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Unsteady MHD Casson Fluid Flow through Infinite Inclined Plate in the Presences of Hall Current and Chemical Reaction

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ABSTRACT

The objective of this paper is to study about the unsteady Casson fluid in the present of hall current and chemical reaction electrically conducting heat fluid near an infinite inclined plate. Casson fluid model is choose to be in this research to characterize the non-Newtonian fluid behaviour. The exact solutions of momentum, energy and concentration equations, under Boussinesq approximation were obtained by Laplace transform technique to transform governing partial diffrential equations into ordinary differential equations with an appropriate boundary condition. All the transformed equations are then solved numerically by using Mathematica. Finally, the exact solution of momentum, energy and concentration of the cases are gained. The results of flow features for different values of governing parameters, unsteadiness parameter and Casson parameter are evaluated in graphs and has been discussed in the results section. The result presented that the velocity is increase when the magnetic parameter increases due to the existence of Lorentz force that helps in reducing heat for electronic system and radiators. Furthermore, the Hall current that we added into this study makes the velocity increase when Hall current increase. These phenomena happened because of the rising of Hall current makes the conductivity become decrease which led the decreasing in magnetic damping, results the increase in velocity.

1. Introduction

Fluids are categorized into Newtonian fluids and non-Newtonian fluids depending on the relationship between shear stress and the rate of strain and its derivatives. Casson fluid is classified as non-Newtonian fluid where it is a shear thinning liquid and assumed to have infinite viscosity at zero of shear, a yield stress below which no flow occurs and zero viscosity at an infinite rate of shear [1]. In other words, Casson fluid does not obey Newton's viscosity law and regarded as non-Newtonian fluids [2] The example of Casson fluids is jelly, tomato sauce, honey, soup, concentrated fruit juice, etc. Goud

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et al., [3] examined the effect of Heat source on an MHD Casson fluid through a vertical fluctuating porous plate. They found that with increasing the heat source parameter the result in the velocity and temperature increases. Aneja *et al.,* [4] are motivated to investigate the phenomena of natural convection in a square porous cavity containing Casson fluid. The interesting research about Casson fluid is then continued by Khan *et al.,* [5] where they are making comparative study of Casson fluid with homogeneous-heterogenous reactions. Javed *et al.,* [6] numerically investigated the influence of heat generation/absorption on axisymmetric Casson liquid flow over a stretched cylinder with the torsional motion of cylinder that caused the flow. A new model of fractional Casson fluid was built by Sheikh *et al.,* [7] based on generalized Fick's and Fourier's laws together with heat and mass transfer. Vaddemani *et al.,* [19] investigates the impact of Soret phenomenon on the transient free convection movement of a viscous, incompressible fluid within a high-porosity porous medium and the medium is enclosed by a vertically oriented infinitely extending moving plate. Shahrim *et al.,* [23] analysed the impact of Caputo fractional derivative on the flow of Casson fluid, initiated by an accelerating plate, subjected to analytical analysis.

Recently, Ali *et al.,* [8] have examined the exact analysis of combined effects of radiation and chemical reaction on the magnetohydrodynamic (MHD) free convection flow of an electrically conducting incompressible viscous fluid over an inclined plate embedded in a porous medium. They use Laplace transform method to solve the dimensionless momentum equation coupled with the energy and mass diffusion equations. They found that the effects of the permeability and magnetic parameters on velocity are opposite. Osman *et al.,* [9] take an opportunity to study the magnetohydrodynamic (MHD) free convection flow past an infinite inclined plate by using Laplace transform method. The concluded that velocity is reduced when magnetic parameter increase due to the existence of Lorentz force that retard the growth of velocity outlines. Rasheed *et al.,* [10] have offered the study of steady two-dimensional MHD free convective flow of Casson fluid over a vertical surface which presented numerically with the impact of thermal radiation and chemical reaction where the interaction of transverse magnetic field, viscous dissipation and Hall current are taken into account. They diminished non-dimensional nonlinear ordinary different equations (ODEs) from governing partial differential equations (PDEs) via fitting transformations. Suganya *et al.,* [11] have discussed a mathematical model of the magnetohydrodynamic free convection flow of a various incompressible fluid, which is based on a system of coupled steady-state nonlinear differential equations. They were tested the efficiency and accuracy of the derived results against highly accurate and widely used numerical methods. Kodi and Mopuri [20] perform unsteady hydrodynamic flow over an inclined plate embedded in the porous medium with Soret-aligned magnetic field and chemical reaction.

