DIFFUSION-THERMO AND THERMAL-DIFFUSION EFFECTS ON RIVLIN-ERICKSEN ROTATORY CONVECTIVE FLOW PAST A POROUS VERTICAL PLATE

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ABSTRACT

Diffusion-thermo and thermal-diffusion effects on unsteady, incompressible Rivlin-Ericksen rotatory convective flow of a magnetic conducting electrical fluid with time dependent suction between two vertical plates of which one is permeable are investigated. The uniform angular velocity rotates about an axis normal to the plate. The equations governing the flow model are non-dimensionalised, perturbed for simplification and solved by Adomian decomposition method. Graphical illustrations of the fluid parameters on velocity, temperature, concentration are presented and discussed. The effect of skin-friction, Nusselt and Sherwood numbers are presented in tabular forms and it is discovered from the results that a rise in thermal-diffusion parameter speedup the skin-friction, while increasing diffusion-thermo parameter slowdown the skin-friction.

Keywords: Diffusion-thermo, Rivlin-Ericksen fluid, Rotatory, thermal-diffusion and Unsteady.

1. INTRODUCTION

Forced and free convection mechanisms contribute significantly to heat transfer. The phenomenon occurs in both industrial and technical problems such as solar collectors, in cooling of electronic devices and nuclear reactors resulting in an emergency shutdown etc. The significance of these applications led some researchers to study natural, forced and mixed convective flows in the presence of heat and mass transfer. Deepthi and Prasada (2017) considered heat and mass transfer with mixed convective flow in the presence of radiation and Soret. In the investigation, rotatory and Dufour effects were considered insignificant. The result shown that a rise in Soret parameter decreased the heat and mass transfer rate on the walls. Soret effect on mixed convection viscoelastic fluid flow in the presence of heat and mass transfer was studied by Devasena and Ratmat (2014). The effects of Dufour and thermal radiation were not considered. Dada and Agunbiade (2016) examined the effects of chemical reaction and radiation on convective non-rotatory Rivlin-Ericksen fluid flow in a vertical porous plate. It was discovered that temperature and velocity decreased as radiation parameter increased. Aruna et al. (2015) investigated the influence of both thermal-diffusion and diffusion-thermo of non-rotatory mixed convective hydromagnetic fluid flow through a vertical wavy porous plate. The finite difference method was used to obtain the solution.

However, the study of rotating medium is of great importance in fluid dynamics as a result of its relevance in many natural phenomena and its applications in technology relating to Coriolis force. Some of the applications of rotating flow, particularly in porous media in the field of engineering, to mention but a few are rotating machinery, food and chemical processing industries. The study of rotating flow has gained the interest of many researchers due to its importance. Sibanda and Makinde (2010) examined steady MHD flow with heat transfer as a result of rotating disk in a porous fluid in the presence of viscous dissipation. Mutua et al. (2013) considered MHD free convection flow of a Newtonian fluid with variable suction through porous plate and the result revealed that skin friction increased both along $x$ and $y$ axes due to a decrease in rotation parameter.

In addition, Singh (2013) studied thermal radiation effects on rotatory viscoelastic MHD flow via a vertical plate. It was reported that rotation parameter enhanced velocity profiles. Oldroyd-B Rotating MHD radiative fluid through a vertical porous channel was carried out by Garg et al. (2014b). Guria and Jana (2013) examined rotatory viscoelastic fluid past a porous plate under a uniform suction. It was discovered that the presence of viscoelastic parameter contributed to the increase in the plate heat transfer. Abdulmajeque (2017) investigated the effects of temperature dependent suction/injection on non-Newtonian casson radiative fluid flow with viscous dissipation. Also, Garg et al. (2014a) presented oscillatory viscoelastic fluid flow through a porous rotating vertical channel with an assumption of an optically thin radiation and constant suction. The result showed that as the rotation parameter increased, the velocity decreased. Even though, the above investigations had contributed to the studies of fluid flow but the effects of chemical reaction was neglected in the studies and chemical reactions have tremendous impacts in changing the rate of mass diffusion.

In fluid flow that involves both heat and mass transfer, driving po-
tentials and the fluxes relation are significantly noted. The energy flux that 
is generated due to concentration gradient is referred to as diffusion-
thermo, while mass flux resulting from temperature gradients is thermal-
diffusion. Mostly, the effects of diffusion-thermo and thermal-diffusion 
are often neglected in most studies on the bases that they are of low mag-
nitude in relation to the rest chemical species. The effects of Dufour and 
Soret become significant phenomena in areas like petrology, hydrology, 
geosciences, etc. The effect of thermal-diffusion is relevant, for example, 
in the separation of isoipe and mixture of gases that has light molecular 
weight. Therefore, Sarma and Govardhan (2016) reported on the effects 
of thermal-diffusion and diffusion-thermo on natural convection heat and 
mass transfer with thermal radiation in the presence of viscous dissipation 
in a porous medium. A Newtonian fluid was examined in the study and 
fine difference method was used in the computations of the results. It 
was reported that velocity profiles was accelerated by increase in viscous 
dissipation. The effects of thermal-diffusion and diffusion-thermo on free 
convection MHD flow of Rivlin-Ericksen fluid was examined by Reddy 
et al. (2016). Rotatory and thermal radiation effects were considered to 
be insignificant, the result shown that an increase in diffusion-thermo and 
thermal-diffusion speedup the skin-friction. Gbadeyan et al. (2011) ex-
amined the influence of Soret and Dufour with heat and mass transfer 
on mixed convective viscoelastic fluid flow past a porous medium. It was 
observed from the result that Soret enhanced both concentration and tem-
perature profiles.

