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Magnetohydrodynamic Radiative Casson Fluid Flow over a Semi-Infinite Vertical Plate: An Analytical Approach

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Abstract:
In this study, we analyzed the heat transfer nature of the magnetohydrodynamic Casson fluid flow over a semi-infinite porous vertical plate in the presence of thermal radiation and heat source/sink with buoyancy effect. The governing partial differential equations are transformed as non-dimensional equations using suitable transformation and resulting equations are solved using Perturbation technique. The effect of non-dimensional parameters namely thermal radiation, heat source/sink, Grashof number, porosity parameter and magnetic field parameter on the flow and heat transfer is analyzed for both Casson and Newtonian fluid cases. Also discussed the friction factor and local Nusselt number for both cases. It is found that momentum and thermal boundary layers of Casson and Newtonian fluids are non-uniform.
Keywords: Casson fluid, MHD, thermal radiation, heat source/sink, buoyancy effect.

Introduction

The study on MHD effects of non-Newtonian Casson fluid flow with heat transfer problems has become industrially more important. Nanofluids are vital applications in science and technology, cancer homeotherapy and aerodynamics. Abo-Eldahab and Aziz [1], analyzed the problem on MHD free convection flow over a semi-infinite vertical plate with the influence of viscous and Joule heating in the presence of Hall and ion-slip currents. Effects of radiation and aligned magnetic field on ferrofluids past a flat plate in the presence of heat source and slip velocity was studied by Raju et al. [2] and concluded that when slip parameter increases the momentum boundary layer thickness enhance. Vedavathi et al. [3] studied the effects of MHD on Casson flow past a vertical plate with Dufour, radiation and chemical reaction. Sekhar et al. [4] studied the effects on MHD boundary layer slip flow of Jeffrey fluid past a flat plate with heat transfer. In this study they found that when the temperature increases the slip parameter increases. Rushi Kumar and Sivaraj [5] investigated the unsteady flow of MHD viscoelastic fluid past a vertical cone and a flat plate with magnetic field and chemical reaction. Chamkha [6] analyzed the problem of incompressible fluid flow over a semi-infinite vertical permeable moving plate with the influence of magnetic field and concentration buoyancy and he found that when Grashof number increased, the fluid velocity also increased. Umar Khan et al. [7] studied the squeezing flow of a viscous fluid between parallel plates in the presence of two-dimensional axisymmetric flow. In this study they used variation of parameters method and discussed the solutions. Afikuzzaman et al. [8] analyzed the problem on MHD Casson Fluid Flow over a parallel plate with heat transfer and Hall Current and analyzed the velocity and temperature distributions for various parameters. The problem of unsteady MHD flow over an infinite vertical heated plate with time-dependent suction was studied by Israel-Cookey et al. [9]. Kim and Fedorov [10] analyzed the flow of micropolar fluid over a semi-infinite vertical plate in the presence of thermal radiation. In this study they used Rosseland approximation to describe the limit of optically thick fluids. Takhar et al. [11] studied the effects of heat transfer and unsteady flow over a semi-infinite flat plate with magnetic field, and analyzed the effect of the impulsive motion of the plate. Kim and Lee [12] analyzed the problem of the oscillatory flow of a micropolar fluid past a vertical porous plate with skin friction. In this problem they analyzed the existence of oscillating behavior in the velocity distribution.

The problem on MHD convective boundary layer flow over a vertical plate in the presence of chemical reaction and thermal radiation was studied by Dulal Pal and Babulal Talukdar [13]. In this problem they used perturbation technique to solve the partial differential equations. Sheikholeslami and Ganji [14] investigated the heat transfer of nanofluid flow between parallel plates in the presence of squeezing effect. In this study they analyzed the effects of the nanofluid volume fraction. Heat and mass transfer of MHD Casson fluid flow past a rotating cone/plate in the presence of cross diffusion studied by Raju and Sandeep [15]. This paper they resulted that increase in magnetic field parameter increase the heat and mass transfer rates. Ramana Reddy et al. [16] analyzed on MHD nanofluid flow towards a flat plate with radiation and chemical reaction. In this study they found the behavior of various dimensionless parameters. Pushpalatha et al. [17] studied the unsteady MHD flow of a Casson fluid past a vertical flat plate with convective boundary conditions in heat and mass transfer. In this study they used perturbation technique to solve the equations. Ibrahim et al. [18] studied the effects of radiation absorption and chemical reaction on MHD flow over a semi-infinite vertical plate in the presence of chemical reaction and radiation. Ramesh and Devakar [19] analyzed the problem on flows of Casson fluid between parallel plates with slip boundary conditions. From this problem it is observed that the volume flow and velocity rate of fluid decreases in the presence of Casson number. Din et al. [20] studied the flow of a nanofluid between parallel plates on heat and mass transfer. In this study they used homotopy analysis method to solve the equations. The article on unsteady MHD free flow of Casson fluid over an oscillating vertical plate with porous medium studied by Asma Khalid et al. [21]. In this paper they analyzed the results for emerging flow parameters. Takhar et al. [22] studied the effects on MHD free flow of a gas towards a semi-infinite vertical plate in the presence of radiation and magnetic field. This article results that the radiation does not affect the velocity and temperature. Aboeldahab and Elbarbary [23] investigates the effects on MHD flow over a vertical plate with mass transfer in the presence of hall current and magnetic field. In this paper they used fourth-order Runge – Kutta method to obtain the results. Mbeledogu and Ogulu [24] studied the MHD natural convection flow over a vertical porous flat plate in the presence of chemical reaction and radiative heat transfer. In this study they concluded that the radiation affects the velocity and temperature. Rajesh Sharma et al. [25] analyzed the influence of heat absorption and magnetic field of micropolar fluid flow over semi-infinite moving plate with heat transfer and viscous dissipation. This article results that the velocity increases with increase of plate velocity. Very recently, the researchers [26-32] studied the heat transfer behavior of magnetic flows by considering the various channels.

In this study, we analyzed the heat transfer nature of the magnetohydrodynamic Casson fluid flow over a semi-infinite porous vertical plate in the presence of thermal radiation and heat source/sink with buoyancy effect. The governing partial differential equations are transformed as non-dimensional equations using suitable transformation and resulting equations are solved using Perturbation technique. The effect of non-dimensional parameters namely thermal radiation, heat source/sink, Grashof number, porosity parameter and magnetic field parameter on the flow and heat transfer is analyzed for both Casson and Newtonian fluid cases.

Formulation of the problem

Consider a 2D unsteady flow of a Casson fluid over a semi-infinite vertical plate embedded in porous medium. Here plate is placed along $\bar{x}$-axis and $\bar{y}$ axis is normal to it. An inclined magnetic field of strength B_0 is considered as depicted in Fig.1. It is assumed that there is no applied voltage which implies the absences of any electrical field. The radiative heat flux in the $\bar{x}$ direction is considered negligible in comparison to that in the $\bar{y}$ direction. The governing equations for this study are based on the conservation of mass, linear momentum and energy. Taking into consideration the assumption made above, these equation in Cartesian frame of reference are given by

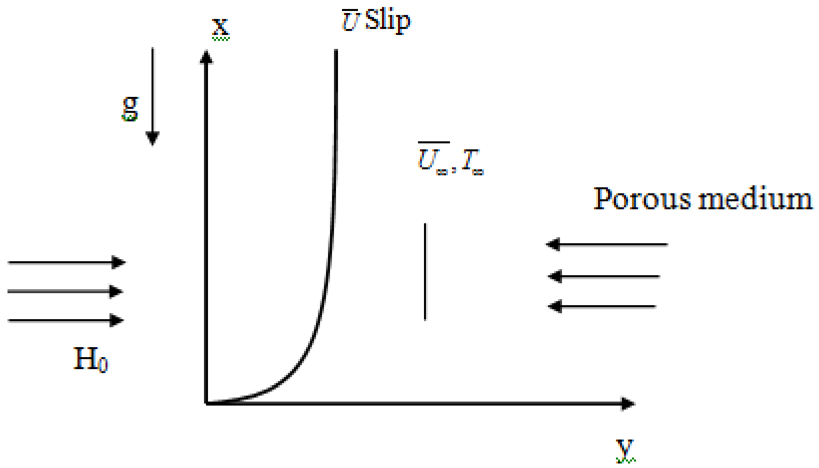

Fig.1 Physical model and the coordinate system.

