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IMPACT OF THERMAL DIFFUSION AND RADIATION EFFECTS ON MHD FLOW OF WALTER'S LIQUID MODEL-B FLUID WITH HEAT GENERATION IN THE PRESENCE OF CHEMICAL REACTION

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ABSTRACT

Our key objective in the present work is to elaborate the concept of study of the magnetohydrodynamic flow of non-Newtonian incompressible fluid obeying (Walters' liquid) model with mass and heat transfer over an infinite porous horizontal stretching sheet under radiation, heat generation (absorption) and chemical reaction. The governing differential equations which describe the motion of the problem are converted into dimensionless formulas by using perturbation technique. The effects of the elasticity, porosity parameter, heat generation, radiation parameter, Chemical reaction parameter effect and magnetic interaction parameter, Prandtl and Schmidt numbers on the velocity, temperature and concentration distributions have been discussed and illustrated graphically.

Keywords: Chemical Reaction; Heat source; Radiation; Viscoelastic Fluid; MHD flow

INTRODUCTION

The study of viscoelastic fluids had become of increasing importance in the last few years. Qualitative analyses of these studies have significant bearing on several industrial applications such as polymer sheet extrusion from a dye, drawing of plastic films etc. When the manufacturing process at high temperature and need cooling the stretching sheet. The flows may need visco elastic fluids to produce a good effect to reduce the temperature from the sheet. In view of the above Afify [1] studied similarity solution in MHD effects of thermal diffusion and diffusion thermo on free convective heat and mass transfer over a stretching surface considering suction or injection, Karunakar Reddy et. al. [2] has been considered MHD heat and mass transfer flow of a viscoelastic fluid past an impulsively started infinite vertical plate with chemical reaction, Beg et. al. [3] discussed numerical study of free convection magnetohydrodynamic heat and mass transfer from a stretching surface to a saturated porous medium with Soret and Dufour effects, Chamkha and Khalid [4] investigated similarity solutions for hydromagnetic simultaneous heat and mass transfer by natural convection from an inclined plate with heat generation and absorption, Srinathuni Lavanya [5] analyzed heat transfer to MHD free convection flow of a viscoelastic dusty gas through a porous medium with chemical reaction, Cortell [7] studied a note on flow and heat transfer of a viscoelastic fluid over a stretching sheet, Datti et. al. [8] has been considered MHD viscoelastic fluid flow over a non- isothermal stretching sheet.

The effect of radiation on magnetohydrodynamics (MHD) flow and heat transfer in porous and non-porous medium due to the effect of magnetic fields on the boundary layer flow control and on the performance of many systems using micropolar fluids. In addition, this type of flow has attracted the interest of many investigators in view of its applications in many engineering problems such as magnetohydrodynamics (MHD) generators, plasma studies, nuclear reactors, geothermal energy extractions. Many processes in engineering areas occur at high temperature and knowledge of radiation heat transfer becomes very important for the design of the pertinent equipment. Nuclear power plants, gas turbines and the various propulsion devices for aircraft, missiles, satellites and space vehicles are examples of such engineering areas. Some of the authors studied on this Chenna Kesavaiah and A Sudhakaraiah [9] studied effects of heat and mass flux to MHD flow in vertical surface with radiation absorption, Kim [10] discussed unsteady MHD convection flow of polar fluids past a vertical moving porous plate embedded in a porous medium, Kumar and Srivastava [11] investigated effects of chemical reaction on MHD flow of dusty viscoelastic (Walter's Liquid model-B) Liquid with Heat source/sink, Mallikarjuna Reddy et. al. [12] analyzed effects of radiation and thermal diffusion on MHD heat transfer flow of a dusty viscoelastic fluid between two moving parallel plates, Makinde [13] discussed free convection flow with thermal radiation and mass transfer past a moving vertical Porous plate, Mbeledogu and Ogulu [14] investigated heat and mass transfer of an unsteady MHD natural convection flow of a rotating fluid past a vertical porous flat plate in the presence of radiative heat transfer.

Combined heat and mass transfer problems with chemical reaction are of importance in much process and have, therefore, received a considerable amount of attention in recent years. In process such as drying, evaporation at the surface of a water body, energy transfer in a wet cooling tower and the flow in desert cooler, heat and mass transfer occur simultaneously. Possible applications of this type of flow can be found in many industries. For example, in the power industry, among the methods of generating electric power is one in which electrical energy is exerted directly from a moving counting fluid. Practically interested in cases in which diffusion and chemical reaction occur at roughly the same speed. When diffusion is much faster than chemical reaction, then only chemical factors influence the chemical reaction rate; when diffusion is not much faster than reaction, the diffusion and kinetics interact to produce very different effects. The study of heat generation or absorption effects in moving fluids is important in view of several physical problems, such as fluids undergoing exothermic or endothermic chemical reaction. Chenna Kesavaiah and P V Satyanarayana [15] considered MHD and Diffusion Thermo effects on flow accelerated vertical plate with chemical reaction, Nandeppanavar et. al. [16] discussed heat transfer in a Walter’s liquid B fluid over an impermeable stretching sheet with Non-uniform heat source/ sink and elastic deformation, Osalusi et. al. [17] investigated thermal diffusion and thermo effect on combined heat and mass transfer of a steady MHD convective and slip flow due to a rotating disk with viscous dissipation and Ohmic heating, Ch Kesavaiah et. al. [18] studied radiation and mass transfer effects on moving vertical plate with variable temperature and viscous dissipation, Patil P M and Kulkarni [19] considered effects of chemical reaction on free convective flow of a polar fluid through a porous medium in the presence of internal heat generation, Chenna Kesavaiah, and Devika [20] discussed Free convection and heat transfer of a Couette flow an infinite porous plate in the presence radiation effect, Seddeek and Abdelmeguid [21] investigated effect of radiation and thermal diffusivity on heat transfer over a stretching surface with variable heat flux, Bhavana and Chenna Kesavaiah [22] considered perturbation solution for thermal diffusion and chemical reaction effects on MHD flow in vertical surface with heat generation.