Furthermore, Dada and Salawu (2017) presented heat and mass trans-
fer of pressure-driven flow with inclined magnetic field. The result re-
vealed that an increase in chemical reaction reduced both pressure and 
concentration profiles. Ibrahim and Suneetha (2015) studied effects of 
Soret and chemical reaction on MHD unsteady viscoelastic fluid past an 
infinite vertical plate. The study concluded that both concentration and 
velocity profiles increased as thermal-diffusion increased. Hayat et al. 
(2017) investigated Dufour and Soret effects on MHD Jeffrey fluid of 
peristaltic transport in a curved channel. It was observed that Dufour and 
Soret have opposite behaviour for concentration and temperature. Babu 
et al. (2017) considered diffusion-thermo and thermal-diffusion effects on 
heat and mass transfer MHD Jeffery fluid flow in a stretching sheet. The 
result revealed that temperature profiles was reduced by an increase in ei-
ther Prandtl number or Soret parameter. Influence of thermal-diffusion on 
Kurvinshiki fluid in the presence of heat and mass transfer past a verti-
cal porous plate was investigated by Jimoh et al. (2014). At the boundary 
layer, the result shown that increase in the heat sources parameter im-
proved both velocity and temperature profiles. However, as impressive as 
the above studies were, rotatory Rivlin-Ericksen fluid flows have received 
no significant attention.

A careful examination of all the above studies on heat and mass trans-
fer showed that combined effects of time dependence suction, pressure 
gradiant and heat absorption in Rivlin-Ericksen convective fluid flow in 
a rotating medium with diffusion-thermo and thermal-diffusion have re-
ceived little or no attention. Considering various phenomena, combined 
effects of all these parameters come into consideration in a prac-
tical flows of fluid and are of practical applications in the field of en-
geering, chemical processing industry, rotating machinery, paper and 
food processing industry, petroleum industry and other areas that involve 
viscoelastic fluid flow. Hence, this present study analyses the effects of 
diffusion-thermo, thermal-diffusion and radiation effects on convective 
Rivlin-Ericksen fluid in a rotating system with chemical reaction.

2. MATHEMATICAL ANALYSIS

Consider a non-Newtonian, two-dimensional incompressible free convect-
ive Rivlin-Ericksen flow of an electrically conducting fluid through a 
rotating vertical channel with a periodic suction. The following assump-
tions are made in the formulation of this problem:

(i) an unsteady and laminar flow is considered;

(ii) induced magnetic field and Hall effects are ignored due to the fact 
that magnetic Reynolds number and transversely applied magnetic 
field is considered to be very small;

(iii) a magnetic field ($B_0$) of uniform strength is perpendicularly applied 

to the plates;

(iv) there is a rotation of the entire system through the perpendicular 
axis to the plates;

(v) thermal-diffusion and diffusion-thermo are assumed to be of sub-
stantial magnitude, hence, they are not negligible;

(vi) the plates are considered to be infinite in relation to the rest chemical 
species. The effects of Dufour and Soret become significant phenomena 
in areas like petrology, hydrology, geosciences, etc. The effect of thermal-
diffusion is relevant, for example, in the separation of isoipe and mixture of gases that has light molecular 
weight. Therefore, Sarma and Govardhan (2016) reported on the effects 
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in a porous medium. A Newtonian fluid was examined in the study and 
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diffusion-thermo, thermal-diffusion and radiation effects on convective 
Rivlin-Ericksen fluid in a rotating system with chemical reaction.

\begin{equation}
\frac{\partial u^*}{\partial z^*} = 0
\end{equation}

\begin{equation}
\frac{\partial u^*}{\partial t^*} + \nu^* \frac{\partial u^*}{\partial z^*} = - \frac{1}{\rho} \frac{\partial p^*}{\partial x^*} + \frac{\nu^2 u^*}{\partial z^*} + 2\Omega^* v^* + \frac{\sigma B_0^2 u^*}{\rho} - \beta_1 \left( \frac{\partial^2 u^*}{\partial t^* \partial z^*} + \nu^* \frac{\partial^3 u^*}{\partial z^3} \right)
\end{equation}

\begin{equation}
\frac{\partial v^*}{\partial t^*} + \nu^* \frac{\partial v^*}{\partial z^*} = - \frac{1}{\rho} \frac{\partial p^*}{\partial x^*} + \frac{\nu^2 v^*}{\partial z^*} - 2\Omega^* u^* - \nu^* \frac{\sigma B_0^2 v^*}{\rho} - \beta_1 \left( \frac{\partial^2 v^*}{\partial t^* \partial z^*} + \nu^* \frac{\partial^3 v^*}{\partial z^3} \right)
\end{equation}
\[
\frac{\partial T^*}{\partial t^*} + \nu^* \frac{\partial T^*}{\partial z^*} = \frac{\partial^2 T^*}{\partial z^*^2} - \frac{\phi_0 \rho c_p}{\rho c_p} (T^* - T_0^*) - \frac{1}{\rho c_p} \frac{\partial q_{R}}{\partial \eta} + \frac{DK_T \partial^2 C^*}{C_p \rho C_z \partial z^*^2} \\
\frac{\partial C^*}{\partial t^*} + \nu^* \frac{\partial C^*}{\partial z^*} = D \frac{\partial^2 C^*}{\partial z^*^2} - K_1^* (C^* - C_n^*) + \frac{DK_T \partial^2 T^*}{T_m} 
\]

The boundary conditions for the problem are:

\[ z^* = 0; u^* = v^* = 0, T^* = T_0^* + \epsilon (T_0^* - T_n^*) \cos \tau^* t, \quad C^* = C_0^* + \epsilon (C_n^* - C_0^*) \cos \tau^* t, \quad z^* = h, \quad u^* = W_0 (1 + \epsilon \cos \tau^* t), \quad v^* = 0, \quad T^* = T_0^*, \quad C^* = C_n^* \]