Continuity:

$$\frac{\partial \bar{v}}{\partial \bar{y}} = 0 \qquad (1)$$

Momentum:

$$\frac{\partial \bar{u}}{\partial \bar{t}} + \bar{v}\frac{\partial \bar{u}}{\partial \bar{y}} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial \bar{x}} + \nu\left(1+\frac{1}{\beta}\right)\frac{\partial^2 \bar{u}}{\partial \bar{y}^2} - \frac{\sigma B_0^2}{\rho}\bar{u} - \frac{\nu \bar{u}}{\bar{K}} + g\beta(\bar{T}-T_\infty) \qquad (2)$$

Energy:

$$\frac{\partial \bar{T}}{\partial \bar{t}}+\bar{v}\frac{\partial \bar{T}}{\partial \bar{y}}=\frac{k}{\rho c_p}\frac{\partial^2 \bar{T}}{\partial \bar{y}^2}-\frac{1}{\rho cp}\frac{\partial \bar{q_r}}{\partial \bar{y}}-\frac{Q_0}{\rho c_p}\left(\bar{T}-T_\infty\right), \tag{3}$$

Where $\bar{u}$ and $\bar{v}$ are the component of the dimensional velocities along $\bar{x}$ and $\bar{y}$ directions respectively. For optically thin limit for a non-gray gas near equilibrium, the radiative heat flux is represented by the following form:

$$\frac{\partial \bar{q_r}}{\partial \bar{y}}=4\left(\bar{T}-T_\infty\right)\bar{I}, \tag{4}$$

Where $\bar{I}=\int K_{\lambda w}\frac{\partial e_{b\lambda}}{\partial \bar{T}}d\lambda$

Under this assumption, the appropriate boundary condition for velocity involving slip flow, concentration fields are given by

$$\bar{u}=\bar{u}_{slip}=\frac{\sqrt{\bar{K}}}{\alpha}\frac{\partial \bar{u}}{\partial \bar{y}},\bar{T}=T_w \qquad at \quad \bar{y}=0, \tag{5}$$

$$\bar{u}\to\overline{U_\infty}=U_0(1+\varepsilon e^{\bar{n}\bar{t}}),\bar{T}\to T_\infty \quad as \quad \bar{y}\to\infty \tag{6}$$

Since the suction velocity normal to the plate is a function of time only, it can be taken in the exponential form as

$$\bar{v}=-V_0\left(1+\varepsilon A e^{\bar{n}\bar{t}}\right), \tag{7}$$

Where A is a real positive constant, ε and εA are small quantities less than unity and $V_0>0$.

Outside the boundary layer, equation (2) gives

$$-\frac{1}{\rho}\frac{d\bar{p}}{d\bar{x}}=\frac{d\overline{U_\infty}}{d\bar{t}}+\frac{\sigma B_0^2}{\rho}\overline{U_\infty}+\frac{v}{\bar{K}}\overline{U_\infty} \tag{8}$$

Now, we introduce the dimensionless variables as follows

$$u=\frac{\bar{u}}{U_0},v=\frac{\bar{v}}{V_0},y=\frac{V_0\bar{y}}{v},U_\infty=\frac{\overline{U_\infty}}{U_0},t=\frac{\bar{t}V_0^2}{v},\theta=\frac{\bar{T}-T_\infty}{T_w-T_\infty},$$

$$n=\frac{\bar{n}v}{V_0^2},K=\frac{\bar{K}V_0^2}{v^2},\Pr=\frac{\mu c_p}{k},M=\frac{\sigma B_0^2}{\rho V_0^2},Gr=\frac{v\beta g(T_w-T_\infty)}{U_0V_0^2},$$

$$S=\frac{Q_0 v}{\rho c_p V_0^2},\ F=\frac{4v\bar{I}}{\rho c_p V_0^2} \tag{9}$$

Using (9), the governing (2) & (3) reduce to the following non-dimensional form:

$$\frac{\partial u}{\partial t}-\left(1+\varepsilon A e^{nt}\right)\frac{\partial u}{\partial y}=\frac{dU_\infty}{dt}+B\frac{\partial^2 u}{\partial y^2}+Gr\theta+N\left(U_\infty-u\right) \tag{10}$$

Where $N=M+\frac{1}{K},\ B=1+\frac{1}{\beta}$

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

The boundary condition (6) and (7) in the dimensionless form can be written as

$$u=u_{slip}=\phi\frac{\partial u}{\partial y},\theta=1 \quad at \quad y=0, \tag{12}$$

Where $\phi=\frac{\sqrt{K}}{\alpha}U_0$

$$u\to U_\infty=1+\varepsilon e^{nt},\theta\to 1 \quad at \quad y\to\infty, \tag{13}$$

Solution of the problem

To solve the equation (10) and (11), we assume the solution in the following form:

$$u = f_0(y) + \varepsilon e^{nt} f_1(y) + O(\varepsilon^2), \tag{14}$$

$$\theta = g_0(y) + \varepsilon e^{nt} g_1(y) + O(\varepsilon^2), \tag{15}$$

Substituting (14) and (15) into the equation (10) and (11) and equating the harmonic and non-harmonic terms, neglecting the coefficient of $O(\varepsilon^2)$, we get the following pairs of equation for (f_0, g_0) and (f_1, g_1).

$$Bf_o'' + f_0' - Nf_0 = -N - Grg_0 \tag{16}$$

$$Bf_1'' + f_1' - (N+n) f_1 = -Af_0' - Grg_1 - (N+n), \tag{17}$$

$$g_0'' + \Pr g_0' - \Pr(F+S) g_0 = 0, \tag{18}$$

$$g_1'' + \Pr g_1' - \Pr(F+S+n) g_1 = -A \Pr g_0', \tag{19}$$

Where the primes denote the differentiation with respect to y.