Hall current effect is the development of a transverse electric field in a solid material when it carries an electric current and placed in a magnetic field that is perpendicular to the current. Bafakeeh *et al.,* [12] investigated the hall current and Soret effects on unsteady MHD free convection heat and mass transfer flow of a viscous, incompressible and electrically conducting fluid passing through a vertical plate embedded in a porous medium in the presence of chemical reaction and thermal radiation. They found that after enhancing the values of Hartmann number, the velocity graph and its associated boundary layer declines. However, because of the Hall current's effect on the entire region, the velocity component rises. Islam *et al.,* [13] examined the effects of Hall current and radiation on magnetohydrodynamic flow and heat transmission of a micropolar hybrid nanofluid between two surfaces inside a rotating system. After detailed study, the noticed that there is a growth in the velocity profile for $\alpha > 0$, while the velocity is reduced with growing values of magnetic parameter and for negative values of α. Rauf *et al.,* [14] attracted to study the magnetohydrodynamic flow and heat transfer of a micropolar tri-hybrid nanofluid between two porous surfaces inside a rotating system with the hall currents and morphological effects. The results from their studies shows the heat transfer rate of tri-hybrid nanofluid is greater than as compared to hybrid nanofluid and nanofluid. Lv *et al.,* [15] considered the problem of unsteady magnetohydrodynamic flow of non-Newtonian fluid through a vertical plate in the presence of Hall current. They examine the impact of pertinent physical constraints like magnetic parameter, thermal radiation and Dufour parameter over the velocity, temperature and concentration of the fluids. Vijayaragavan *et al.,* [22] investigated the influence of the Hall current on the flow chemically reactive MHD Casson fluid, considering the presence of Dufour effects and themal radiation.

Fluid flow, chemical reaction and activation energy are actually the plays an important rule for widespread application including the destruction of harvest due to freezing, manufacturing of paper, food processing, ceramics, drying, dehydration processes, water emulsion and oil. In fact, activation energy can be explained as the reactant in chemical reaction that require minimum energy to prompt a reaction. Hayat *et al.,* [16] analysed the chemical reaction and thermal radiation impact on a nanofluid flow in a rotating channel with Hall current. They applied the appropriate similarity transformation to transform the formulated problem into ordinary differential equations (ODEs). They noticed that the increment values of Schmidt number and chemical reaction parameter caused the concentration profile declined while a reverse trend is seen for activation energy. Gopal *et al.,* [17] investigated the mixed convective peristaltic flow of Prandtl fluid in a planar channel with compliant walls in the presence of magnetic field and Hall current. Their results showed the Hall parameter and Hartmann number on velocity have opposite characteristics. Sulochana *et al.,* [18] analysed the numerical analysis of higher order chemical reaction on electrically MHD nanofluid under influence of viscous dissipation. They considered the porous medium have two space coordinates, laminar, time-invariant, MHD incompressible Newtonian nanofluid. The conclusion that has been made from the study was the significant velocity profile is achieved for increment of electric parameter, Eckert number and mixed convection parameter while velocity fluid profile supressed by Hartmann number. Swarnalathamma *et al.,* [21] explored the unsteady MHD free convective Casson fluid movement over a boundless straight up inclined absorbent plate with heat source and/or heat absorption.

Motivated by the above applications the aim here is to study about the unsteady Casson fluid in the present of hall current and chemical reaction electrically conducting heat fluid near an infinite inclined plate. To our knowledge, no study has been carried out yet to investigate about this. We considered the Hall current in this study because of its character that always perpendicular to with electric field. In other words, when a piece of metal or semiconductor is placed in magnetic field and direct current is allowed to pass through it, the electric fields get developed across the edges of semiconductor specimen, hence, it's called Hall current. The applications of Hall current are employed in the magnetic field sensing equipment, proximity detectors, for detecting wheel speed and accordingly assist the anti-lock braking system and etc. The exact solutions of momentum, energy and concentration equations, under Boussinesq approximation were obtained by Laplace transform technique. The variations in fluid velocity, fluid temperature and concentration were shown graphically with numerical result.