The time dependent suction velocity is expressed in exponential form as:

\[ v^* = -W_0 (1 + \epsilon A e^{i\omega t} t) \] (Das et al. 2011), \( \epsilon \) and \( \epsilon A \) is small values less than unity. \( q_{R} \) is the radiative heat flux and is defined base on Rosseland approximation (Blob and BOOM 1972) as:

\[ q_{R} = -\frac{4\sigma}{3} \frac{\partial T}{\partial \eta} \]

This present analysis is limited to optically thick fluid, hence Rosseland approximation is used. Considering the temperature differences within the flow to be sufficiently small, \( T^* \) (quartic temperature function) can be expanded using Taylor series expansion and neglecting higher order terms gives:

\[ T^{*^4} \approx 4T^n_0^3 T^* - 3T^n_0^4 \]

This is substituted into radiative heat flux term that was used in Eq. (4). The pressure gradient for the fluid is considered in the form:

\[ -\frac{1}{\rho} \frac{\partial \rho}{\partial \eta} = 0 \quad \text{and} \quad -\frac{1}{\rho} \frac{\partial \rho}{\partial T} = H \cos \omega t \]

where \( H \) is a constant and it oscillates only in \( x \)-axis direction.

The accompanying non-dimensional variables are utilized to reduce the governing equations to non-dimensional form.

\[
\begin{align*}
\xi & = \frac{w^*}{W_0}, \quad v = \frac{v^*}{\psi^*}, \quad t = \frac{t^*W_0}{L}, \quad \eta = \frac{W_0 z^*}{L}, \quad \tau = \frac{\omega t^*}{L}, \\
\theta & = \frac{v}{\nu \psi^*}, \quad \nu \psi \frac{\partial \psi}{\partial x} = \frac{\nu \psi}{\partial x}, \quad x = \frac{W_0}{W_0}, \\
M & = \frac{\nu \psi C_p}{\nu \psi C_z}, \quad G_m = \frac{\nu \psi C_p}{\nu \psi C_z}, \quad S_0 = \frac{k_0}{\nu \psi C_z}, \quad V_T = \frac{\nu \psi C_p}{\nu \psi C_z}, \\
G_m & = \frac{\nu \psi C_p}{\nu \psi C_z}, \quad y = \frac{W_0}{W_0}, \quad P = \frac{P_T}{\nu \psi C_z}, \quad \zeta = \frac{\nu \psi C_p}{\nu \psi C_z}, \\
E & = \frac{k_1 k_p}{4 \nu \psi T_0}, \quad \Omega = \frac{\nu \psi}{\nu \psi C_z}, \quad K_p = \frac{k_1 k_p}{4 \nu \psi T_0}, \quad \phi = \frac{\nu \psi}{\nu \psi C_z}, \\
S_p & = \frac{\nu \psi C_p}{\nu \psi C_z}, \quad 2 \nu \psi C_z, \quad D_p = \frac{\nu \psi C_p}{\nu \psi C_z}, \quad 2 \nu \psi C_z, \quad k_p = \frac{k_1 k_p}{4 \nu \psi T_0}
\end{align*}
\]

By applying non-dimensional variables (10), Eqs. (2)-(5) become

\[ \frac{\partial \xi}{\partial \tau} - \left(1 + \epsilon A e^{i\omega t} \right) \frac{\partial \xi}{\partial \eta} = H \cos \omega t + \frac{\partial^2 \xi}{\partial \eta^2} + 2 \Omega v + G_m \theta - \left( M \frac{1}{k_p} \right) \xi + G_m \zeta - V_R \left( \frac{\partial^3 \xi}{\partial \eta^3} - \left(1 + \epsilon A e^{i\omega \eta} \right) \frac{\partial^2 \xi}{\partial \eta^2} \right) \]

\[ \frac{\partial v}{\partial \tau} - \left(1 + \epsilon A e^{i\omega t} \right) \frac{\partial v}{\partial \eta} = \frac{\partial^2 v}{\partial \eta^2} - 2 \Omega - \left( M \frac{1}{k_p} \right) \nu \psi - V_R \left( \frac{\partial^3 v}{\partial \eta^3} - \left(1 + \epsilon A e^{i\omega \eta} \right) \frac{\partial^2 \nu \psi}{\partial \eta^2} \right) \]

\[ \frac{\partial \psi}{\partial \tau} - \left(1 + \epsilon A e^{i\omega t} \right) \frac{\partial \psi}{\partial \eta} = \left( \frac{1}{F_r} + \frac{4}{3 \nu \psi T_0} \right) \frac{\partial^2 \psi}{\partial \eta^2} - \phi \theta + D_p \frac{\partial^2 \zeta}{\partial \eta^2} \]

The boundary conditions for the problem are:

\[ \psi = 0, \quad \theta = 1 + \frac{1}{2} (e^{i\omega \eta} e^{i\omega t} + e^{-i\omega \eta} e^{-i\omega t}), \quad \zeta = 1 + \frac{1}{2} (e^{i\omega \eta} e^{i\omega t} + e^{-i\omega \eta} e^{-i\omega t}), \quad \phi = 0, \quad \zeta = 0 \text{ at } \eta = 1 \]

where \( \xi, \tau, \zeta, \psi, \Omega, R, \nu, k, M, \Omega, \theta, \phi, V_r, A, D_p, S_p, G_h, G_m \) are velocity, temperature, concentration, plates distance apart, rotation parameter, resultant velocity, radiation parameter, chemical reaction parameter, magnetic parameter, Prandtl number, Schmidt number, heat absorption parameter, viscoelasticity parameter, suction velocity parameter, Dufour number, Thermal-diffusion parameter, Grashof number for heat and mass transfer, respectively. Taking \( \psi = \xi + iv \) then, Eqs. (11) and (12) combine to

\[ \frac{\partial \psi}{\partial \tau} - \left(1 + \epsilon A e^{i\omega \eta} \right) \frac{\partial \psi}{\partial \eta} = H \cos \omega t + \frac{\partial^2 \psi}{\partial \eta^2} + 2 \Omega \psi + G_m \theta + \left(1 + \epsilon A e^{i\omega \eta} \right) \frac{\partial^2 \psi}{\partial \eta^2} \]

where

\[ F = M + \frac{1}{k_p} \]