The corresponding boundary conditions can be written as

$$f_0 = \phi_1 f_0',\ f_1 = \phi_1 f_1',\ g_0 = 1,\ g_1 = 0\ \ at\ y = 0, \tag{20}$$

$$f_0 = 1,\ f_1 = 1,\ g_0 \to 0,\ g_1 \to 0\ \ as\ \ y \to \infty, \tag{21}$$

The solution of equation (16)-(19) which satisfy the boundary conditions (20) and (21) are given by

$$f_0(y) = 1 + D_3 e^{-m_3 y} + D_2 e^{-m_1 y} \tag{22}$$

$$f_1(y) = 1 + D_7 e^{-m_4 y} + D_4 e^{-m_3 y} + D_5 e^{-m_2 y} + D_6 e^{-m_1 y}, \tag{23}$$

$$g_0(y) = e^{-m_1 y} \tag{24}$$

$$g_1(y) = -D_1 e^{-m_2 y} + D_1 e^{-m_1 y} \tag{25}$$

Substituting equation (22) - (25) in equation (14) and (15), we obtain the velocity and concentration distributions in the boundary layer as follows:

$$u(y,t) = 1 + D_3 e^{-m_3 y} + D_2 e^{-m_1} + \varepsilon e^{nt}\left(1 + D_7 e^{-m_4 y} + D_4 e^{-m_3 y} + D_5 e^{-m_2 y} + D_6 e^{-m_1 y}\right), \tag{26}$$

$$\theta(y,t) = e^{-m_1 y} + \varepsilon e^{nt}\left(-D_1 e^{-m_2 y} + D_1 e^{-m_1 y}\right), \tag{27}$$

Where

$$m_1 = \frac{\Pr\sqrt{\Pr^2 + 4\Pr(F+S)}}{2},\ m_2 = \frac{\Pr\sqrt{\Pr^2 + 4\Pr(F+S+n)}}{2},\ m_3 = \frac{1}{2}\left(1 + \sqrt{1+4BN}\right),$$

$$m_4 = \frac{1}{2}\left(1 + \sqrt{1+4B(n+N)}\right),\ D_1 = \frac{A\Pr m_1}{m_1^2 - \Pr m_1 - (F+S+n)\Pr},\ D_2 = \frac{-Gr}{Bm_1^2 - m_1 - N},$$

$$D_3 = \frac{-(1 + D_2 + \phi m_1 D_2)}{1+\phi m_3},\ D_4 = \frac{AD_3 m_3}{Bm_3^2 - m_3 - (N+n)},$$

$$D_5 = \frac{GrD_1}{Bm_2^2 - m_2 - (N+n)},\ D_6 = \frac{AD_2 m_1 - GrD_1}{Bm_1^2 - m_1 - (N+n)},$$

$$D_7 = \frac{-(1 + D_4 + D_5 + D_6) - \phi(D_4 m_3 + D_5 m_2 + D_6 m_1)}{1+\phi m_4},$$

Skin friction at the wall is given by

$$C_{fx} = \frac{\tau_w}{\rho U_0 V_0} = \left.\frac{\partial u}{\partial y}\right|_{y=0}$$

$$C_{fx} = -(D_3 m_3 + D_2 m_1) - \varepsilon e^{nt}(D_7 m_4 + D_4 m_3 + D_5 m_2 + D_6 m_1) \tag{28}$$

We calculate the heat transfer coefficient in terms of Nusselt number as follows:

$$N_{ux} = x\frac{\left.\frac{\partial T}{\partial \bar{y}}\right|_w}{T_w - T_\infty} \Rightarrow Nu_x / \mathrm{Re}_x = \left.\frac{\partial \theta}{\partial y}\right|_{y=0} \tag{29}$$

$$Nu_x / \mathrm{Re}_x = -m_1 + \varepsilon e^{nt} D_1 \left(m_2 - m_1 \right) \tag{30}$$

Where $\mathrm{Re}_x = \frac{V_0 x}{\nu}$ is the Reynolds number.

Results and discussion

Results shows the effect of non-dimensional parameters namely thermal radiation, heat source/sink, Grashof number, porosity parameter and magnetic field parameter on the flow and heat transfer for both Casson and Newtonian fluid cases. Also discussed the friction factor and local Nusselt number for both cases. For graphical results we used the non-dimensional parameter values as $\mathrm{Pr} = 6, M = 3, K = 1, S = 0.5, F = 1, n = 0.1, t = 1, \varepsilon = 0.2, \phi = 0.3, Gr = 10$. These values are kept as common in entire study except the variations displayed in respective figures and tables.

Fig.2 depicts the effect of permeability parameter on velocity profile. It is evident that increasing values of permeability parameter enhances the velocity profiles of both fluids. It is also observed that momentum boundary layer of Newtonian fluid is highly effective when compared with the non-Newtonian fluid. Fig.3 illustrate the influence of time on velocity profile. It is observed that enhancing the values of time increases the velocity profile of both fluids.

The effect of Grashof number Gr on velocity profiles is displayed in Fig.4. We noticed that increasing values of Grashof number Gr enhances the velocity field of Newtonian fluid. But reverse trend has been observed for non-Newtonain case. Fig.5 shows the effect of radiation parameter F on the momentum boundary layer. It is observed that Newtonian fluid decreases with the increasing values of radiation parameter F and increases the non-Newtonian fluid velocity profiles. Typical variations in the velocity profiles along the span wise coordinate are shown in Fig.6 for different values of ε . As expected, the results shows that an increase in the ε value enhances the velocity profiles of both fluids.

Fig.7 represents the variation of velocity profiles for different values of heat source parameter S. It is observed that rising values of heat source parameter S decreases the velocity profile for Newtonian fluid and enhances the flow field of non-Newtonian fluid. The velocity profiles for different values of magnetic parameter M are displayed in Fig.8 which shows that, rising values of magnetic parameter implies the decrease in velocity profile. This may be due to drag force acting opposite to flow field.

Fig.9 depicts the effect of temperature profiles for different values of Prandtl number Pr. It shows that an increase in the Prandtl number leads to a decrease in the temperature boundary layer. Fig.10 and Fig.11 are plotted to depict the variation of temperature profiles for different values of radiation parameter F and heat source parameter S. This shows that, an increase in the radiation parameter F and heat source parameter S implies the decrease in temperature profile. Fig.12 and Fig.13 shows the variation in friction factor with increase in radiation parameter F and heat source parameter S against magnetic field parameter. It is observed that rising values of radiation parameter F and heat source parameter S with increasing values of M tend to gradual decrease in the skin friction coefficient. An increase in Prandtl number Pr against the Grashof number Gr leads to enhance the skin friction coefficient as shown in Fig.14. Fig.15 represents the effect of Prandtl number against the magnetic field parameter M on skin friction coefficient. The result shows that rising the Prandtl number against the magnetic field parameter enhance the skin friction coefficient.

Fig.16 illustrates the effect of Prandtl number Pr against radiation parameter F on Nusselt number. It is noticed that increasing the Prandtl number Pr against radiation parameter F decreases the Nusselt number. The effect of radiation parameter F against Prandtl number Pr on Nusselt number shown in Fig.17. This figure results that rising values of radiation parameter F against Prandtl number reduces the Nusselt number. Fig.18 plots the heat source parameter S against the radiation parameter F on Nusselt number, which shows that an increase in heat source parameter S against radiation parameter F gradually decreases the Nusselt number. Fig.19 illustrates that heat source parameter S against the time t on Nusselt number. It is observed that rising the values of heat source parameter S against the time t implies the decrease in Nusselt number.

