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UNSTEADY HEAT TRANSFER FLOW OF A CASSON FLUID WITH NEWTONIAN HEATING AND THERMAL RADIATION

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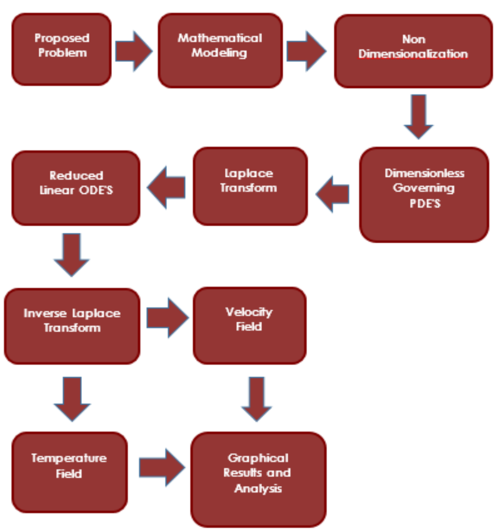
Graphical abstract



Abstract

This study investigates the unsteady heat transfer flow of a non-Newtonian Casson fluid over an oscillating vertical plate with Newtonian heating on the wall under the effects of thermal radiation. With the help of non-dimensional variables, governing equations are written into dimensionless form and then solved analytically by Laplace transform technique to find the solutions of temperature and velocity. The corresponding solutions of Nusselt number and skin friction are also calculated. The solution in term of viscous fluid is recovered as a limiting case of this work. The effects of the pertinent parameters on temperature and velocity are presented graphically and discussed details in this paper.

Keywords: Heat transfer; laplace transforms; newtonian heating; radiation effects

1.0 INTRODUCTION

During the last few years, the study of non-Newtonian fluids has got the attention of several authors because of its many applications in engineering and industry. For example, in process of plastic sheets, glass fiber production, movement of lubricants and biological fluids. The mathematical models for non-Newtonian fluid flows are non-linear and more complicated compared to classical Newtonian (Navier-Stokes) model. Due to the diversity in the physical structure of non-Newtonian fluids, several models have been developed in the previous published paper [1-4]. Amongst them, one of the most popular recently which accounts the rheological effects of an isotropic, incompressible and structure-based fluid is called Casson model. Casson [5] pioneered this model for the flow of pigment-oil suspensions. This model in fact is a plastic fluid and require a critical shear stress (greater than the yield stress) to overcome before fluid can flow. If stress magnitude that applied on the fluid is less than the yield stress, it behaves like solid whereas if stress magnitude exceeds the yield stress, it begins to flow. However, Casson fluid model is diluted to a Newtonian fluid, when shear stress is much greater as compare to yield stress. This fluid model has its origin in modeling of flow of many biological fluids especially food products and blood. It is also a good approximation for many other materials such as foams, syrups, nail polish, yoghurt, cosmetics and chocolate. In the last few years, a substantial study has been done on the Casson fluid flows because of its important practical applications. Haq *et al*. [6] investigated the heat and mass transfer of magnetohydrodynamic Casson nanofluid flow past a shrinking sheet. Recently, unsteady MHD Casson fluid flow due to oscillations of the vertical plate and free convection are studied by Khalid *et al*. [7]. Some recent research in this area can also be found in [8-10].

On the other hand, the study of natural convection flow with thermal radiation has been raise greatly during the past two decades because its importance in many practical applications. Chandrakala [11] studied the free convection flow over a vertical oscillating plate with uniform heat flux in the presence of radiation effects. Deka and Das [12] analyzed the radiation effects on free convection flow over vertical plate subjected to ramped wall temperature. Radiation effects on unsteady free convection flow past a vertical plate with Newtonian heating were studied by Das *et al*. [13]. Chandrakala and Bhaskar [14] studied the same problem by considering the vertical plate that oscillates with constant velocity with mass diffusion and uniform heat flux.