### 3. Method of Solution

#### 3.1. Perturbation Method

The partial differential Eqs. (13), (14) and (16) are reduced to ordinary differential equations by Perturbation technique. Due to the nature of the boundary conditions, the assumed solutions can be written as follows (Garg et al. 2014b):

\[ \psi(\eta, t) = \psi_0(\eta) + \frac{1}{2} \left( \psi_1(\eta)e^{i\omega t} + \psi_2(\eta)e^{-i\omega t} \right) \]

\[ \psi(\eta, t) = \psi_0(\eta) + \frac{1}{2} \left( \psi_1(\eta)e^{i\omega t} + \psi_2(\eta)e^{-i\omega t} - \psi_3(\eta)e^{-i\omega t} \right) \]

Substituting equation (17) into Eqs. (13), (14) and (16) gives:

\[ V_R \psi_0'' + \psi_0'' + \left(2i\Omega + F \right) \psi_0 = -G_m \theta_0 - G_m \zeta_0 \]

\[ V_R \psi_1'' + (1 - V_R i\Omega) \psi_0'' + \psi_1'' - (i\pi + 2i\Omega + F) \psi_1 = -2A \psi_0 - G_h \theta_0 - G_h \zeta_0 - 2V_R \psi_0'' \]

\[ V_R \psi_2'' + (1 + V_R i\Omega) \psi_0'' + \psi_2'' - (2i\Omega + F - i\pi) \psi_2 = -2A \psi_0 - G_h \theta_0 - G_h \zeta_0 - 2V_R \psi_0'' \]

Where

\[ B = \frac{1}{F_r} + \frac{4}{3 \nu \psi T_0} \]

The boundary conditions for the problem are:

\[ \psi_0 = \psi_1 = \psi_2 = 0, \quad \theta_0 = \theta_1 = \theta_2 = 1, \quad \zeta_0 = \zeta_1 = \zeta_2 = 0 \text{ at } \eta = 0 \]

\[ \psi_0 = \psi_1 = \psi_2 = 1, \quad \theta_0 = \theta_1 = \theta_2 = 0, \quad \zeta_0 = \zeta_1 = \zeta_2 = 0 \text{ at } \eta = 1 \]
Equations (18)-(20) are third order differential equations with only two boundary conditions. In order to obtain necessary and sufficient boundary conditions (Beard and Walters (1964)) and (Garg et al. (2014b)), the solutions are expressed in the forms:

\[
\begin{align*}
\psi_0(\eta) &= \psi_{01}(\eta) + V_B \psi_{02}(\eta) + 0(V_B^2) \\
\psi_1(\eta) &= \psi_{11}(\eta) + V_B \psi_{12}(\eta) + 0(V_B^2) \\
\psi_2(\eta) &= \psi_{21}(\eta) + V_B \psi_{22}(\eta) + 0(V_B^2) \\
\phi_0(\eta) &= \phi_{01}(\eta) + V_B \phi_{02}(\eta) + 0(V_B^2) \\
\phi_1(\eta) &= \phi_{11}(\eta) + V_B \phi_{12}(\eta) + 0(V_B^2) \\
\phi_2(\eta) &= \phi_{21}(\eta) + V_B \phi_{22}(\eta) + 0(V_B^2) \\
\zeta_0(\eta) &= \zeta_{01}(\eta) + V_B \zeta_{02}(\eta) + 0(V_B^2) \\
\zeta_1(\eta) &= \zeta_{11}(\eta) + V_B \zeta_{12}(\eta) + 0(V_B^2) \\
\zeta_2(\eta) &= \zeta_{21}(\eta) + V_B \zeta_{22}(\eta) + 0(V_B^2)
\end{align*}
\]

subject to the following boundary conditions:

\[
\begin{align*}
\psi_{01} &= \psi_{02} = \psi_{11} = \psi_{12} = \psi_{21} = \psi_{22} = 0 \quad \eta = 0 \\
\psi_{01} &= \psi_{02} = \psi_{11} = \psi_{12} = \psi_{21} = \psi_{22} = 0 \quad \eta = 1 \\
\phi_{01} &= \phi_{11} = \phi_{21} = 1, \quad \phi_{02} = \phi_{12} = \phi_{22} = 0 \quad \eta = 0 \\
\phi_{01} &= \phi_{11} = \phi_{21} = 0, \quad \phi_{02} = \phi_{12} = \phi_{22} = 0 \quad \eta = 1 \\
\zeta_{01} &= \zeta_{02} = \zeta_{11} = \zeta_{12} = \zeta_{21} = \zeta_{22} = 0 \quad \eta = 0 \\
\zeta_{01} &= \zeta_{11} = \zeta_{12} = \zeta_{21} = \zeta_{22} = 0 \quad \eta = 1
\end{align*}
\]