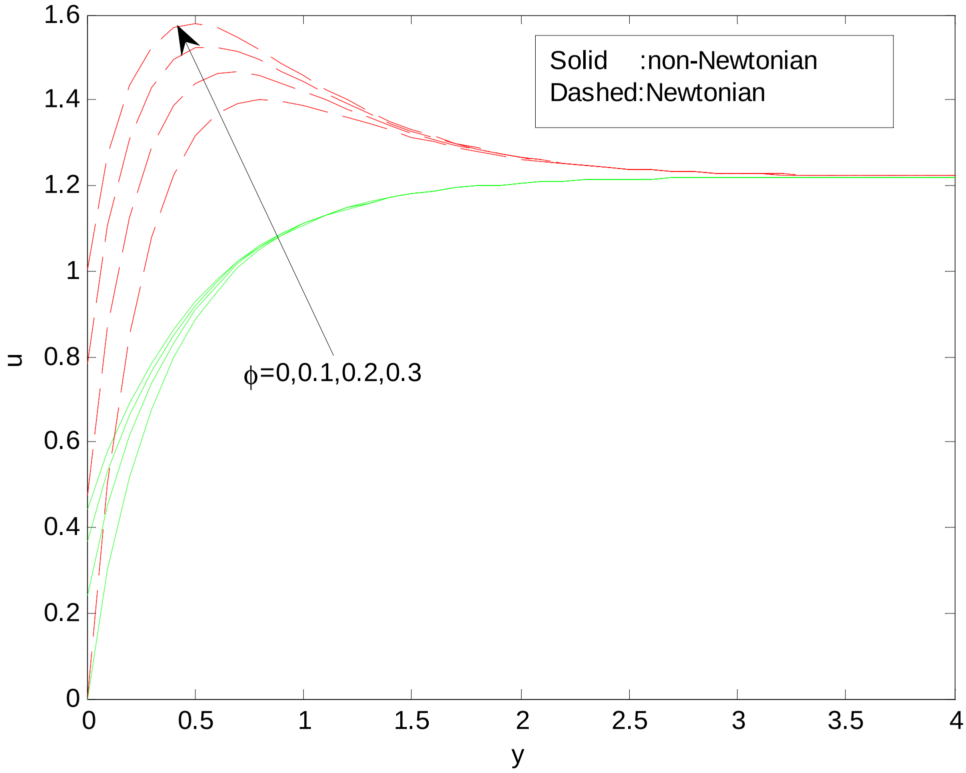

Fig. 2. Velocity profiles for different values of permeability parameter.

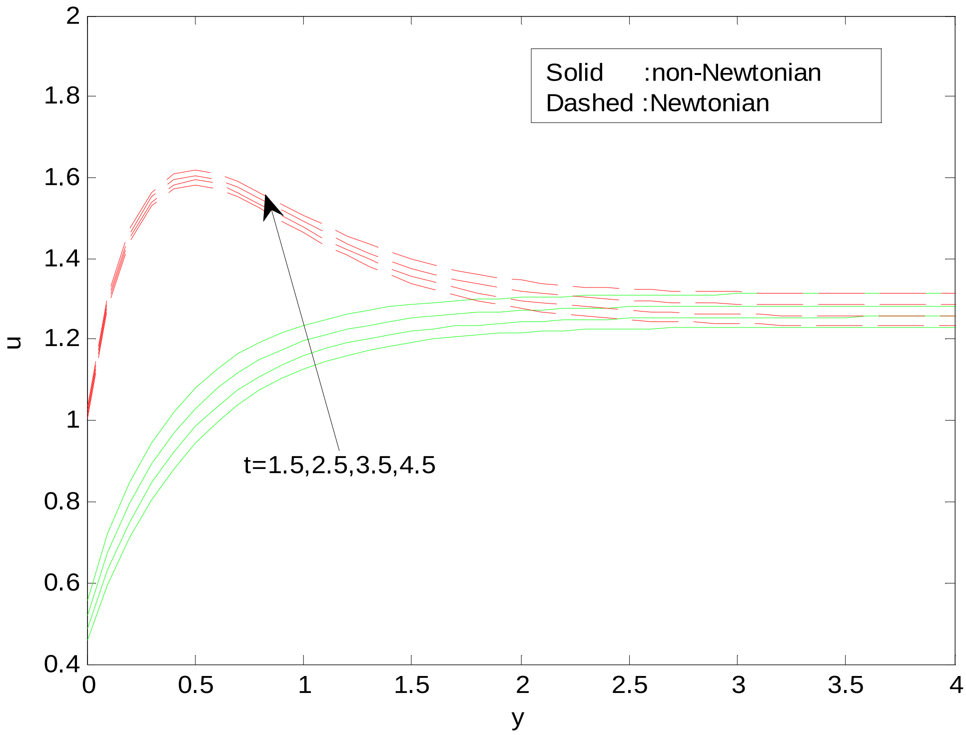

Fig. 3. Velocity profiles for different values of time.

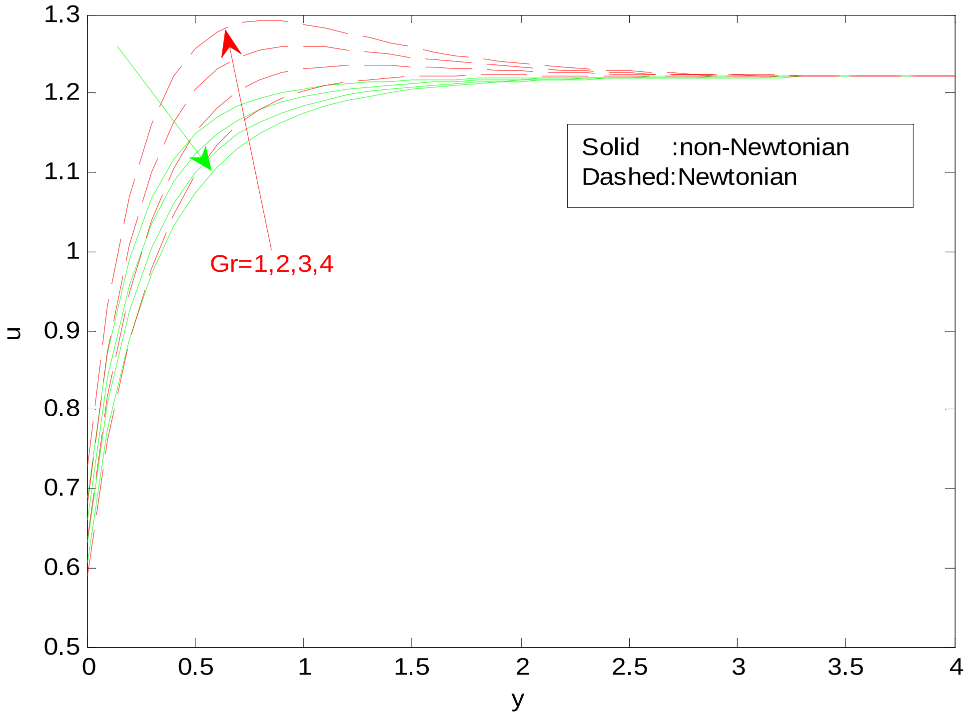

Fig. 4. Velocity profiles for different values of Grashof number.