Due to the fast growth of electronic technology, effective cooling of electronic equipment has become warranted and cooling of electronic equipment ranges form individual transistors to main frame computers and from energy suppliers to telephone switch boards and thermal diffusion effect has been utilized for isotopes separation in the mixture between gases with very light molecular weight (hydrogen and helium) and medium molecular weight. A reaction is of order n, if the reaction rate is

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proportional to the nth power of concentration. In particular, a reaction is of first order, if the rate of reaction is directly proportional to concentration itself. Experimental and theoretical works on MHD flow with thermal diffusion and chemical reaction have been done extensively in various areas *i.e.* sustain plasma confinement for controlled thermo nuclear fusion, liquid metal cooling of nuclear reactions and electromagnetic casting of metals. In many engineering and physical problems in which fluid undergoes exothermic or endothermic reaction, it is highly important to study the effect of heat generation and absorption. a numerical solution of steady MHD convection heat and mass transfer on a semi infinite vertical porous moving plate using element free Galerkin method, by Sharma R, Bhargava R and Bhargava [23], Chenna Kesavaiah and Venkateswarlu [24] considered chemical reaction and radiation absorption effects on convective flows past a porous vertical wavy channel with travelling thermal waves, Siddheshwar and Mahabaleswar [25] investigated effects of radiation and heat source on MHD flow of a viscoelastic liquid and heat transfer over a stretching sheet, Srinathuni Lavanya et. al. [26] investigated radiation effect on unsteady free convective MHD flow of a viscoelastic fluid past a tilted porous plate with heat source; *Sujit* Kumar Khan [27] discussed heat transfer in a viscoelastic fluid flow over a stretching surface with heat Source/sink, suction/blowing and radiation, Mallikarjuna Reddy et. al. [28] analysed radiation and diffusion thermo effects of viscoelastic fluid past a porous surface in the presence of magnetic field and chemical reaction with heat source, Satyanarayana et. al. [29] considered viscous dissipation and thermal radiation effects on an unsteady MHD convection flow past a semi-infinite vertical permeable moving porous plate, Rajaiah et. al. [30] studied radiation and Soret effects on unsteady MHD flow past a parabolic started vertical plate in the presence of chemical reaction with magnetic dissipation through porous medium.

The aim of this study of the Magnetohydrodynamic flow of non-Newtonian incompressible fluid obeying (Walters' liquid) model with mass and heat transfer over an infinite porous horizontal stretching sheet under radiation, heat generation (absorption) and chemical reaction. The governing differential equations which describe the motion of the problem are converted into dimensionless formulas by using perturbation technique.

MATHEMATICAL FORMULATION

We consider the effects of radiation and chemical reaction on the unsteady dusty flow of an incompressible, slightly conducting, visco elastic fluid between two heated porous infinite parallel plates (distance 2 h apart) under the influence of uniform magnetic field normal to the flow field in

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presence of heat source/sink. We assume $x-$axis along the flow in the midway of the plates and y-axis perpendicular to it. Let u, v be the velocities of dusty fluid and dust particles respectively in the direction of x-axis. The present analysis is based on the following assumptions:

- The flow is in the direction of x-axis and is driven by a constant pressure $\frac{\partial p}{\partial x}$ with negligible body forces.
- The dust particles are non-conducting, solid, spherical, and equal in size, uniformly and symmetrically distributed in the flow field and their number density is constant throughout the motion.
- The interactions between the particles, chemical reaction and radiation between the particles and liquid have been considered. This is necessary in order to get multiple equations.
- There is no externally applied electric field and the induced magnetic field is negligible.
- Initially, when $t \le 0$, the channel, walls as well as dusty fluid are assumed to be at the same temperature T0. The foreign mass is assumed to be present at low level and it is uniformly distributed such that it is everywhere C_0.
- When $t > 0$, the temperature of the walls is instantaneously raised to T_w and the species concentration is raised to C_w.
- There exists a chemical reaction in the mixture.

Under these assumptions and Boussinesq's approximation with concentration, the equations governing the flow are:

$$\frac{\partial u}{\partial t} = g\left(T-T_0\right)+g\left(C-C_0\right)+v\left(\frac{\partial^2 u}{\partial y^2}-K_0\frac{\partial^2 u}{\partial t \partial y^2}\right)\frac{\partial^2 u}{\partial y^2}+\frac{KN_0}{\rho}\left(v-u\right)-\frac{\sigma}{\rho}B_0{}^2 u-\frac{v}{K}u \quad (1)$$

$$m\frac{\partial v}{\partial t} = K'\left(u-v\right) \quad (2)$$

$$\frac{\partial T}{\partial t} = \frac{K_T}{\rho C_p}\frac{\partial^2 T}{\partial y^2}-\frac{1}{\rho C_p}\frac{\partial q'}{\partial y'}-\frac{Q_0}{\rho C_p}\left(T-T_0\right) \quad (3)$$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 T}{\partial y^2}-Kr'\left(C-C_0\right) \quad (4)$$

(where the symbols have their usual meaning), at t = 0, the temperature and concentration level changes according to the following laws:

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with the following boundary conditions:

$$T = T_0 + (T_w - T_0)(1 - e^{-at})$$
$$C = C_0 + (C_w - C_0)(1 - e^{-at})$$

The initial and boundary conditions relevant to the problem are:

$$\begin{aligned}
&t = 0 : u = 0 = v, T = T_0 && y\varepsilon(-d, d) \\
&t > 0 : u = 0 = v, T = T_0 + (T_w - T_0)(1 - e^{-at}) && \\
&C = C_0 + (C_w - C_0)(1 - e^{-at}) && for\ \ y = -d \\
&u = 0 = v, T = T_0 + (T_w - T_0)(1 - e^{-at}) && \\
&C = C_0 + (C_w - C_0)(1 - e^{-at}) && for\ \ y = d
\end{aligned} \tag{5}$$

The radiative heat flux given by Equation (3), in the spirit of Cogley et al. [6], becomes

$$\frac{\partial q_r}{\partial y} = 4(T - T_0)I'$$

where $I' = \int_0^\infty K_{iw} \frac{\partial e_{b\lambda}}{\partial T} d\lambda$, where K_{iw} is the absorption at the wall and $e_{b\lambda}$ Planck's function

We now introduce the following non-dimensional quantities:

$$y^* = \frac{y}{d}, t^* = \frac{t\nu}{d^2}, u^* = \frac{u}{d}, v^* = \frac{v}{d}, \ T = \frac{T - T_o}{T_w - T_0}, C = \frac{C - C_o}{C_w - C_0}, a^* = \frac{d^2 a}{\nu}$$