2. Mathematical Formulation

We consider the unsteady flow of Casson fluid in the presence of chemical reaction electrically conducting heat fluid near an infinite inclined plate. Magnetic field B is applied to the plate and a first-order chemical reaction effect is assumed to exist. In the unsteady boundary layer equations governing the Casson fluid, radiation heat transfer and concentration fields can be written in dimensional form as shown below:

$$\frac{\partial u^*}{\partial t^*} = v\left(1+\frac{1}{\gamma}\right)\frac{\partial^2 u^*}{\partial y^{*2}} - \frac{\sigma B_0^2}{\rho(1-m)}u^* - \frac{v}{K^*}u^* + g\beta_T \cos\varphi\left(T^* - T_\infty^*\right) + g\beta_C \cos\varphi\left(C^* - C_\infty^*\right) \tag{1}$$

$$\frac{\partial T^*}{\partial t^*} = \frac{k}{\rho c_p}\frac{\partial^2 T^*}{\partial y^{*2}} - \frac{1}{\rho c_p}\frac{\partial q_r}{\partial y} \tag{2}$$

$$\frac{\partial C^*}{\partial t^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} - K_r\left(C^* - C_\infty^*\right) \tag{3}$$

where u^*, T^*, C^* are velocity, temperature and concentration respectively. v is kinematic viscosity, γ is Casson fluid, σ is the electrical expansion, ρ is the fluid density, K^* is the permeability of the porous medium, g is the gavity and its assume to be zero, β_T and β_C are the thermal expansion and concentration expansion, k is the thermal conductivity, c_p is the specific heat, q_r is the radiative heta flux, D is the mass diffusion and K_r is the chemical reaction parameter.

The approximate boundary conditions are defined as:

$$\begin{aligned} &u^* = 0,\ T^* = T_\infty^*,\ C^* = C_\infty^* \text{ for } y^* \geq 0, \text{ and } t^* \leq 0 \\ &u^* = 0,\ T^* = T_w^*,\ C^* = C_w^* \text{ for } y^* = 0 \text{ and } t^* > 0 \\ &u^* \to 0,\ T^* \to T_\infty^*,\ C^* \to C_\infty^* \text{ for } y^* \to \infty \text{ and } t^* \geq 0 \end{aligned} \tag{4}$$

In the above boundary conditions, at time $t^* \leq 0$, the plate and the fluid initially at rest with the same temperature T_∞^* and C_∞^*. When $t^* > 0$, both temperature and concentration is raised to constant temperature and concentration , T_w^* and C_w^*. Temperature and concentration are approaching to zero when $t^* \geq 0$.

The dimensionless variable is introduced as follows:

$$y = \frac{y^*}{L},\ t = \frac{t^*(vg)^{1/3}}{L},\ u = \frac{u^*}{(vg)^{1/3}},\ T = \frac{T^* - T_\infty^*}{T_w^* - T_\infty^*},\quad C = \frac{C^* - C_\infty^*}{C_w^* - C_\infty^*} \tag{5}$$

The temperature of the plates T_∞^* and T_w^* are supposed to produce radiative heat flux term and simplified using Rosseland approximation as shown below:

$$\frac{\partial q_r}{\partial y} = -\frac{4\sigma^*}{3K^*}\frac{\partial T^{*4}}{\partial y^*} \tag{6}$$

where σ^* represent Stefan-Boltzmann constant and K^* represent mean absorption coefficient. The temperature differences within the flow are assume to be adequately small such that T^{*4} and it can be expressed as a linear function of the temperature. Taylor series is used to expand T^{*4} to T_∞^* and neglecting higher-order terms, hence;

$$T^{*4} \cong 4T_\infty^{*}T - 3T_\infty^4 \tag{7}$$

Eq. (1), Eq. (2) and Eq. (3) are then reduced to dimensionless form by using Eq. (5) and they become :

$$\frac{\partial u}{\partial t} = \left(1+\frac{1}{\gamma}\right)\frac{\partial^2 u}{\partial y^2} - M\left(1-m\right)u - \frac{u}{K} + G_r T + G_c C \tag{8}$$

$$\frac{\partial T}{\partial t} = \frac{(1+R)}{Pe}\frac{\partial^2 t}{\partial y^2} \tag{9}$$

$$\frac{\partial C}{\partial t} = \frac{1}{Pe_c}\frac{\partial^2 C}{\partial y^2} - KrC \tag{10}$$

where;

$$M = \frac{\sigma B_0^2}{\mu}\left(\frac{v}{\sqrt{g}}\right)^{4/3},\ G_r = \cos\varphi\beta_T\left(T_w^* - T_\infty^*\right),\ G_c = \cos\varphi\beta_c\left(C_w^* - C_\infty^*\right)$$

$$R = \frac{16\alpha\sigma^* T_\infty^* L^2}{k},\ Pe = \mathrm{Re}\,\mathrm{Pr},\ Pe_c = \mathrm{Re}\,Sc$$