Applying Eqs. (28) to Eqs. (18)-(26) gives:

\[
\begin{align*}
\psi_{01}'' &+ \psi_{01}' - (2\Omega + F) \psi_{01} = -G_3 \theta_{01} - G_m \zeta_{01} \\
\psi_{02}'' &+ \psi_{02}' - (2\Omega + F) \psi_{02} = -\psi_{01}'' - G_3 \theta_{02} - G_m \zeta_{02} \\
\psi_{11}'' &+ \psi_{11}' - (i\pi + 2\Omega + F) \psi_{11} = -H - 2A \psi_{01} \\
&\quad - G_3 \theta_{11} - G_m \zeta_{11} \\
\psi_{12}'' &+ \psi_{12}' - (i\pi + 2\Omega + F) \psi_{12} = i\pi \psi_{11}' - \psi_{11}'' - 2A \psi_{02} \\
&\quad - 2A \psi_{01}'' - G_3 \theta_{12} - G_m \zeta_{12} \\
\psi_{21}'' &+ \psi_{21}' - (2\Omega + F - i\pi) \psi_{21} = -H - G_3 \theta_{21} - G_m \zeta_{21} \\
\psi_{22}'' &+ \psi_{22}' - (2\Omega + F - i\pi) \psi_{22} = -\psi_{21}'' - i\pi \psi_{21}' - G_3 \theta_{22} - G_m \zeta_{22}
\end{align*}
\]

\[
\begin{align*}
B \theta_{01}'' &+ \dot{\theta}_{01} - \dot{\theta}_{01} = -D_p \zeta_{01}'' \\
B \theta_{02}'' &+ \dot{\theta}_{02} - \dot{\theta}_{02} = -D_p \zeta_{02}'' \\
B \theta_{11}'' &+ \dot{\theta}_{11} - (\phi - i\pi) \theta_{11} = -2A \theta_{01}'' - D_p \zeta_{11}'' \\
B \theta_{12}'' &+ \dot{\theta}_{12} - (\phi - i\pi) \theta_{12} = -2A \theta_{02}'' - D_p \zeta_{12}'' \\
B \theta_{21}'' &+ \dot{\theta}_{21} - (\phi - i\pi) \theta_{21} = -D_p \zeta_{21}'' \\
B \theta_{22}'' &+ \dot{\theta}_{22} - (\phi - i\pi) \theta_{22} = -D_p \zeta_{22}'' \\
\zeta_{01}'' &+ S_c \zeta_{01}'' = -S_c \theta_{01}'' \\
\zeta_{02}'' &+ S_c \zeta_{02}'' = -S_c \theta_{02}'' \\
\zeta_{11}'' &+ S_c \zeta_{11}'' = -2A \theta_{01}'' - S_c \theta_{01}'' \\
\zeta_{12}'' &+ S_c \zeta_{12}'' = -2A \theta_{02}'' - S_c \theta_{02}'' \\
\zeta_{21}'' &+ S_c \zeta_{21}'' = -S_c \theta_{21}'' \\
\zeta_{22}'' &+ S_c \zeta_{22}'' = -S_c \theta_{22}''
\end{align*}
\]

3.2. Adomian Decomposition method

The ordinary differential Eqs. (29)-(46), though linear but are highly coupled, hence Adomian decomposition methods is applied in solving the problem. A differential equation can be written in a general form as:

\[
F\psi(\eta) = b
\]

where \(F\) represents an operator of nonlinear ordinary differential equation containing both linear and nonlinear terms. \(\psi\) represents the linear term, and the invertible linear operator is \(L\). Taking the highest-ordered derivative as \(L^1\), \(L^{-1}\) is n-fold integration operator from \(0\) to \(\eta\) for \(L = \frac{d^n}{d\eta^n}\). For the linear operator \(L\), the remainder is \(R\) and \(N\psi\) is the nonlinear term. Hence,

\[
L\psi + R\psi + N\psi = b
\]

Since \(L\) is invertible, thus

\[
L^{-1} L\psi = L^{-1} b - L^{-1} R\psi - L^{-1} N\psi
\]

The highest-order in Equations (29)-(46) is two, therefore,

\[
L^{-1} L\psi = \int_0^\eta \int_0^\eta \psi''(\eta) d\eta d\eta s
\]

\[
L^{-1} L\psi = \psi - \psi(0) - \eta \psi'(0)
\]

substituting for \(L^{-1} L\psi\) in Equation (51), the equation becomes;

\[
\psi = \psi(0) + \eta \psi'(0) + L^{-1} b - L^{-1} R\psi - L^{-1} N\psi
\]

Hence,

\[
\psi = \psi(0) + \eta \psi'(0) + b \frac{\eta^2}{2} - \int_0^\eta \int_0^\eta (R\psi + N\psi) \, d\eta d\eta s
\]

\[
\psi\text{ can be written in series form as:}
\]

\[
\psi = \sum_{n=0}^\infty \psi_n
\]

also, the nonlinear term as:

\[
N\psi = \sum_{n=0}^\infty A_n
\]

where

\[
A_n = \frac{1}{n!} \frac{d^n}{d\eta^n} \left( F \left( \sum_{i=0}^n \lambda^i \psi_i \right) \right)_{\lambda=0} \quad n = 0, 1, 2, 3, ...
\]

Substituting Equations (56) and (57) into equation (55) gives:

\[
\sum_{n=0}^\infty \psi_n = \psi(0) + \eta \psi'(0) + b \frac{\eta^2}{2}
\]

\[
- \int_0^\eta \int_0^\eta \left( R \sum_{n=0}^\infty \psi_n + \sum_{n=0}^\infty A_n \right) \, d\eta d\eta s
\]

The first three terms are identified as \(\psi_0\) which is the initial approximation, that is

\[
\psi_0 = \psi(0) + \eta \psi'(0) + b \frac{\eta^2}{2}
\]

and

\[
\psi_{n+1} = - \int_0^\eta \int_0^\eta \left( R \sum_{n=0}^\infty \psi_n + \sum_{n=0}^\infty A_n \right) \, d\eta d\eta s
\]
is the recurrence relation. All the components can be determined since $A_0$ depends on $\psi_0$ only, $A_1$ depends on $\psi_0$ and $\psi_1$ and so on. The solution then is the n-term approximation or approximant to $\psi$.