Introducing these non-dimensional quantities, equations (1), (2), (3) & (4) reduce to

$$\frac{\partial u}{\partial t} = GrT + GmC + \left(1 - E\frac{\partial}{\partial t}\right)\frac{\partial^2 u}{\partial y^2} + \frac{\lambda}{w}(v - u) - \frac{u}{K_1} - M^2 u \tag{6}$$

$$W\frac{\partial v}{\partial t} = (u - v) \tag{7}$$

$$\frac{\partial^2 \theta}{\partial y^2} = \Pr\frac{\partial T}{\partial t} - (S + R)T \tag{8}$$

$$\frac{\partial^2 C}{\partial y^2} - Sc\frac{\partial C}{\partial t} - KrSc = 0 \tag{9}$$

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Now initial and boundary condition (5) according to new system become,

$$T=0: u=0=v, T=0 \qquad y\varepsilon(-1,1)$$
$$u=0=v, T=T_0+(T_w-T_0)(1-e^{-at}), C=1-e^{-at} \qquad for\ y=-1 \qquad (10)$$
$$u=0=v, T=1-e^{-at}, C=1-e^{-at} \qquad for\ y=1$$

where $\lambda=\frac{mN_0}{\rho}$ (mass concentration of dust particle), $M=B_0 d\sqrt{\frac{\sigma}{\mu}}$ (Hartmann number), $Gr=\frac{g\beta d(T_w-T_0)}{\nu}$ (Grashof number), $Kr=\frac{K_1 d^2}{\nu}$ (Chemical reaction parameter), $R=\frac{4\nu I'}{d^2}$ (radiation parameter) $W=\frac{m\nu}{K'd^2}$ (relaxation time parameter for particles), $Gm=\frac{g\beta' d(C_w-C_0)}{\nu}$ (Modified Grashof number), $E=\frac{K_0}{d^2}$ (Visco-elastic parameter), $Sc=\frac{\nu}{D}$ (Schmidt number), $S=\frac{Qd^2}{K_T}$ (heat source/sink parameter), $\Pr=\frac{\mu C_p}{K_T}$ (Prandtl number), $K_1=\frac{k}{d^2}$

SOLUTION OF THE PROBLEM

To solve the equations (6) to (9) subject to the boundary conditions (10), according to Pop [31], we assume

$$\begin{aligned}
u(y,t)&=u_0(y)+\varepsilon u_1(y,t)e^{-at}+\ldots\ldots\ldots\\
v(y,t)&=v_0(y)+\varepsilon v_1(y,t)e^{-at}+\ldots\ldots\ldots\\
T(y,t)&=T_0(y)+\varepsilon T_1(y,t)e^{-at}+\ldots\ldots\ldots\\
C(y,t)&=C_0(y)+\varepsilon C_1(y,t)e^{-at}+\ldots\ldots\ldots
\end{aligned} \qquad (11)$$

Substituting the equations like (11) into the equations (6) to (9) and equating harmonic and non-harmonic terms, we get the following set of equations.

$$u_0''-\left(\frac{1}{K_1}+M^2\right)u_0=-GrT_0-GmC_0 \qquad (12)$$

$$(1+aE)u_1''-\frac{\lambda}{w}u_1-\left(\frac{1}{K_1}+M^2-a\right)u_1-\frac{\lambda}{w}v_1=-GrT_1-GmC_1 \qquad (13)$$

$$u_0=u_0\ \ \& u_1=v_1(1-aw) \qquad (14)$$

$$T_0''-N_1T_0=0 \qquad (15)$$

$$T_1'' - N_2 T_1 = 0 \tag{16}$$

$$C_0'' - Kr\,Sc\,C_0 = 0 \tag{17}$$

$$C_1'' - N_3\,C_1 = 0 \tag{18}$$

where $N_1 = (S+R)$ $N_2 = (a\Pr + S + R), N_3 = (Kr - a)Sc$

where dashes represents differentiation w. r. t. to y

Boundary conditions are reduced to:

$$\begin{aligned} u_0 = v_0 = u_1 = v_1, T_0 = C_0 = 1, T_1 = C_1 = -\frac{1}{\varepsilon} \quad & at\ \ y = -1 \\ u_0 = v_0 = u_1 = v_1, T_0 = C_0 = 1, T_1 = C_1 = -\frac{1}{\varepsilon} \quad & at\ \ y = 1 \end{aligned} \tag{19}$$

Solutions of the equations (12) to (18) under the boundary conditions (19) after substituting in (11), we have:

$$\begin{aligned} u(y,t) = {} & J_1 e^{m5y} + J_2 e^{m6y} + J_3 e^{m1y} + J_4 e^{m2y} + J_6 e^{m9y} + J_8 e^{m10y} \\ & + \varepsilon e^{-at}\left(J_9 e^{m7y} + J_{10} e^{m8y} + J_{11} e^{m3y} + J_{12} e^{m4y} + J_{14} e^{m12y} + J_{16} e^{m11y}\right) \end{aligned}$$

$$\begin{aligned} v(y,t) = {} & J_1 e^{m5y} + J_2 e^{m6y} + J_3 e^{m1y} + J_4 e^{m2y} + J_6 e^{m9y} + J_8 e^{m10y} \\ & + \left(\frac{1}{1-aw}\right)\varepsilon e^{-at}\left\{J_9 e^{m7y} + J_{10} e^{m8y} + J_{11} e^{m3y} + J_{12} e^{m4y} + J_{14} e^{m12y} + J_{16} e^{m11y}\right\} \end{aligned}$$

$$T(y,t) = L_1 e^{m5y} + L_2 e^{m6y} + \varepsilon e^{-at}\left(L_3 e^{m7y} + L_4 e^{m8y}\right)$$

$$C(y,t) = D_1 e^{m1y} + D_2 e^{m2y} + \varepsilon e^{-at}\left(D_3 e^{m3y} + D_4 e^{m4y}\right)$$

SKIN FRICTION

Let τ_f and τ_p be the skin friction for dusty fluid and dust particles respectively then we have:

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$$\tau_f = \left|\frac{\partial u}{\partial y}\right|_{y=1} = m_5 J_1 e^{m5} + m_6 J_2 e^{m6} + m_1 J_3 e^{m1} + m_2 J_4 e^{m2} + m_9 J_6 e^{m9} + m_{10} J_8 e^{m10}$$
$$+ \varepsilon e^{-at}\left\{m_7 J_9 e^{m7} + m_8 J_{10} e^{m8} + m_3 J_{11} e^{m3} + m_4 J_{12} e^{m4} + m_{12} J_{14} e^{m12} + m_{11} J_{16} e^{m11}\right\}$$

$$\tau_f = \left|\frac{\partial v}{\partial y}\right|_{y=1} = m_5 J_1 e^{m5} + m_6 \ldots$$
$$+\left(\frac{1}{1-aw}\right)\varepsilon e^{-a \ldots}$$
$$+ m_{12} J_{14} e^{m12} + \ldots$$

RESULTS AND DISCUSSION

The present investigation is to obtain analytical expressions for various profiles like velocity, skin friction for dusty fluid as well as dust particles and also temperature, concentration for dusty fluid are discussed for different profiles. The effects of the elasticity, porosity, heat, radiation, Chemical reaction effect and magnetic interaction parameter, Prandtl and Schmidt numbers on the velocity, temperature and concentration distributions have been discussed and illustrated graphically. Numerical solutions for velocity profile, skin friction for dusty fluid as well as dust particles and also temperature field, concentration profile for dusty fluid have been calculated. The values of different parameters and their effects on velocity, Temperature, concentration and skin friction have been displayed through graphs. The numerical values considered as $a = 0.2$, $S = 1$, $t = 1$, $w = 0.5$, $E = 1$, $Gm = 5$, $Gr = 5$, $K = 1$, $\Pr = 0.71$, $Sc = 0.65$, $M = 1$. The temperature field has been represented in **figures (1) – (3)**; which indicate the effects of radiation parameter, Prandtl number and heat source parameters. For different values of radiation parameter, Prandtl number and heat source parameters fixing the other values; form these figures we observed that increasing values of radiation parameter, Prandtl number and heat source parameter decreases the temperature field. Also we see that the temperature is minimum at the centre of the channel (y = 0) and increasing towards the plates. Concentration field for the different values of chemical reaction and Schmidt number depicted in **figures (4) – (5)**. We noticed that an increasing value of chemical reaction parameter decreases the concentration. While the reverse effect observed for Schmidt number. Concentration is minimum at the centre of the channel (y = 0) and increasing towards the plates. Velocity field for the different values of modified Grashof number, thermal Grashof number, radiation parameter, porosity parameter, chemical reaction, heat source and Schmidt number are illustrated form **figures (6) – (13)**. These figures distinguished that an increasing values of modified Grashof number, thermal Grashof number, radiation parameter, chemical reaction the velocity field increases, In a recent research carried out on the effects of Grashof number on the flow of different fluids driven by convection over various surfaces. Using slope of the linear regression line through data points, it is concluded that increase in the value of Grashof number or any buoyancy related parameter implies an increase in the wall temperature and this makes the bond(s) between the fluid to become weaker, strength of the internal friction to decrease, the gravity to becomes stronger enough. The effects of buoyancy parameter are highly significant in the laminar flow within the boundary layer formed on a vertically moving cylinder. This is only achievable when the prescribed surface temperature and prescribed wall heat flux are considered. It can be concluded that buoyancy parameter has a negligible positive effect on the local Nusselt number. This is only true when the magnitude of Prandtl number is small or prescribed wall heat flux is considered. Sherwood number, Bejan Number, Entropy generation, Stanton Number and pressure gradient are increasing properties of buoyancy related parameter while concentration profiles, frictional force, and motile microorganism are decreasing properties. While the reverse effect shown with porosity parameter heat source and Schmidt number.

CONCLUSIONS

The theoretical and numerical solutions are obtained for different profiles. From graphical representations, we observed the following results:

- Velocity and skin friction of the dust particles behaves same as dusty fluid.
- Increasing value of y increases the temperature, concentration while decreases the velocity of dusty fluid and dust particles.
- Velocity of dust particles is less than velocity of dusty fluid and skin friction of dust particles is greater than that of dusty fluid.

APPENDIX

$$m_1 = \sqrt{KrSc}, m_2 = -\sqrt{KrSc},\ m_3 = N_3, m_4 = -N_3,\ m_5 = N_1, m_6 = -N_1,\ m_7 = N_2, m_8 = -N_2$$

$$m_9 = N_1, m_{10} = -N_1,\ m_{11} = N_4, m_{12} = -N_4,$$

$$N_1 = (S+R)\ N_2 = (a\Pr + S + R), N_3 = (Kr - a)Sc\ \ N_5 = \left(\frac{1}{K_1} + M^2 + a - \frac{\lambda a}{1-aw}\right) N_6 = \left(\frac{N_3}{N_4}\right),$$

$$J_1 = -\frac{Gr\,L_1}{m_5{}^2 - N_1},\ J_2 = -\frac{Gr\,L_2}{m_6{}^2 - N_1}\ \ J_3 = -\frac{Gc\,D_1}{m_1{}^2 - N_1},\ J_4 = -\frac{Gc\,D_2}{m_2{}^2 - N_1}$$

$$J_5 = v_0 - J_8 e^{-m_{10}} - J_1 e^{-m_5} - J_2 e^{-m_6} - J_3 e^{-m_1} - J_4 e^{-m_2},\ J_6 = \frac{J_5}{e^{-m_9}}$$

$$J_7 = v_0 - \sinh m_9 - J_1 \sinh(m_9 - m_5) - J_2 \sinh(m_9 - m_6) - J_3 \sinh(m_9 - m_1) - J_4 \sinh(m_9 - m_2)$$

$$J_8 = \frac{J_7}{v_0 \sinh m_9},\ J_9 = -\frac{Gr\,L_3}{m_7^{\ 2} - N_4},\ J_{10} = -\frac{Gr\,L_4}{m_8^{\ 2} - N_4},\ J_{11} = -\frac{GcD_3}{m_3^{\ 2} - N_4},\ J_{12} = -\frac{GcD_4}{m_4^{\ 2} - N_4}$$

$$J_{13} = v_1 - \sinh m_1 - J_9 \sinh(m_{11} - m_8) - J_{10} \sinh(m_{11} - m_8) - J_{11} \sinh(m_{10} - m_3) - J_{12} \sinh(m_{11} - m_4)$$