From the above equation, M is magnetic parameter known as Hartmann number, K is the porosity parameter, Gr is the thermal Grasof number, Gc is the mass Grasof number, R is radiation parameter Pe known as Peclet's number of mass transfer, Pe_c is known as Peclet's number of concentration, Re is Reynold number, Pr is Prandtl number and Sc is Schmidt number. The characteristic length can be defined as:

$$L = \frac{v^{2/3}}{g^{1/3}} \tag{11}$$

The initial and boundary conditions reduced to dimensionless form as follows:

$$\begin{aligned} &u=0,\ T=0,\ C=0 \text{ for } y\geq 0 \text{ and } t\leq 0 \\ &u=0,\ T=1,\ C=1 \text{ for } y=0 \text{ and } t>0 \\ &u\to 0,\ T\to 0,\ C\to 0 \text{ for } y\to\infty \text{ and } t\geq 0 \end{aligned} \tag{12}$$

2.1 Solution of the Problem

The energy Eq. (2) and Eq. (3) is uncoupled from the momentum Eq. (1). Therefore, temperature variable $T(y,t)$ and concentration variable $C(y,t)$ can be solve where the solution $u(y,t)$ can be achieved. In order to solve the equations, Laplace transform is applied to Eq. (8), Eq. (9) and Eq. (10) with respect to t with the present of Eq. (16) and solving the result from different equations, we obtained:

Energy Equation

$$\bar{T} = \frac{1}{s} e^{-y\sqrt{\frac{s(Pe_m)}{1+R}}} \tag{13}$$

$$\bar{C} = \frac{1}{s} e^{-y\sqrt{Pe_c(Kr+s)}} \tag{14}$$

Momentum Equation

$$\begin{aligned}\bar{u} = {} & a_1\left[\frac{1}{a_2(s-a_2)} - \frac{1}{a_2 s}\right] e^{-y\sqrt{\Pr s+R}} + a_3\left[\frac{1}{a_4(s-a_4)} - \frac{1}{a_4 s}\right] e^{-y\sqrt{(Kr+s)Sc}} - a_1\left[\frac{1}{a_2(s-a_2)} - \frac{1}{a_2 s}\right] e^{-y\sqrt{\frac{\lambda+s}{n}}} \\ & -a_3\left[\frac{1}{a_4(s-a_4)} - \frac{1}{a_4 s}\right] e^{-y\sqrt{n}}\end{aligned} \tag{15}$$

where;

$$a_1 = \frac{-Gr\cos\phi}{\left(\frac{Pe}{1+R} - 1\right)},\ a_2 = \frac{\lambda(1+R)}{Pe-1},\ a_3 = \frac{-Gc\cos\phi}{(1-\operatorname{Re}Sc)},\quad n = 1+\frac{1}{\gamma}$$

Hence, we obtained the exact solution for velocity, temperature and concentration from Eq. (13), Eq. (14), and Eq. (15) by using inverse Laplace transform. These solutions are:

$$T = erfc\left(\frac{y}{2}\sqrt{\frac{\theta}{t}}\right) \tag{16}$$

$$C = \frac{1}{2}\left[e^{y\sqrt{\operatorname{Re}ScKr}} erfc\left(\frac{y}{2}\sqrt{\frac{\operatorname{Re}Sc}{t}}\right) + \sqrt{Krt} + e^{-y\sqrt{\operatorname{Re}ScKr}} erfc\left(\frac{y}{2}\sqrt{\frac{\operatorname{Re}Sc}{t} - \sqrt{Krt}}\right)\right] \tag{17}$$