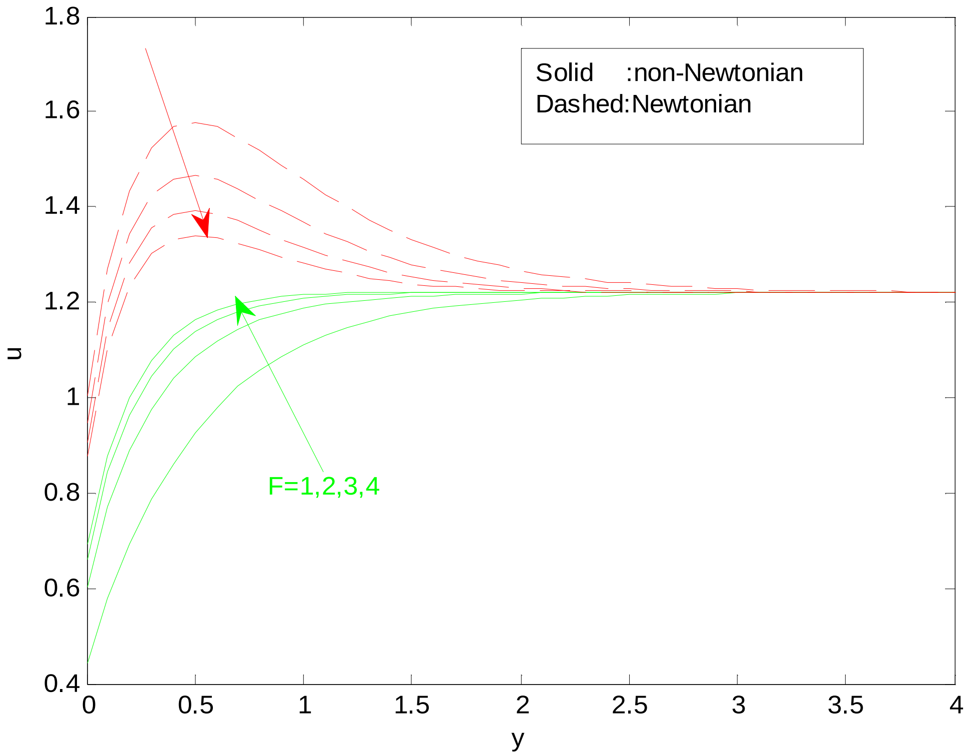

Fig. 5. Velocity profiles for different values of radiation parameter .

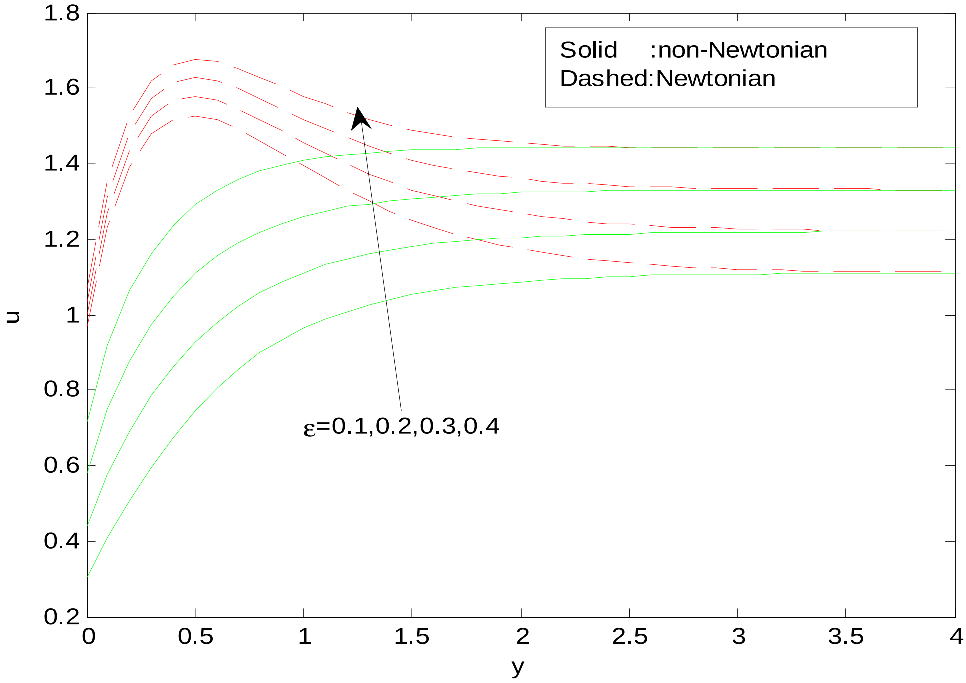

Fig. 6. Velocity profiles for different values of ε .

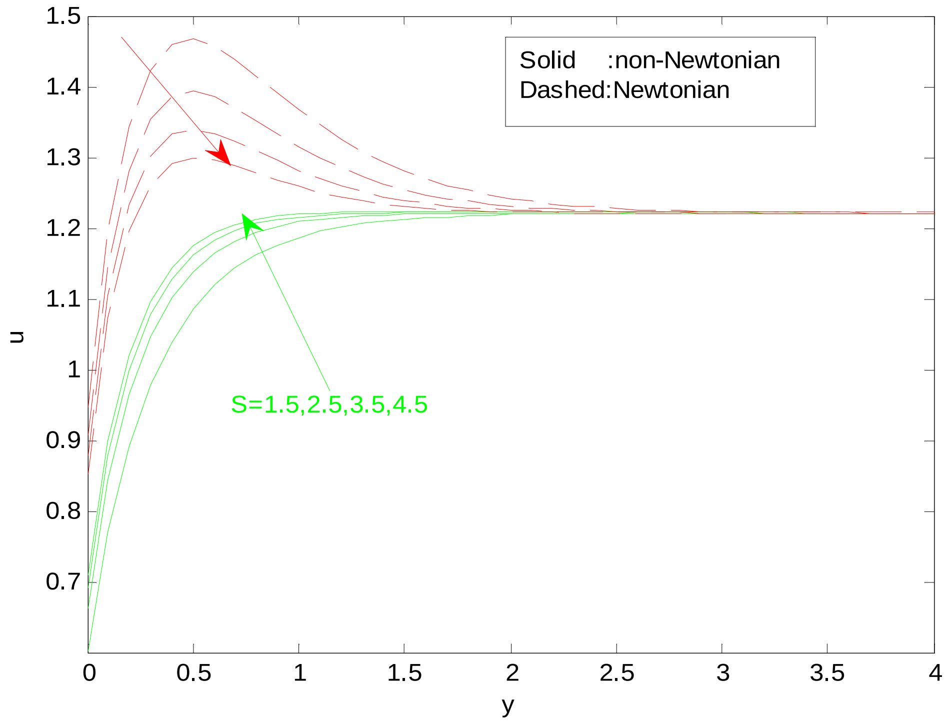

Fig. 7. Velocity profiles for different values of heat source parameter .

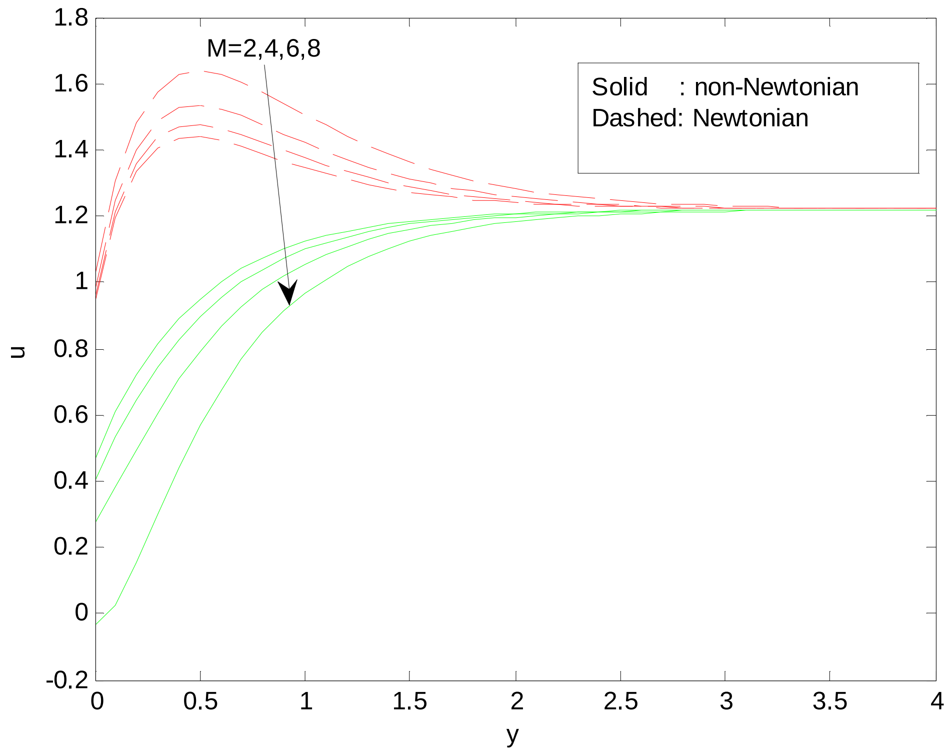

Fig. 8. Velocity profiles for different values of magnetic field parameter .