$$J_{14} = \frac{J_{13}}{\sinh(m_{11} - m_{12})},\ D_1 = e^{m_1}\left(\frac{1 - \sinh m_1 e^{m_2}}{\sinh(m_1 - m_2)}\right),\ D_2 = e^{m_1}\left(\frac{\sinh m_1}{\sinh(m_1 - m_2)}\right)$$

$$J_{15} = v_1 - J_{14}e^{-m_{12}} - J_9 e^{-m_9} - J_{10}e^{-m_8} - J_{11}e^{-m_3} - J_{12}e^{-m_4},\ J_{16} = \frac{J_{15}}{e^{-m_{11}}}$$

$$D_3 = e^{m_3}\left(\frac{1 - \sinh m_3 e^{-m_4}}{\sinh(m_3 - m_4)} - \frac{1}{\varepsilon}\right),\ D_4 = e^{m_1}\left(\frac{\sinh m_3}{\varepsilon \sinh(m_1 - m_2)}\right) L_1 = e^{-m_5} - \left(\frac{\sinh m_5}{\varepsilon \sinh(m_5 - m_6)} e^{(m_5 - m_6)}\right),$$

$$L_2 = \frac{\sinh m_5}{\sinh(m_5 - m_6)}$$

$$L_3 = e^{-m_7} - \left(\frac{\sinh m_7}{\varepsilon \sinh(m_7 - m_8)} e^{(m_7 - m_8)}\right),\ L_4 = \frac{\sinh m_7}{\sinh(m_7 - m_8)}$$

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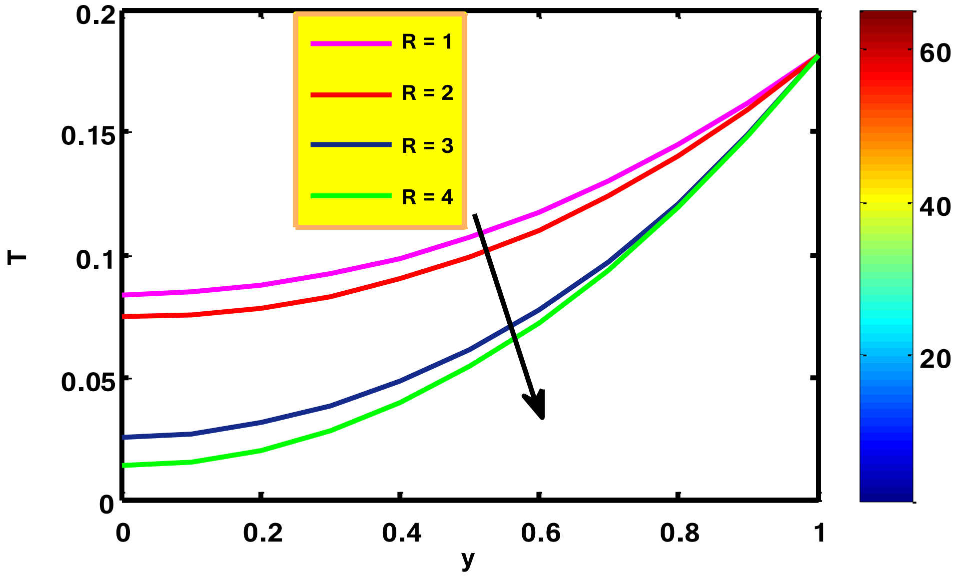
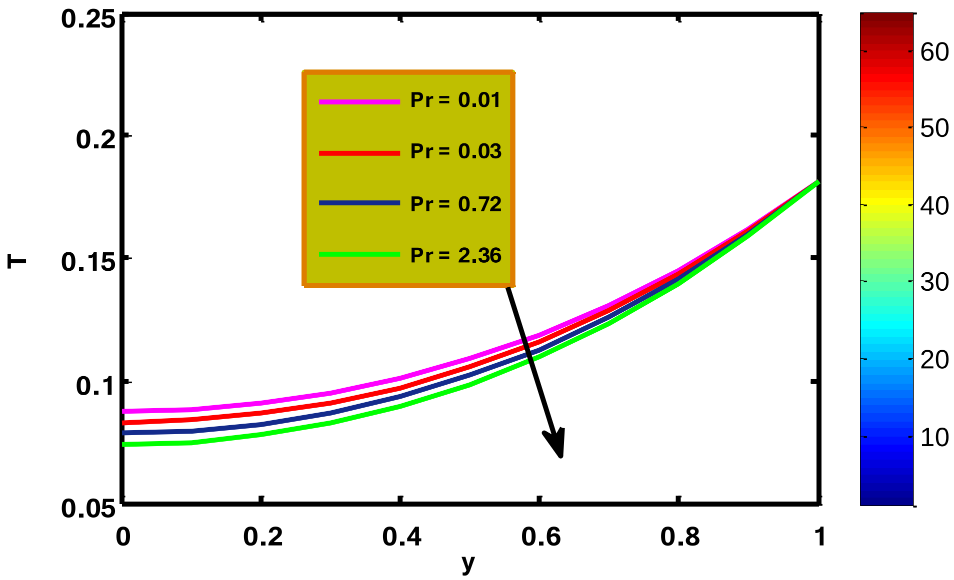


Fig. (1). Temperature field for R



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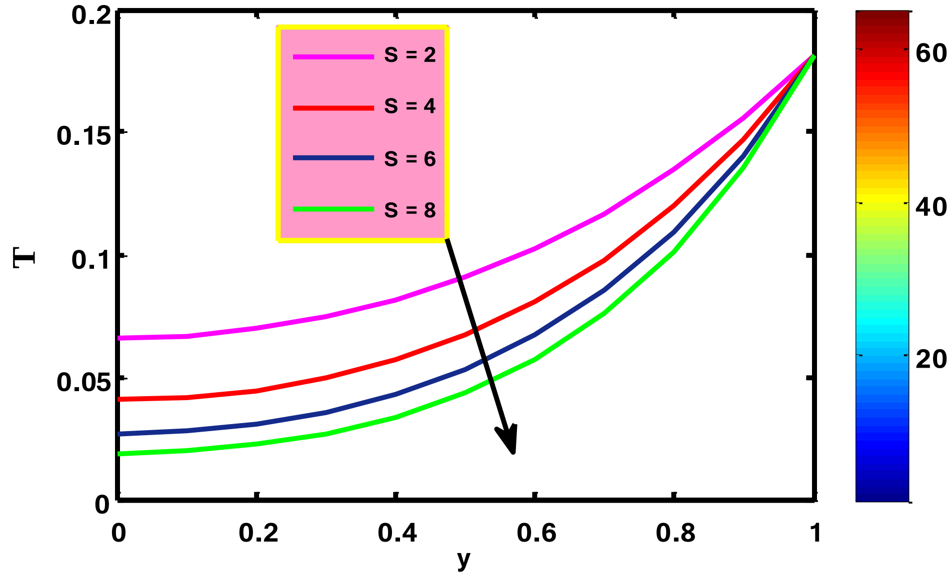