From Eqs. (60) and (61), the approximate solutions for Eqs (29)-(46), which converges at $n = 5$, can be written as:

$$
\begin{align*}
\zeta_0 &= \sum_{a=0}^{5} \zeta_0[a], \quad \theta_0 = \sum_{a=0}^{5} \theta_0[a], \\
\psi_0 &= \sum_{a=0}^{5} \psi_0[a], \quad \zeta_0 = \sum_{a=0}^{5} \zeta_0[a], \\
\theta_0 &= \sum_{a=0}^{5} \theta_0[a], \quad \psi_0 = \sum_{a=0}^{5} \psi_0[a], \\
\zeta_1 &= \sum_{a=0}^{5} \zeta_1[a], \quad \theta_1 = \sum_{a=0}^{5} \theta_1[a], \\
\psi_1 &= \sum_{a=0}^{5} \psi_1[a], \quad \zeta_2 = \sum_{a=0}^{5} \zeta_2[a], \\
\theta_2 &= \sum_{a=0}^{5} \theta_2[a], \quad \psi_2 = \sum_{a=0}^{5} \psi_2[a], \\
\zeta_2 &= \sum_{a=0}^{5} \zeta_2[a] \\
\theta_2 &= \sum_{a=0}^{5} \theta_2[a] \quad \psi_2 = \sum_{a=0}^{5} \psi_2[a]
\end{align*}
$$

(62)

Series solutions (62) are substituted in Eqs. (17) and (28) to give the final solution for velocity, temperature and concentration distributions.

$$
\begin{align*}
\psi(\eta, t) &= \sum_{a=0}^{5} \psi_0[a](\eta) + V_R \sum_{a=0}^{5} \psi_2[a](\eta) + \\
&\quad \frac{\epsilon}{2} \left( \sum_{a=0}^{5} \psi_{11}[a](\eta) + V_R \sum_{a=0}^{5} \psi_{12}[a](\eta) \right) e^{i\omega t} + \\
&\quad \frac{\epsilon}{2} \left( \sum_{a=0}^{5} \psi_{21}[a](\eta) + V_R \sum_{a=0}^{5} \psi_{22}[a](\eta) \right) e^{-i\omega t}
\end{align*}
$$

(63)

$$
\begin{align*}
\theta(\eta, t) &= \sum_{a=0}^{5} \theta_0[a](\eta) + V_R \sum_{a=0}^{5} \theta_2[a](\eta) + \\
&\quad \frac{\epsilon}{2} \left( \sum_{a=0}^{5} \theta_{11}[a](\eta) + V_R \sum_{a=0}^{5} \theta_{12}[a](\eta) \right) e^{i\omega t} + \\
&\quad \frac{\epsilon}{2} \left( \sum_{a=0}^{5} \theta_{21}[a](\eta) + V_R \sum_{a=0}^{5} \theta_{22}[a](\eta) \right) e^{-i\omega t}
\end{align*}
$$

(64)

$$
\begin{align*}
\zeta(\eta, t) &= \sum_{a=0}^{5} \zeta_0[a](\eta) + V_R \sum_{a=0}^{5} \zeta_2[a](\eta) + \\
&\quad \frac{\epsilon}{2} \left( \sum_{a=0}^{5} \zeta_{11}[a](\eta) + V_R \sum_{a=0}^{5} \zeta_{12}[a](\eta) \right) e^{i\omega t} + \\
&\quad \frac{\epsilon}{2} \left( \sum_{a=0}^{5} \zeta_{21}[a](\eta) + V_R \sum_{a=0}^{5} \zeta_{22}[a](\eta) \right) e^{-i\omega t}
\end{align*}
$$

(65)

3.3. Skin-friction, Nusselt and Sherwood number in term of Amplitude

With reference to the boundary conditions, the amplitude is defined in terms of primary and secondary velocities for steady and unsteady flow. Therefore, total resultant velocity can be written as:

$$
R_v = \sqrt{d^2 + f^2}
$$

(66)

where velocity is defined as

$$
\psi(\eta, t) = d + if
$$

(67)

The Skin-friction is given as:

$$
\tau(\eta) = \left( \frac{\partial \psi}{\partial \eta} \right)_{\eta=0.1} = \tau_m + i\tau_n
$$

(68)

$$
\beta_1 = \sqrt{\tau_m^2 + \tau_n^2}
$$

(69)

Nusselt number (Heat transfer coefficient) is defined as:

$$
Nu(\eta) = - \left( 1 + \frac{4}{3}E \right) \left( \frac{\partial \theta}{\partial \eta} \right)_{\eta=0.1} = \beta_m + i\beta_n
$$

(70)

Sherwood Number(Mass transfer coefficient) is expressed as:

$$
Sh(\eta) = \left( \frac{\partial \zeta}{\partial \eta} \right)_{\eta=0.1} = \lambda_m + i\lambda_n
$$

(72)

4. DISCUSSION OF RESULTS

The solutions for the partial differential equations (13), (14) and (16) with the corresponding boundary conditions (15) are acquired by Adomian decomposition methods alongside with MATHEMATICA programming. The impacts of different parameters governing the flow field on velocity, temperature and species in the fluid are depicted in tabular and graphical forms. The parameters considered in this study include: dimensionless viscoelasticity parameter of the Rivlin-Ericksen fluid ($V_R$), suction velocity parameter ($A$), rotation parameter ($\Omega$), scalar constant ($\epsilon$), chemical reaction parameter ($K_r$), thermal radiation parameter ($E$), Prandtl number ($Pr$), Schmidt number ($Sc$), heat absorption coefficient ($\phi$), Mass transfer Grashof number ($G_m$), Heat transfer Grashof number ($G_h$), permeability of the porous medium ($k_p$), Dufour parameter ($D_f$), Soret parameter ($S_f$) and magnetic parameter ($M$). Throughout the computations, the following are taken as default values: $t = 1$, $G_h = G_m = M = 5$, $V_R = 0.05$, $\phi = 0.005$, $Pr = 0.71$, $E = 3$, $\epsilon = 0.01$, $A = k_p = 0.5$, $K_r = 2$, $\Omega = 10$, $D_f = 0.1$, $G_h = 2, Sc = 2$ and $Sc = 1.002$.