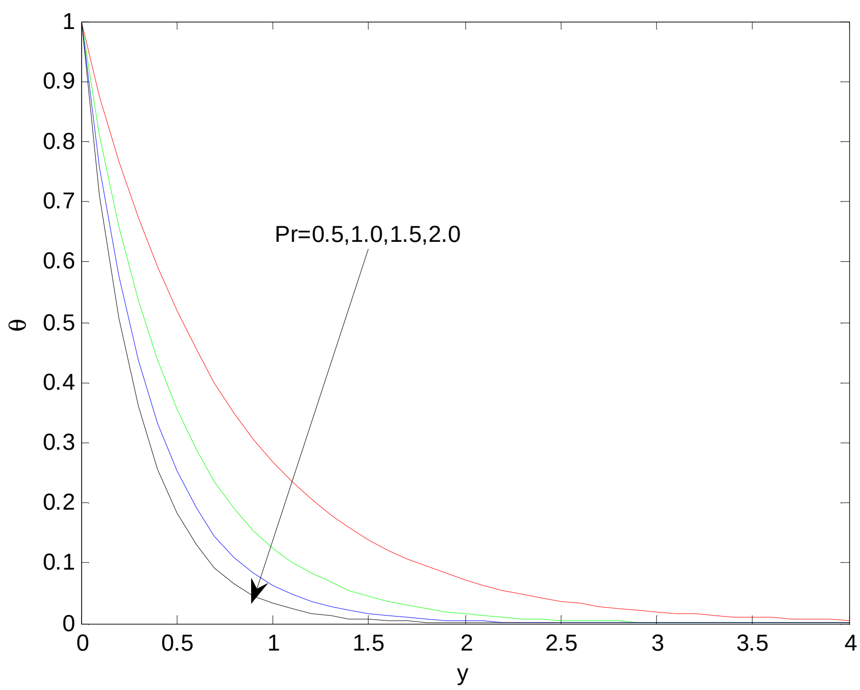

Fig. 9. Temperature profiles for different values of Prandtl number.

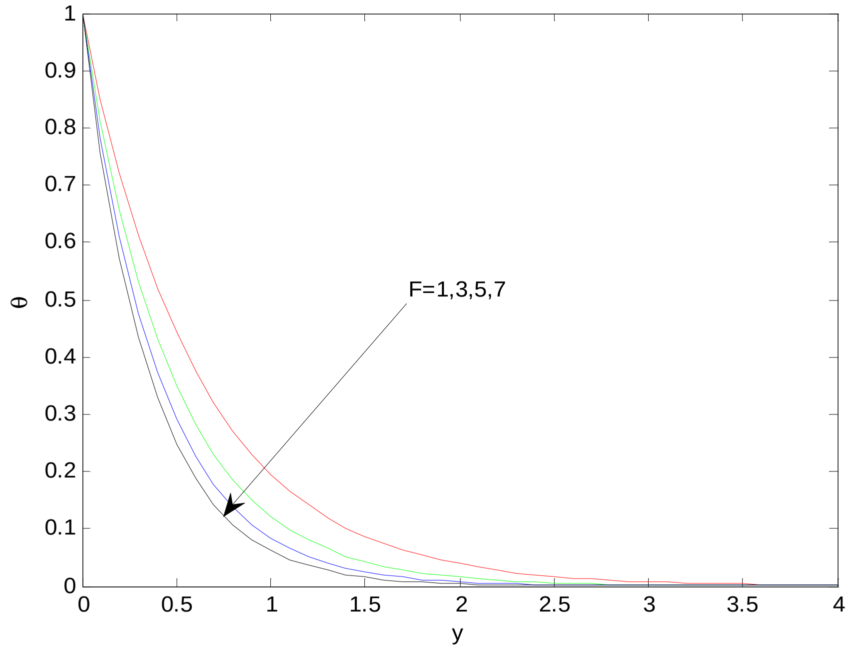

Fig. 10. Temperature profiles for different values of radiation parameter.

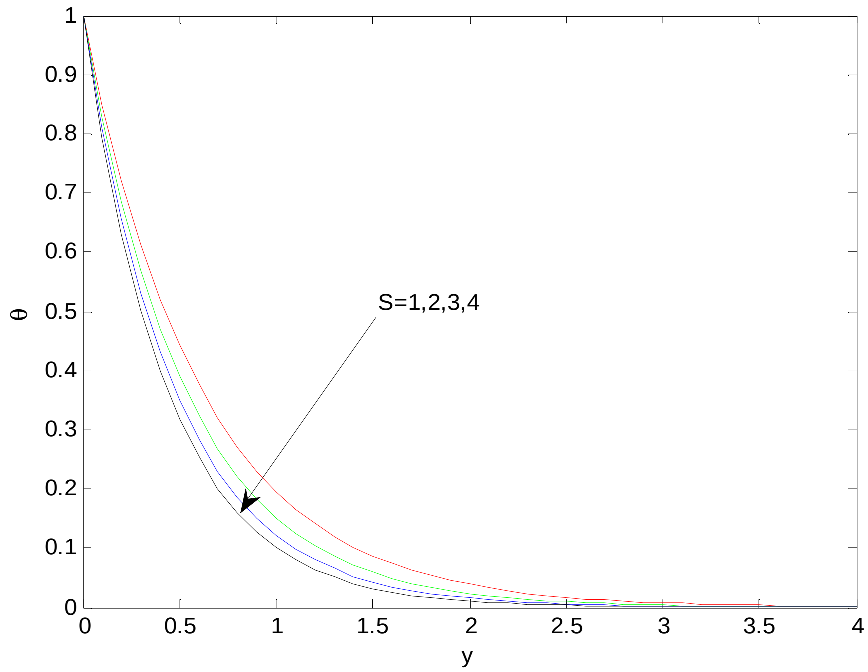

Fig. 11. Temperature profiles for different values of heat source parameter.