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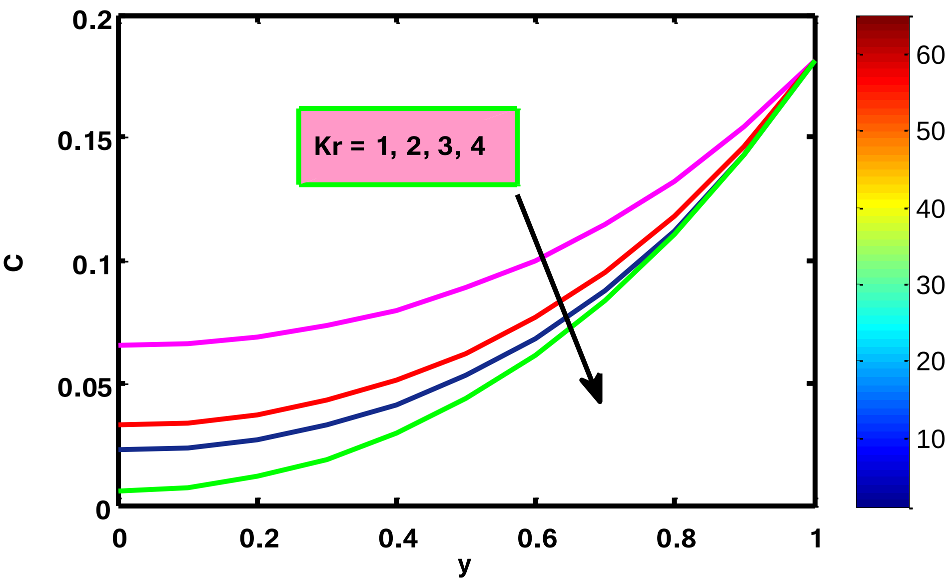

Fig. (4). Concentration field for Kr

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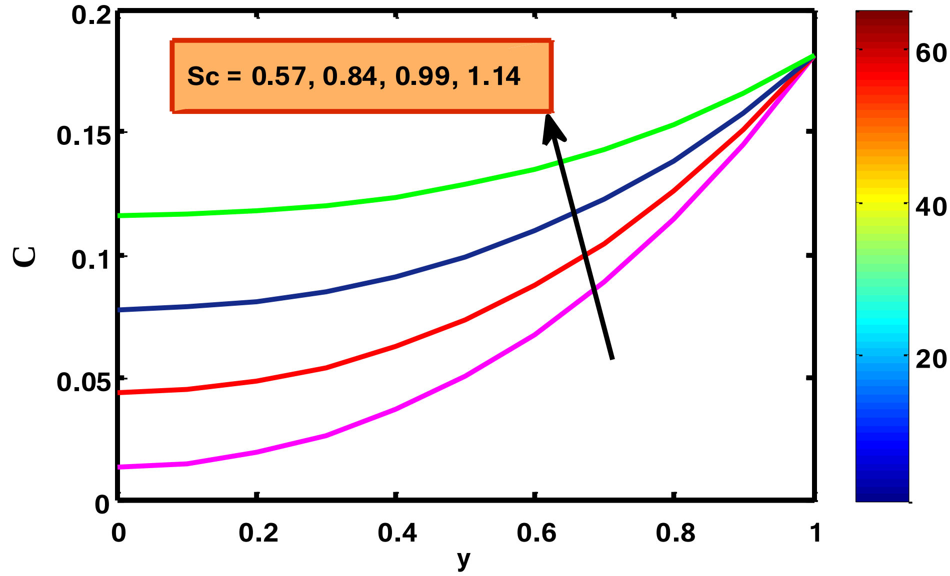