Free convection flow with Newtonian heating is very important as it occurs in many engineering process, for example, in heat exchanger and conjugate heat transfer through fins. Merkin [15] was the first who used this condition in boundary layer heat transfer flow problem. Following him, Uddin *et al*. [16] investigated the MHD free convection of nanofluid past a vertical surface subjected to the Newtonian heating. Unsteady magnetohydrodynamic flow over a flat plat subjected to the Navier slip and Newtonian heating was studied by Makinde [17]. Recently, Alkasasbeh and Salleh [18] considered the thermal radiation and magnetic effects on the free convection flow about a solid sphere with Newtonian heating. All these researchers used numerical methods to obtain the required results. However, very little work has been done by analytically. For instance, Chaudhary and Jain [19] found the first analytic solutions of free convection unsteady flow with Newtonian heating over an impulsively started vertical plate. Later on, Hussanan *et al*. [20, 21] extended the same idea by incorporating the MHD and porosity effects, and slip condition, respectively. Recently, Hussanan *et al*. [22, 23] also studied the non-Newtonian Casson and micropolar fluids flow with Newtonian heating respectively, and find the exact solutions by Laplace transform method.

The purpose of the present work is to determine the effects of thermal radiation on the heat transfer unsteady flow of a non-Newtonian Casson fluid with Newtonian heating over vertical plate oscillates with constant velocity. In the next sections the dimensionless partial differential equations are solved analytically by Laplace transform technique. Finally, the obtain solutions for velocity and temperature field are written in terms of complementary error and exponential functions.

2.0 MATHEMATICAL FORMULATION

Let us consider the unsteady flow of a Casson fluid past a vertical plate fixed at $y=0$. Initially, at $t=0$, both the fluid and plate are at rest with the temperature T_∞. At $t=0^+$, the plate starts oscillation in its plane $(y=0)$ with velocity

$$\mathbf{V} = UH(t)\cos(\omega t)\mathbf{i};\; t>0. \tag{1}$$

According to Newtonian heating, the heat transfer from the surface to the fluid is directly proportional to the T. Physical configuration and coordinate system are given below in Figure 1.

In view of the above assumptions and taking into account the rheological equation reported by Casson [5], is

$$\tau = \tau_0 + \mu\alpha^{\bullet},$$

equivalently

$$\tau_{ij} = \begin{cases} 2\left(\mu_B + \dfrac{p_y}{\sqrt{2\pi}}\right)e_{ij}, & \pi > \pi_c \\ 2\left(\mu_B + \dfrac{p_y}{\sqrt{2\pi_c}}\right)e_{ij}, & \pi < \pi_c \end{cases}.$$

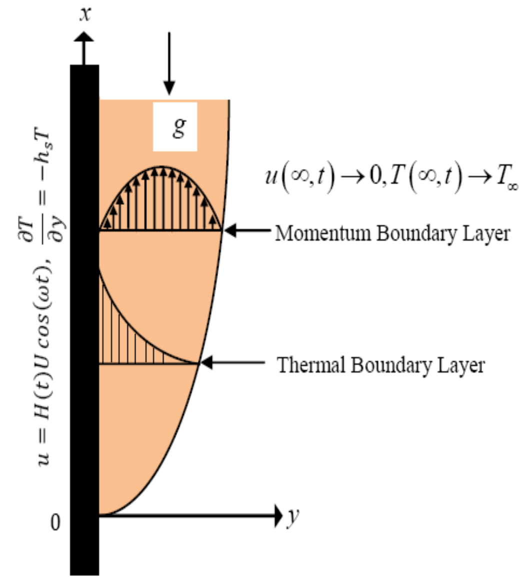


Figure 1 Physical configuration and coordinate system

Under the Boussinesq approximation, the flow is governed as

$$\frac{\partial u}{\partial t} = \nu\left(1+\frac{1}{\alpha}\right)\frac{\partial^2 u}{\partial y^2} + g\beta\left(T - T_\infty\right), \tag{2}$$