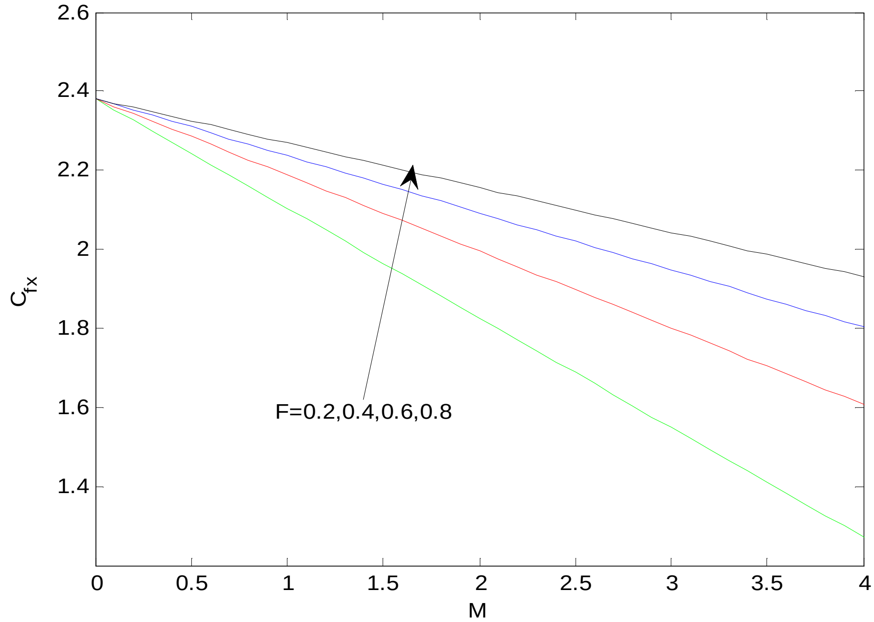

Fig. 12. Variation in skin friction coefficient for different values of F.

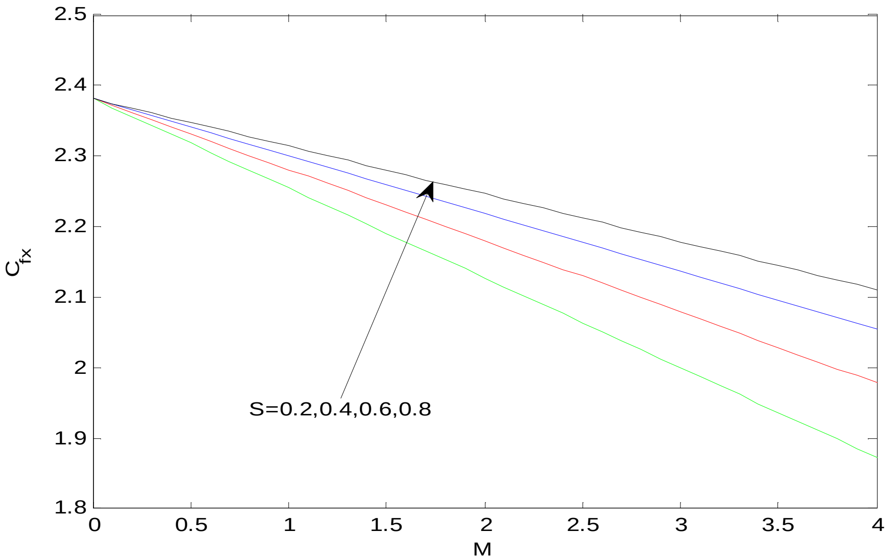

Fig. 13. Variation in skin friction coefficient for different values of S.

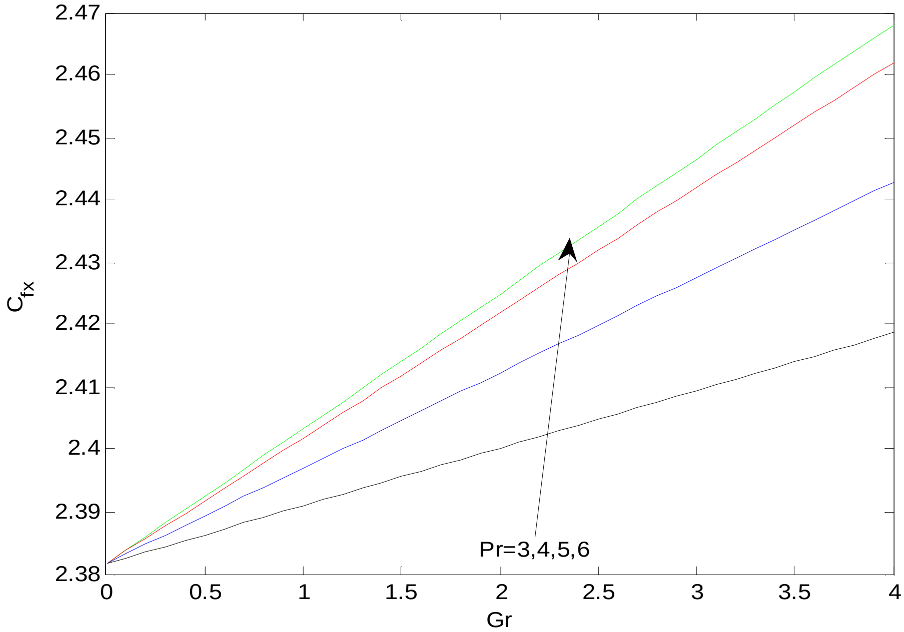

Fig. 14. Variation in skin friction coefficient for different values of Pr with Gr.

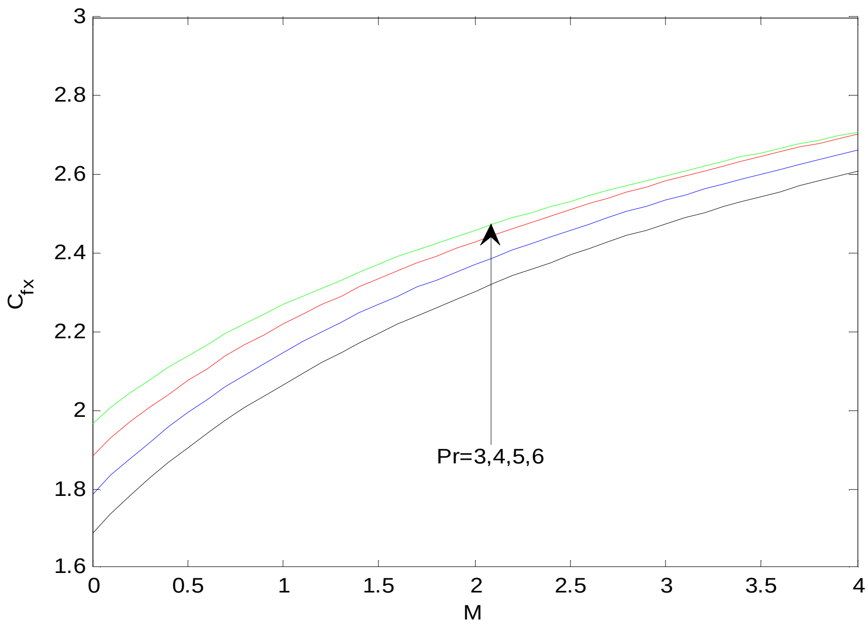

Fig. 15. Variation in skin friction coefficient for different values of Pr with M.