$$U = u_1 + u_2 + u_3 + u_4 + u_5 + u_6 + u_7 + u_8 \tag{18}$$

$$u_1(y,t)=\frac{a_1 e^{a_2 t}}{2a_2}\left[e^{y\sqrt{\theta a_2}}erfc(\frac{y}{2}\sqrt{\frac{\theta}{t}}+\sqrt{a_2 t})+e^{-y\sqrt{\theta a_2}}erfc(\frac{y}{2}\sqrt{\frac{\theta}{t}}-\sqrt{a_2 t})\right]$$
$$u_2(y,t)=\frac{a_1}{a_2}erfc(\frac{y}{2}\sqrt{\frac{\Pr}{t}})$$
$$u_3(y,t)=\frac{a_3 e^{a_4 t}}{2a_4}\left[e^{y\sqrt{Pe_m(Kr+a_4)}}erfc(\frac{y}{2}\sqrt{\frac{Pe_m}{t}}+\sqrt{(Kr+a_4)t})+e^{-y\sqrt{Pe_m(Kr+a_4)}}erfc(\frac{y}{2}\sqrt{\frac{Pe_m}{t}}-\sqrt{(Kr+a_4)t})\right]$$
$$u_4(y,t)=\frac{a_3}{2a_4}\left[e^{y\sqrt{Pe_m Kr}}erfc(\frac{y}{2}\sqrt{\frac{Pe_m}{t}}+\sqrt{Krt})+e^{-y\sqrt{Pe_m Kr}}erfc(\frac{y}{2}\sqrt{\frac{Pe_m}{t}}-\sqrt{Krt})\right]$$
$$u_5(y,t)=\frac{a_1 e^{a_2 t}}{2a_2}\left[e^{y\sqrt{\lambda+a_4)}}erfc(\frac{y}{2\sqrt{t}}+\sqrt{(\lambda+a_2)t})+e^{-y\sqrt{\lambda+a_2}}erfc(-\frac{y}{2\sqrt{t}}-\sqrt{(\lambda+a_2)t})\right]$$
$$u_6(y,t)=\frac{a_1}{2a_2}\left[e^{y\sqrt{\lambda)}}erfc(\frac{y}{2\sqrt{t}}+\sqrt{\lambda t})+e^{-y\sqrt{\lambda}}erfc(\frac{y}{2\sqrt{t}}-\sqrt{\lambda t})\right]$$
$$u_7(y,t)=\frac{a_3 e^{a_4 t}}{2a_4}\left[e^{y\sqrt{\lambda+a_4)}}erfc(\frac{y}{2\sqrt{t}}+\sqrt{(\lambda+a_4)t})+e^{-y\sqrt{\lambda+a_4)}}erfc(-\frac{y}{2\sqrt{t}}-\sqrt{(\lambda+a_4)t})\right]$$
$$u_8(y,t)=\frac{a_3}{2a_4}\left[e^{y\sqrt{\lambda}}erfc(\frac{y}{2\sqrt{t}}+\sqrt{\lambda t})+e^{-y\sqrt{\lambda}}erfc(\frac{y}{2\sqrt{t}}-\sqrt{\lambda t})\right]$$

$erfc(x)$ being the complimentary error function defined by $erfc(x)=1-erf(x)$, $erf(x)\frac{2}{\sqrt{n}}\int_0^x e^{-\eta^2}d\eta$

3. Results and Discussion

In this section, the results from the previous section are presented to understanding clearly the physical insight and graphical interpretation. While keeping $\gamma=0.5$, $R=0.3$, $m=1.0$, $Gr=2.0$, $Gm=2.0$, $M=0.5$ and $\phi=\pi/4$. All these values considered constant unless they are cited [10].

Figure 1 shows the velocity profile with magnetic parameter. As we can see from the graph, the velocity profiles rise when the magnetic parameter decrease. However, the outlines are very close to each other to describe the slow growth of velocity. Literally, the application of the transverse magnetic field that give a resistive type of force called Lorentz force. Hence, it develops the thickness of boundary layers of momentum and thermal region which helps to cool the electronic systems and radiators and it slow down the growth of velocity. Figure 2 shows the velocity curves increase with the increasing of inclination angle. This explain that the increasing of inclination angle accelerates the fluid motion along the plate. When the plate is inclined from the vertical, the buoyancy force also effected due to the thermal and mass diffusion reduced as $\cos\phi$ decreased. Figure 3 illustrate the nature of velocity field curve against the changed values of porous medium. The higher value of porous medium developed the resistance to flow resulting the increasing in the flow of velocity. In fact, the frictional force to oppose the flow also decrease that makes the velocity become higher. Figure 4 displays the result of the fluid velocity with the variation values of chemical reaction. From this graph, the velocity is increase with the increment of chemical reaction. As the chemical reaction increase, the boundary layer become thin because of the effect of hydrodynamic and concentration along the way. Figure 5 illustrate the velocity profile against Hall current. The plot explained when the Hall current increase, the velocity also increases. When the Hall parameter is rising, the effective of conductivity decreases which lead the decreasing in magnetic damping, results the increase in velocity.