Fig. (5). Concentration field for Sc

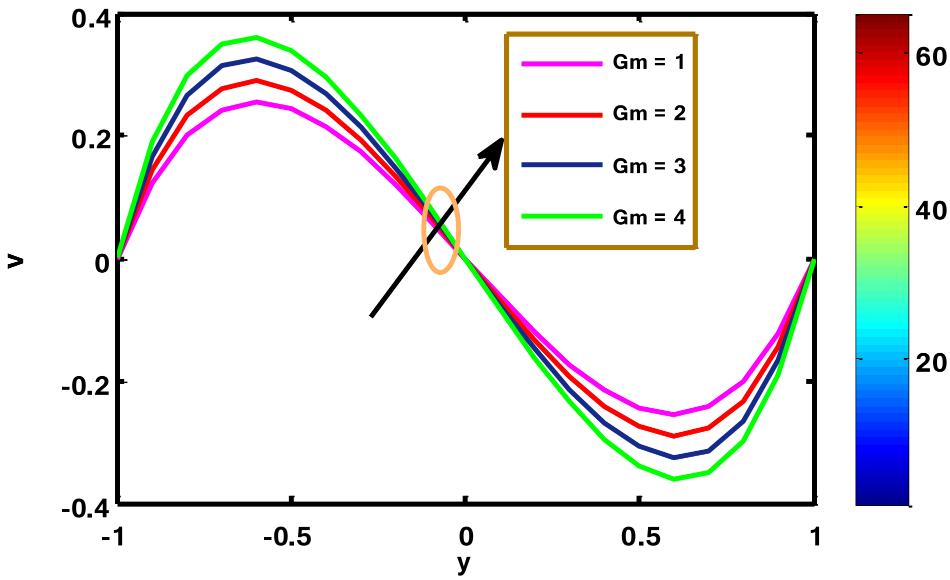

Fig. (6). Velocity field for Gm on dusty fluid

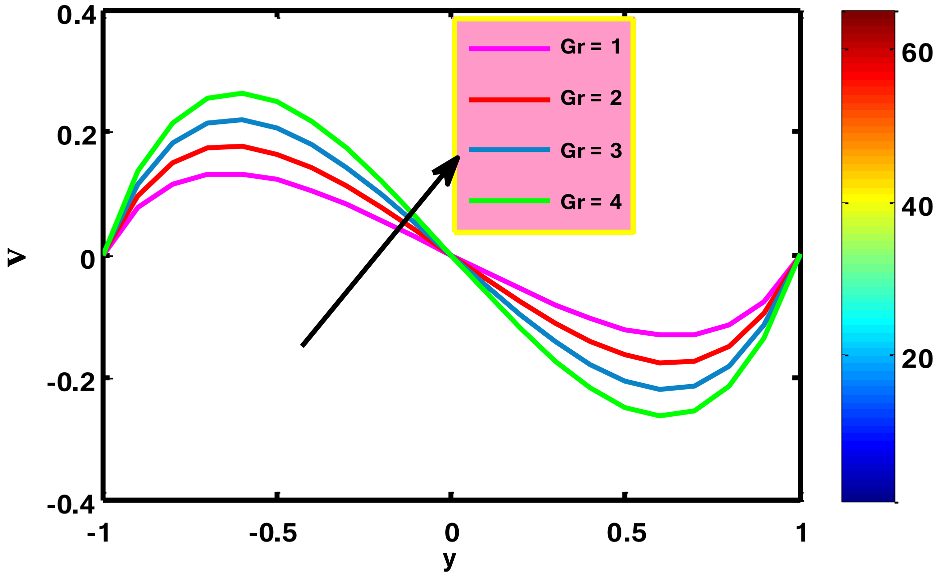

Fig. (7). Velocity field for Gr on dusty fluid

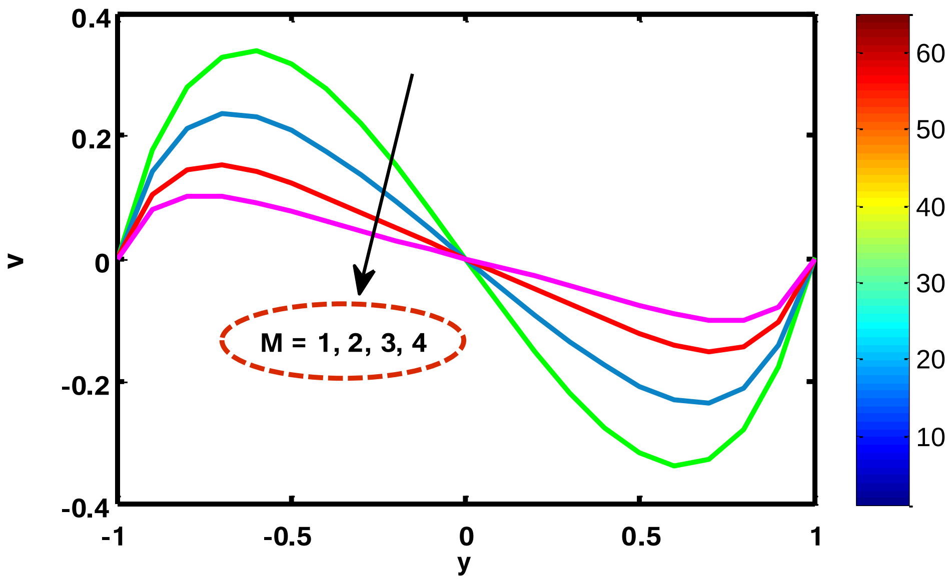

Fig. (8). Velocity field for M on dusty fluid

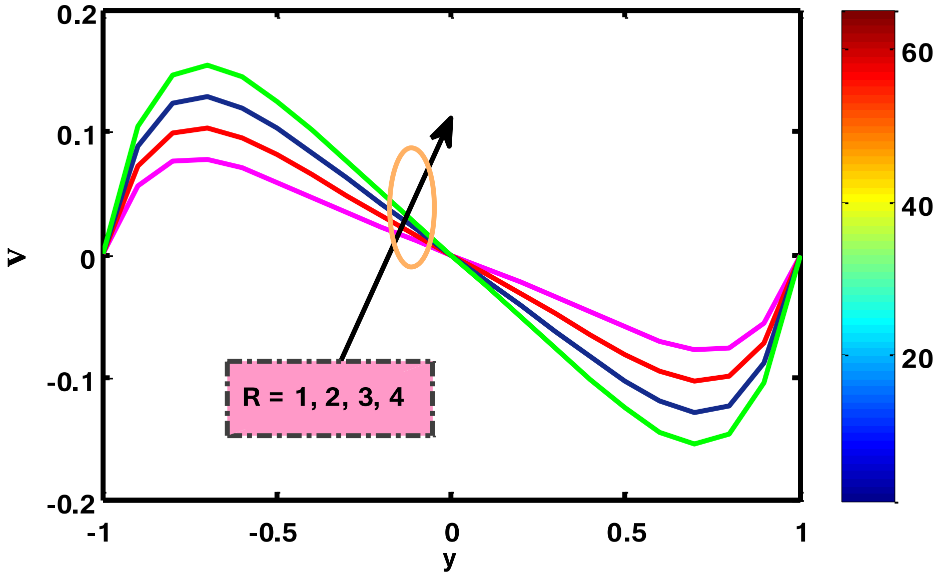

Fig. (9). Velocity profiles for R on dusty fluid