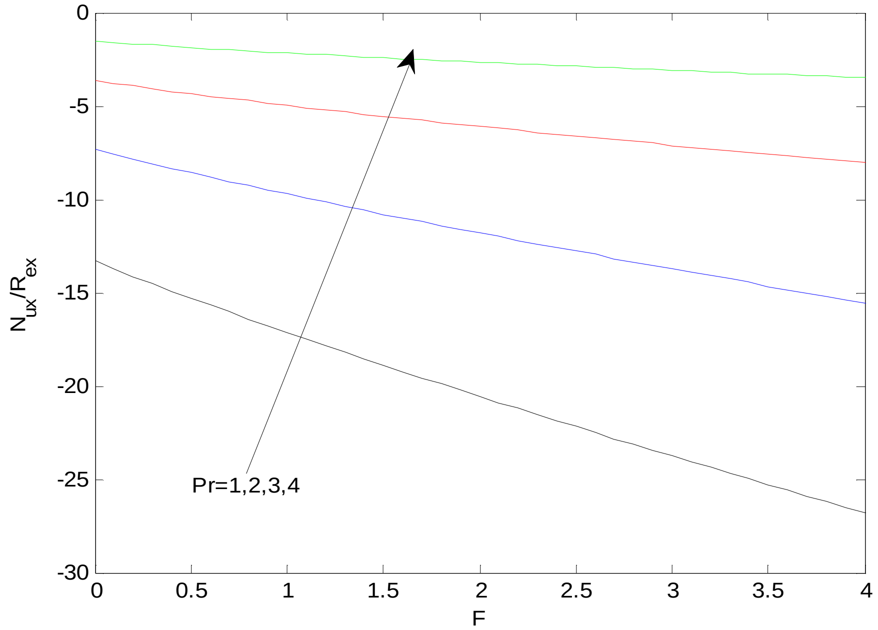

Fig. 16. Variation in Nusselt number for different values of Pr with F.

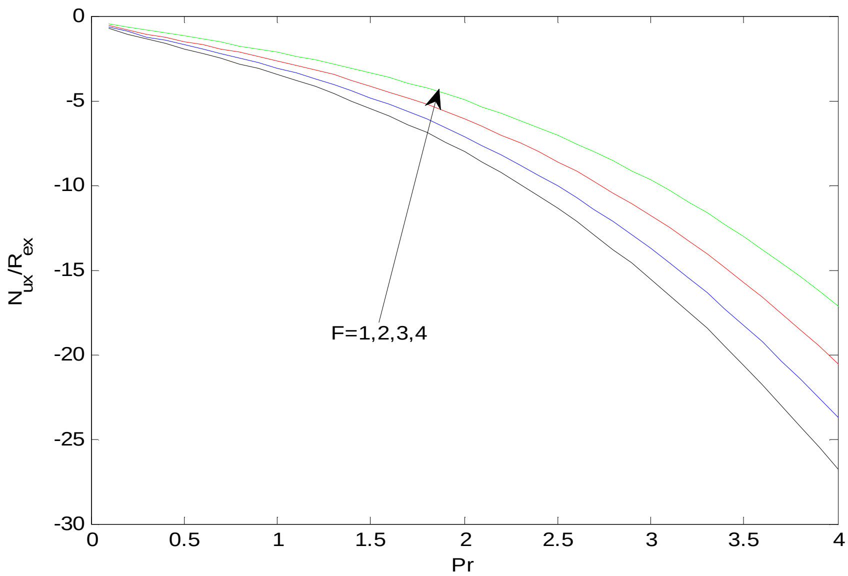

Fig. 17. Variation in Nusselt number for different values of F with Pr.

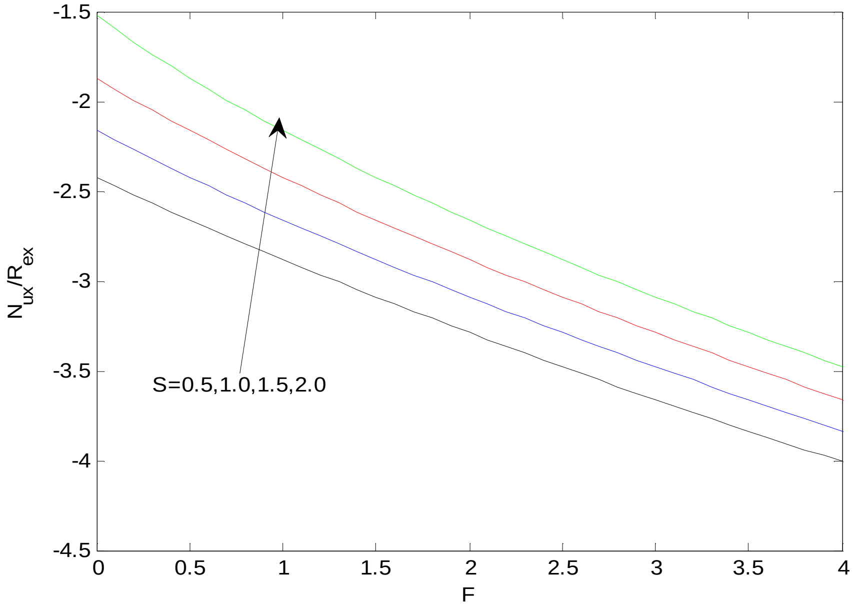

Fig. 18. Variation in Nusselt number for different values of S with F.

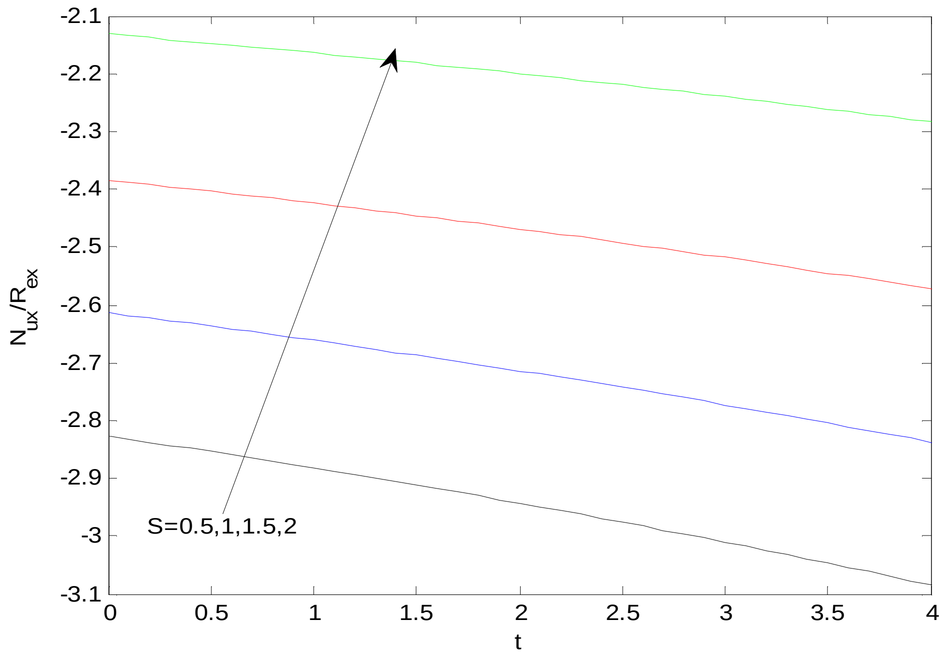

Fig. 19. Variation in Nusselt number for different values of S with t.

Conclusions

Heat transfer nature of the magnetohydrodynamic Casson fluid flow over a semi-infinite porous vertical plate in the presence of thermal radiation and heat source/sink with buoyancy effect is investigated. The governing partial differential equations are transformed as non-dimensional equations using suitable transformation and resulting equations are solved using Perturbation technique. The effect of non-dimensional parameters namely thermal radiation, heat source/sink, Grashof number, porosity parameter and magnetic field parameter on the flow and heat transfer is analyzed for both Casson and Newtonian fluid cases. Observations of the present study are as follows:

- Momentum and thermal boundary layers of Newtonian and Casson fluids are non-uniform.

- The influence of buoyancy and thermal radiation on Newtonian and non-Newtonian fluids are not uniform.
- Magnetic field parameter have tendency to control the flow field.
- Rising the heat source parameter and thermal radiation reduces the heat transfer rate.
- Increasing the Prandtl number with buoyancy effects hikes the friction factor.

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