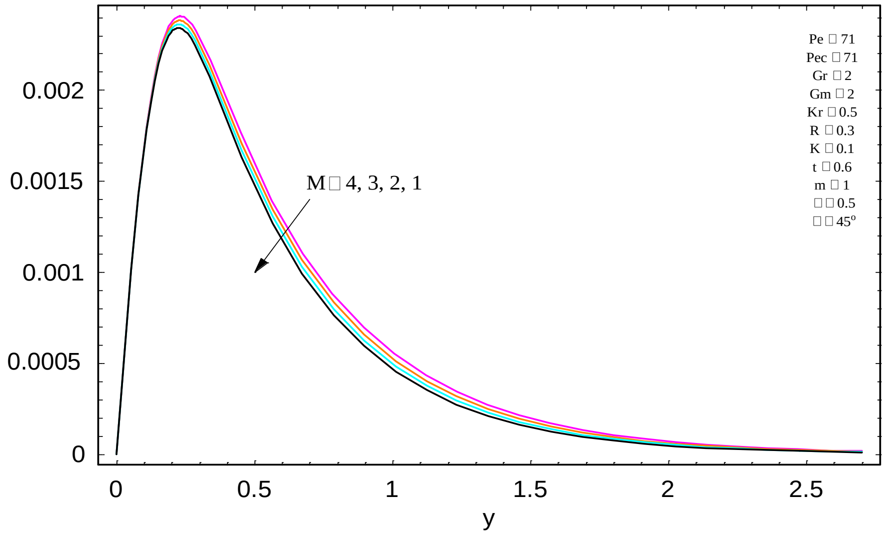

Fig. 1. The influence of magnetic parameter, M on the velocity profile

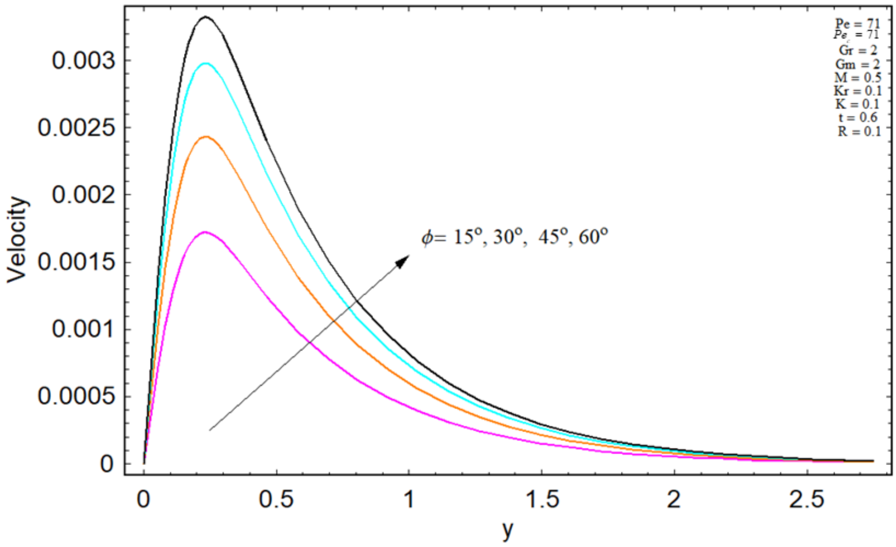

Fig. 2. The influence of inclination angle, ϕ on the velocity profile

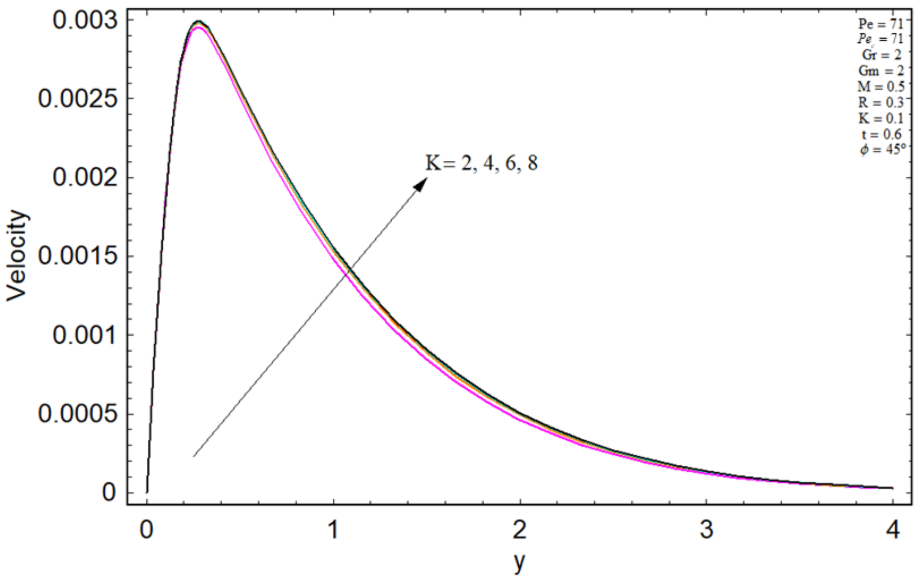

Fig. 3. The influence of porous medium, K on the velocity profile

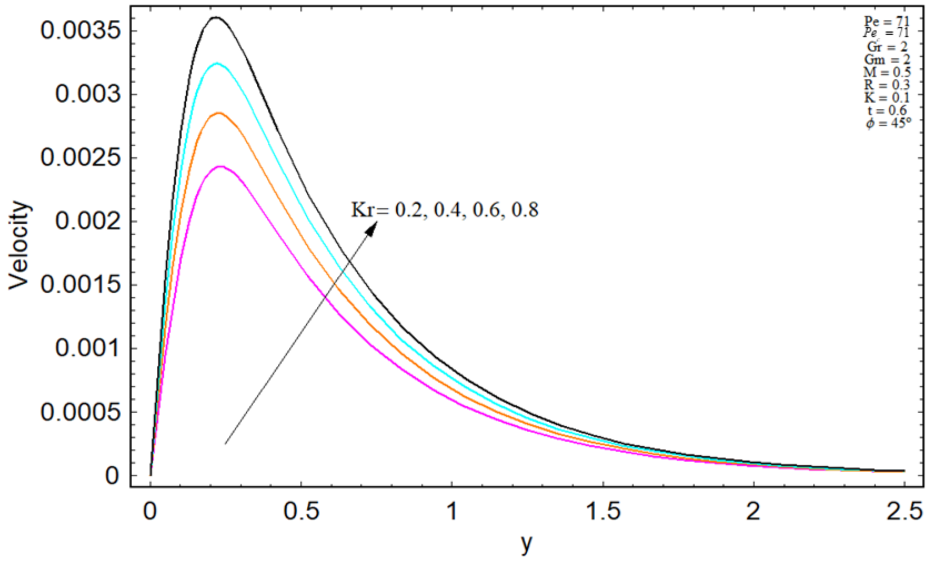

Fig. 4. The influence of chemical reaction, Kr on the velocity profile

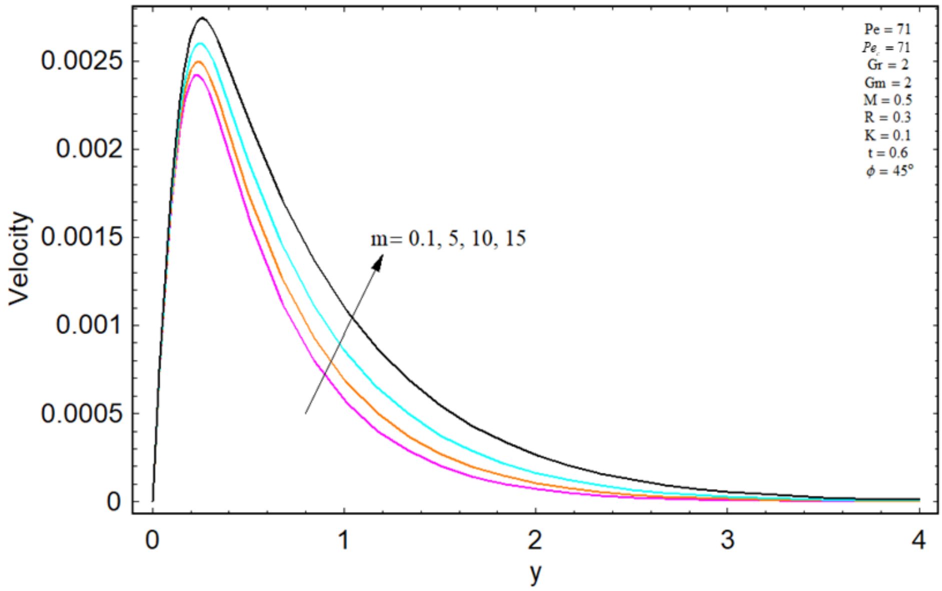

Fig. 5. The influence of Hall current, m on the velocity profile

Attribute of radiation on thermal field curves are interpreted in Figure 6. The temperature field lines upsurges with an increasing value of radiation parameter. The upshot of conduction rises when the value of parameter increased, hence the fluid temperature increases at every point away from the surface which increases the thermal outlines. Figure 7 describes Pe_c results against concentration field. The plot shows the decline of concentration profile when Pe_c increase. The Sc parameter that consist in Pe_c parameter actually the reason a decay in the fluid concentration profiles. In reality, Schmidt number is defined as the ratio of viscosity towards thermal diffusivity.