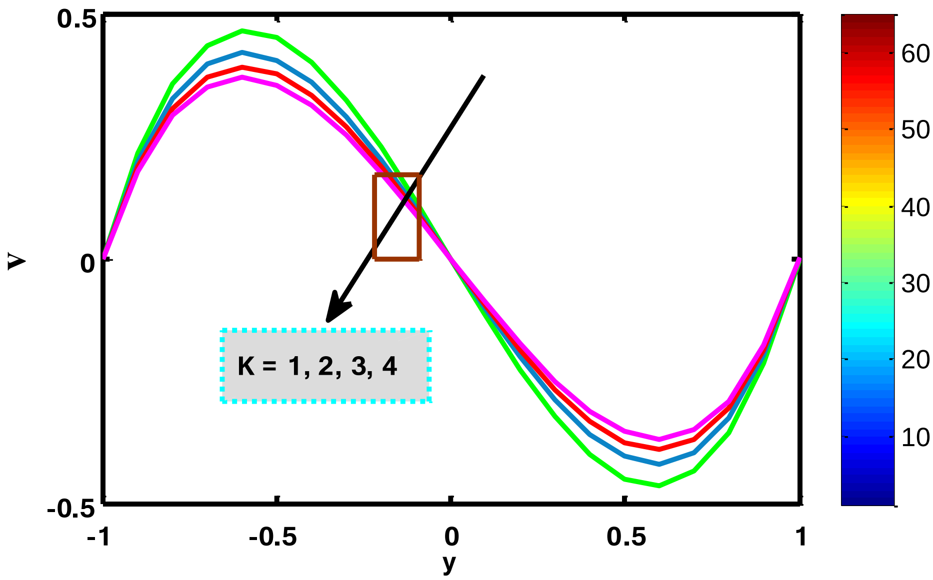

Fig. (10). Velocity profiles for K on dusty fluid

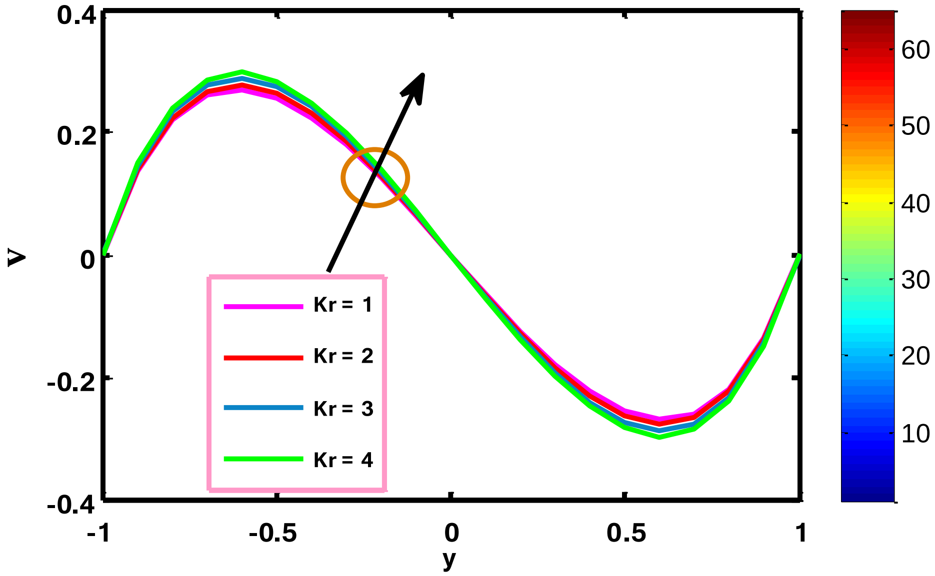

Fig. (11). Velocity profiles for Kr on dusty fluid

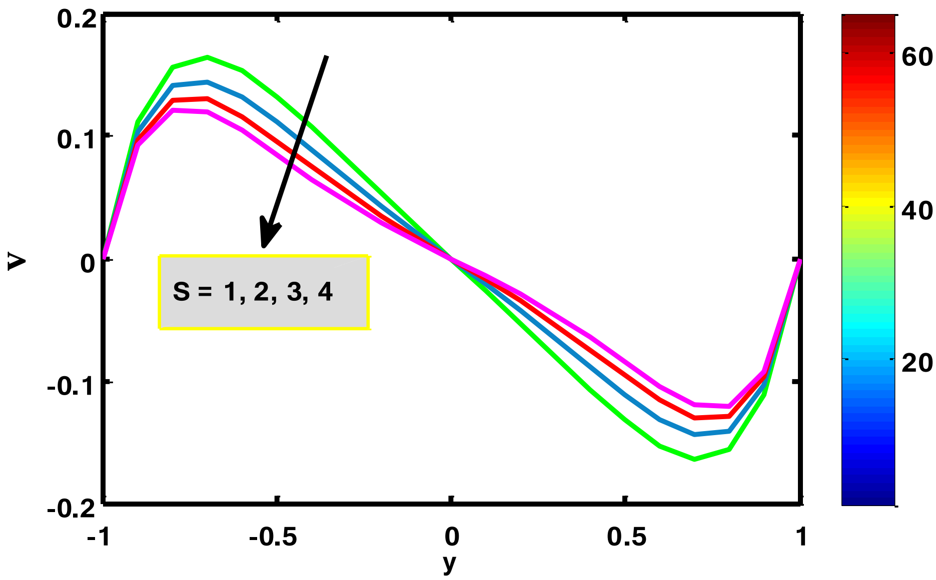

Fig. (12). Velocity profiles for S on dusty fluid

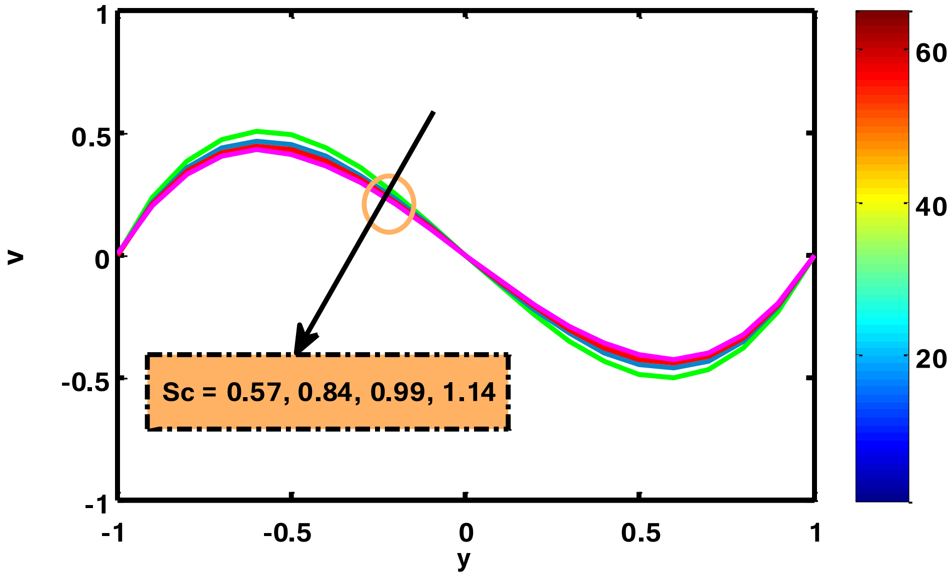

Fig. (13). Velocity profiles for Sc on dusty fluid