table-2: Numerical values of Nusselt and Sherwood numbers

Pr	*R*	*Q*	*Nu*	*Sc*	*Kr*	*Sh*
0.70	0.5	0.5	1.5997371674	0.22	0.5	1.3697352409
2.00	0.5	0.5	1.1940317154	0.30	0.5	1.2269530296
0.70	1.0	0.5	1.3875653744	0.60	0.5	1.1187126637
0.70	0.5	1.0	1.6387772560	0.22	1.0	1.4032427692

VI. Conclusions

In this paper, the combined effects of thermal radiation and heat absorption on unsteady MHD free (natural) convective viscoelastic Rivlin-Ericksen fluid flow past an infinite vertical plate with chemical reaction and heat-mass transfer. Numerical analysis is made and the upshots are summarized as follows:

1. As increasing of *M*, Pr, *Sc*, *Q*, *Kr* and λ, the skin-friction coefficient decreases while it increases with an increase in *Gr*, *Gc*, *K* and *R*.
2. Temperature decreases with an increase in Pr and *Q* while it increases with an increase in *R*.
3. Concentration decreases with an increase in *Sc* and *Kr*.
4. Local skin-friction increases with an increase in *Gr*, *Gc*, *K* and *R* while it decreases for rising values of *M*, Pr, *Sc*, *Q*, *Kr* and λ.
5. Nusselt number decreases with an increase in Pr and *Q* while it increases with an increase in *R*.
6. Sherwood number decreases with an increase in *Sc* and *Kr*.
7. Finally, the present numerical results coincides with the published results of Mohamed et al. [67].

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