Figures 2 and 3 depict the effects of Suction velocity parameter ($A$) on concentration and resultant velocity ($R_v$). It is obvious that as Suction velocity parameter increases, resultant velocity and concentration increase.
Variation of values of scalar constant ($\epsilon$) on resultant velocity, temperature and species distribution is shown in Figs. 4 - 6. It is detected that increasing $\epsilon$ causes a corresponding increment on resultant velocity, temperature and species profiles.

Fig. 4 Variation of dimensionless concentration $\zeta$ with scalar constant $\epsilon$

Fig. 5 Variation of dimensionless temperature $\vartheta$ with scalar constant $\epsilon$

Fig. 6 Variation of resultant velocity $R_v$ with scalar constant $\epsilon$

The influence of $G_m, G_h$ and $k_p$ on velocity is illustrated in Figs. 7 - 9. From these Figures, resultant velocity is enhanced by an increase in $G_m, G_h$ and $k_p$.

Fig. 7 Variation of resultant velocity $R_v$ with mass transfer Grashof number $G_m$

Fig. 8 Variation of resultant velocity $R_v$ with heat transfer Grashof number $G_h$

Fig. 9 Variation of resultant velocity $R_v$ with permeability of the porous medium $k_p$

Figures 10 and 11 display the effect of the different values of $K_r$ on species and velocity profiles. It is observed that the more the value of $K_r$, the less the species and resultant velocity.
Figure 10 reveals the influence of \( M \) on the resultant velocity. It is clear from the figure that a higher value of \( M \) decreases the flow velocity throughout the domain of the fluid. A drag force identified as Lorentz force is produced in electrically conducting fluid where magnetic field is applied. There is a decrease in the velocity of the fluid as a result of the effect of this drag force since fluid transport is resisted in the presence of the magnetic field.

Figure 12 reveals the influence of \( M \) on the resultant velocity. It is clear from the figure that a higher value of \( M \) decreases the flow velocity throughout the domain of the fluid. A drag force identified as Lorentz force is produced in electrically conducting fluid where magnetic field is applied. There is a decrease in the velocity of the fluid as a result of the effect of this drag force since fluid transport is resisted in the presence of the magnetic field.

The effect of \( \Omega \) on resultant velocity is seen in Fig. 15. The result revealed that, higher values of rotation parameter enhanced resultant velocity profiles, which showed an overwhelming effect of rotation. A diminishing in \( R_v \) due to a decrease in \( \Omega \) is because of the presence of gravitational and Lorentz force rotating at very low speeds. This indicates that a friction factor is noticed, hence \( R_v \) decreases. The same trend is apparent in Figs. 16 and 17, which represented velocity and temperature profiles for different values of \( Pr \). Prandtl number can be defined as the ratio of momentum diffusivity to thermal diffusivity. It is, therefore, obvious that a lower thermal conductivity material leads to high velocity and a different trend is seen for higher thermal conductivity. Hence, in Fig. 17, it is seen that an increase in Prandtl number accelerates the resultant velocity profiles. Likewise, in Figs. 16, an increase in \( Pr \) reduces the thermal boundary layer thickness and average temperature within the boundary. This implies that, an increase in \( Pr \) makes the thermal conductivity of the fluid to increase. Thus, resulting in rapid diffusivity of the heated surface.
Furthermore, effect of $S_c$ on concentration and resultant velocity profiles is revealed in Figs. 18 and 19. Here, it is observed that higher $S_c$ leads to a decline in concentration profiles, while the resultant velocity is enhanced.
Figures 22 - 24 detect the effects of variation of $S_p$ on resultant velocity, temperature and species profiles. A careful study of these figures shown that the presence of $S_p$ enhances both resultant velocity and concentration profiles, while a different trend is noticed in temperature profiles. Temperature profiles decline with a rise in $S_p$.

Effect of $D_p$ on resultant velocity, temperature and concentration profiles is presented in Figs. 25 - 27. Resultant velocity profiles diminish as $D_p$ is increased, while temperature profiles increases. This is as a result of the generation of energy flux that enhances the temperature. A rise in $D_p$ makes concentration profiles to fall within $0 \leq \eta \leq 0.7$, and within $0.7 \leq \eta \leq 1$, a rise in concentration profile is observed.
Tables 1 and 2 display the variation of fluid parameters ($K_r$, $E$, $\Omega$, $S_p$, $D_p$, and $V_R$) on Skin-friction, Nusselt number and Sherwood Number at $\eta = 0$ and $\eta = 1$. It is seen in Table 1 that the Skin-friction is diminished with the presence of $K_r$, $\Omega$, $D_p$, and $V_R$, while it is strengthened by $E$ and $S_p$. Nusselt number is reduced with an increase in $K_r$, $N$, and $D_p$. On the other hand, increasing the values of $S_p$ enhances the Nusselt number. In like manner, Sherwood number increases with an increase in chemical reaction and Dufour parameter. The mass transfer coefficient value is reduced with an increase in $E$ and $S_p$. Consequently, Table 2 shows that skin friction is quickened by an increase in $K_r$, $E$, $\Omega$, $S_p$, and $V_R$, while higher values of Dufour parameter decreases the Skin-friction. Nusselt number is risen with an increase in $K_r$ and $D_p$ but diminishes with increment in the values of $E$ and $S_p$. Increasing $E$, $S_p$, and $D_p$ make Sherwood number to rise and it decelerates by increasing the values of $K_r$.