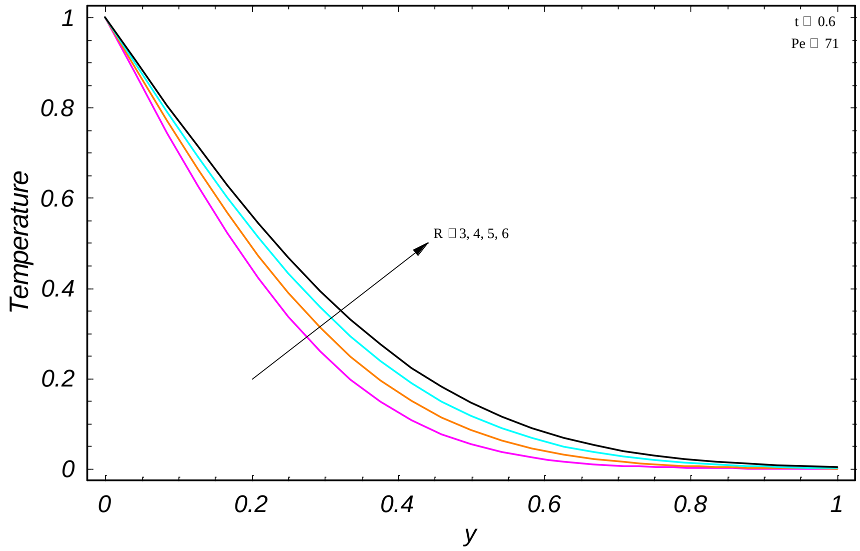

Fig. 6. The influence of radiation, R on the temperature profile

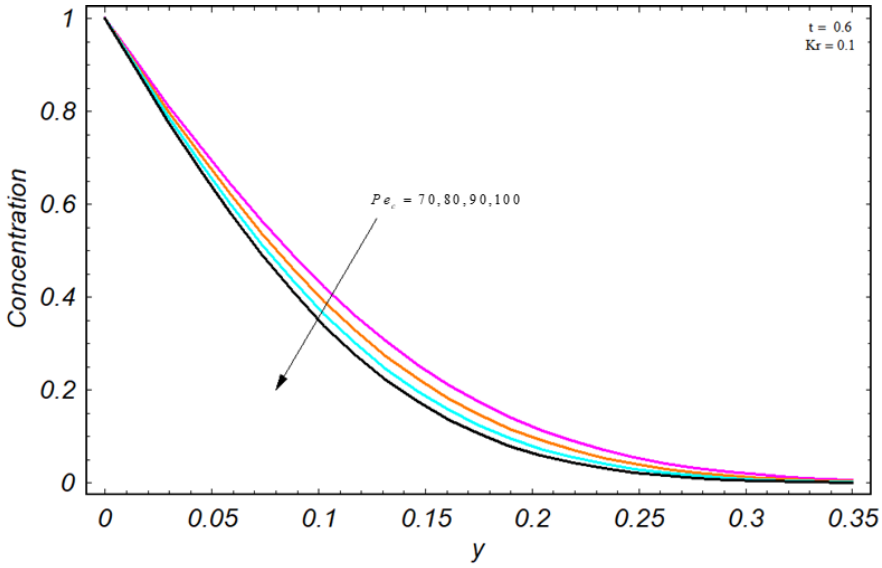

Fig. 7. The influence of Peclet's number of concentrations, Pe_c on the concentration profile

4. Conclusion

The investigation of research is to solved the exact solution of unsteady Casson fluid in the present of hall current and chemical reaction electrically conducting heat fluid near an infinite inclined plate. The result of velocity, temperature as well as concentration expressions were obtained from Laplace transform method. The outcomes of momentum, thermal and concentration fields are represented graphically. The most decisive findings of the research are summarized. Fluid velocity rises with the increment of magnetic parameter. However, the outlines are very close to one another because of the slow growth of velocity. Increasing of inclination angle accelerates the fluid motion along the plate. The rises of porous medium developed the resistance to flow, hence the velocity increases. The velocity is increase with the increment of chemical reaction. Increasing value of Hall current makes the velocity field also increase. The temperature field lines upsurges with an increasing value of radiation parameter. Concentration profile is declined when Peclets number of concentrations, Pe_c increase.

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