$$\rho C_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial y^2} - \frac{\partial q_r}{\partial y}, \tag{3}$$

with following conditions

$$u(y,0) = 0,\ T(y,0) = T_\infty,\ \text{for all } y \geq 0, \tag{4}$$

$$u(0,t) = H(t)U\cos(\omega t),\ \frac{\partial T}{\partial y}(0,t) = -h_s T(0,t),\ t > 0, \tag{5}$$

$$u(\infty,t) \to 0,\ T(\infty,t) \to T_\infty,\ t > 0. \tag{6}$$

Under Rosseland approximation [20, 24], the radiation heat flux can be expressed as

$$q_r = -\frac{4\sigma}{3k^*}\frac{\partial T^4}{\partial y}. \tag{7}$$

In view of equations (7), equation (3) reduces to

$$\rho C_p \frac{\partial T}{\partial t} = k\left(1+\frac{16\sigma T_\infty^3}{3kk^*}\right)\frac{\partial^2 T}{\partial y^2}. \tag{8}$$

We introduce the following dimensionless variables

$$y^* = \frac{U}{\nu}y,\ t^* = \frac{U^2}{\nu}t,\ u^* = \frac{u}{U},\ \theta = \frac{T - T_\infty}{T_\infty},\ \omega^* = \frac{\nu}{U^2}\omega.$$

Substituting the above dimensionless variables into equations (2) and (8), we get the following system of equations (* are dropped for simplicity)

$$\frac{\partial u}{\partial t} = \left(1+\frac{1}{\alpha}\right)\frac{\partial^2 u}{\partial y^2} + Gr\theta, \tag{9}$$

$$\Pr\frac{\partial \theta}{\partial t} = (1+R)\frac{\partial^2 \theta}{\partial y^2}. \tag{10}$$

The corresponding conditions in dimensionless form are

$$u(y,0) = 0,\ \theta(y,0) = 0,\ \text{for all } y \geq 0, \tag{11}$$

$$u(0,t) = H(t)\cos(\omega t),\ \frac{\partial \theta}{\partial y}(0,t) = -\gamma\left[1+\theta(0,t)\right],\ t > 0, \tag{12}$$

$$u(\infty,t) \to 0,\ \theta(\infty,t) \to 0,\ t > 0, \tag{13}$$

where

$$Gr = \frac{\nu g\beta T_\infty}{U^3},\ \Pr = \frac{\mu C_p}{k},\ R = \frac{16\sigma T_\infty^3}{3kk^*},\ \gamma = \frac{h_s \nu}{U}.$$

3.0 METHOD OF SOLUTION

Using the Laplace transform to the equations (9-13), we obtain

$$\begin{aligned}\bar{u}(y,q) &= \frac{H(t)}{2(q+i\omega)}e^{-y\sqrt{qa_1}} + \frac{H(t)}{2(q-i\omega)}e^{-y\sqrt{qa_1}} \\ &+ \frac{a_1a_2a_3}{q^2(\sqrt{q}-a_2)}e^{-y\sqrt{qa_1}} - \frac{a_1a_2a_3}{q^2(\sqrt{q}-a_2)}e^{-y\sqrt{q\Pr_{\text{eff}}}},\end{aligned} \tag{14}$$

$$\bar{\theta}(y,q) = \frac{a_2}{q(\sqrt{q}-a_2)}e^{-y\sqrt{q\Pr_{\text{eff}}}}. \tag{15}$$