Table 1

| $K_r$ | $E$ | $\Omega$ | $S_p$ | $D_p$ | $V_R$ | $\tau$ | $N_u$ | $Sh$ |
|------|----|--------|------|------|------|------|------|------|
| 1    | 3  | 15     | 2    | 0.1  | 0.05 | 1.26547 | 2.11822 | 1.51979 |
| 2    | 3  | 15     | 2    | 0.1  | 0.05 | 1.23144 | 2.05517 | 1.88701 |
| 3    | 3  | 15     | 2    | 0.1  | 0.05 | 1.20171 | 1.99740 | 2.21109 |
| 2    | 2  | 15     | 2    | 0.1  | 0.05 | 1.22856 | 2.24886 | 2.02036 |
| 2    | 3  | 15     | 2    | 0.1  | 0.05 | 1.23144 | 2.05517 | 1.88701 |
| 2    | 4  | 15     | 2    | 0.1  | 0.05 | 1.23326 | 1.95820 | 1.80325 |
| 2    | 3  | 10     | 2    | 0.1  | 0.05 | 2.30656 | 2.05517 | 1.88701 |
| 2    | 3  | 12     | 2    | 0.1  | 0.05 | 1.91408 | 2.05517 | 1.88701 |
| 2    | 3  | 14     | 2    | 0.1  | 0.05 | 1.47608 | 2.05517 | 1.88701 |
| 2    | 3  | 15     | 0.5  | 0.1  | 0.05 | 1.15877 | 1.96696 | 2.39242 |
| 2    | 3  | 15     | 1    | 0.1  | 0.05 | 1.18374 | 1.99150 | 2.23485 |
| 2    | 3  | 15     | 1.5  | 0.1  | 0.05 | 2.02080 | 2.02105 | 2.06581 |
| 2    | 3  | 15     | 2    | 0.2  | 0.05 | 1.23902 | 1.91244 | 2.24897 |
| 2    | 3  | 15     | 2    | 0.3  | 0.05 | 1.22160 | 1.68476 | 2.84090 |
| 2    | 3  | 15     | 2    | 0.4  | 0.05 | 1.17973 | 1.28395 | 3.77168 |
| 2    | 3  | 15     | 2    | 0.1  | 0.03 | 1.88677 | 2.05517 | 1.27000 |
| 2    | 3  | 15     | 2    | 0.1  | 0.04 | 1.24755 | 2.05517 | 1.88689 |
| 2    | 3  | 15     | 2    | 0.1  | 0.05 | 1.23144 | 2.05517 | 1.88701 |

5. CONCLUSION

An investigation of the joint influence of the fluid parameters on convective Rivlin-Ericksen flow of an unsteady incompressible and electrically conducting fluid in vertical plates with a time dependence is discussed. The governing equations of the flow field were non-dimensionalised and the solutions are obtained using Adomian decomposition method. The effects of various parameters on velocity, temperature, concentration, skin friction, Nusselt number and Sherwood number are presented in graphical and tabular forms.

The study reveals that:

1. Resultant velocity is strengthened by the presence of $\Omega$, $E$, $V_R$, and $S_p$ and weakened with the presence of $K_r$ and $D_p$.

2. An increase in $D_p$ tends to accelerate temperature profiles, while it is slowed down by higher values of $E$ and $S_p$.

3. Concentration distribution is enhanced with increase in $S_p$, however, the profile is reduced with an increase in $K_r$ and $D_p$. Within $0.7 \leq \eta \leq 1$, higher values of $D_p$ improved the profile.

4. Skin friction is enhanced with an increase in the values of $S_p$ and decelerated by increasing $D_p$ and $\Omega$ at $\eta = 0$. The same effect is noticed for $S_p$ and $D_p$ at $\eta = 1$. But, $\Omega$ tends to accelerate the skin friction.

5. At $\eta = 0$, it is observed that increasing in the Soret number strengthens the heat transfer coefficient and weakens mass transfer coefficient. The reverse effect is noticed for Dufour number.

6. Both heat and mass transfer coefficients are improved by high values of $D_p$ at $\eta = 1$.

NOMENCLATURE

$x^*$, $y^*$, $z^*$: dimensional distance upward the plate (m)
$x^+$, $y^+$, $z^+$: dimensional distance normal to the plate (m)
$u^*$, $v^*$, $w^*$: dimensional velocity components in the $x^*$, $y^*$, $z^*$ directions respectively (ms$^{-1}$)
t$^*$: dimensional time (s)
\( C_p \) specific heat at constant pressure (Jkg\(^{-1}\)K\(^{-1}\))

\( B_0 \) magnetic induction (tesla)

\( T^* \) dimensional temperature (K)

\( C^* \) dimensional concentration (kmol/m\(^3\))

\( P^* \) dimensional pressure (N/m\(^2\))

\( D \) chemical molecular diffusivity

\( g \) gravitational acceleration (m/s\(^2\))

\( T_{p*} \) plate dimensional temperature (K)

\( C_{p*} \) plate dimensional concentration (kmol/m\(^3\))

\( \kappa_p \) non-dimensional permeability of the porous medium

\( \kappa \) mean absorption coefficient

\( W_o \) scale of suction velocity contain non-zero positive constant

\( T_m \) mean fluid temperature

\( K\_T \) thermal diffusion ratio

\( C_s \) concentration susceptibility

\( K \) thermal conductivity (W/m · K)

\( T_0 \) temperature at the left plate (K)

\( C_0 \) concentration at the left plate (kmol/m\(^3\))

\( h \) distance of the plate (m)

**Greek Symbols**

\( \rho \) fluid density (kgm\(^{-3}\))

\( \nu^* \) kinematic viscosity (m\(^2\)s\(^{-1}\))

\( \sigma \) Stefan-Boltzman constant (W/m\(^2\) · K\(^4\))

\( \phi_o \) dimensional heat absorption coefficient (j/kg)

\( \alpha \) thermal diffusivity

\( \beta T, \beta C \) thermal, concentration expansion coefficient

\( \beta_k \) kinematic viscoelasticity

\( \epsilon \) scalar constant

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