The inverse Laplace transforms of equation (14) and (15), yields

$$\begin{aligned}\theta(y,t) &= e^{\left(a_2^2 t - y a_2\sqrt{\Pr_{\text{eff}}}\right)}\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{\Pr_{\text{eff}}}{t}} - a_2\sqrt{t}\right) \\ &- \operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{\Pr_{\text{eff}}}{t}}\right),\end{aligned} \tag{16}$$

$$u(y,t)=\frac{H(t)}{4}e^{-i\omega t}\left[\begin{array}{l} e^{-y\sqrt{-i\omega a_1}}\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{a_1}{t}}-\sqrt{-i\omega t}\right) \\ +e^{y\sqrt{-i\omega a_1}}\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{a_1}{t}}+\sqrt{-i\omega t}\right)\end{array}\right]$$

$$+\frac{H(t)}{4}e^{i\omega t}\left[\begin{array}{l} e^{-y\sqrt{i\omega a_1}}\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{a_1}{t}}-\sqrt{i\omega t}\right) \\ +e^{y\sqrt{i\omega a_1}}\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{a_1}{t}}+\sqrt{i\omega t}\right)\end{array}\right]$$

$$+\frac{a_1a_3}{a_2^2}\left[e^{\left(a_2^2t-ya_2\sqrt{a_1}\right)}\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{a_1}{t}}-a_2\sqrt{t}\right)-\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{a_1}{t}}\right)\right]$$

$$-\frac{a_1a_3}{a_2}\left[2\sqrt{\frac{t}{\pi}}e^{-\frac{y^2a_1}{4t}}-y\sqrt{a_1}\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{a_1}{t}}\right)\right]$$

$$-a_1a_3\left[\left(t+\frac{y^2a_1}{2}\right)\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{a_1}{t}}\right)-y\sqrt{a_1}\sqrt{\frac{t}{\pi}}e^{-\frac{y^2a_1}{4t}}\right]$$

$$-\frac{a_1a_3}{a_2^2}\left[e^{\left(a_2^2t-ya_2\sqrt{\mathrm{Pr_{eff}}}\right)}\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{\mathrm{Pr_{eff}}}{t}}-a_2\sqrt{t}\right)-\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{\mathrm{Pr_{eff}}}{t}}\right)\right]$$

$$+\frac{a_1a_3}{a_2}\left[2\sqrt{\frac{t}{\pi}}e^{-\frac{y^2\mathrm{Pr_{eff}}}{4t}}-y\sqrt{\mathrm{Pr_{eff}}}\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{\mathrm{Pr_{eff}}}{t}}\right)\right] \tag{17}$$

$$+a_1a_3\left[\left(t+\frac{y^2\mathrm{Pr_{eff}}}{2}\right)\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{\mathrm{Pr_{eff}}}{t}}\right)-y\sqrt{\mathrm{Pr_{eff}}}\sqrt{\frac{t}{\pi}}e^{-\frac{y^2\mathrm{Pr_{eff}}}{4t}}\right],$$

where

$$a_1=\frac{\alpha}{1+\alpha},\ a_2=\frac{\gamma}{\sqrt{\mathrm{Pr_{eff}}}},\ a_3=\frac{Gr}{\mathrm{Pr_{eff}}-a_1}\ \text{and}\ \mathrm{Pr_{eff}}=\frac{\mathrm{Pr}}{1+R}.$$

Note that the solution given by equation (17) is valid for $\mathrm{Pr_{eff}}\neq a_1$. The solution for $\mathrm{Pr_{eff}}=a_1$, can be easily obtained by substituting $\mathrm{Pr_{eff}}=a_1$ into equation (10) and follow the same procedure as discussed above. The skin friction for Casson fluid defined as

$$\tau'=-\left(1+\frac{1}{\alpha}\right)\frac{\partial u}{\partial y}|_{y=0},$$

$$\tau^*=\frac{\tau'}{\rho U^2}=-\left(1+\frac{1}{\alpha}\right)\frac{\partial u^*}{\partial y^*}|_{y^*=0},$$

$$=\frac{1}{2a_1}\left[\begin{array}{l}\sqrt{-i\omega a_1}e^{-i\omega t}\left[1-\operatorname{erfc}\left(\sqrt{-i\omega t}\right)\right] \\ +\sqrt{i\omega a_1}e^{i\omega t}\left[1-\operatorname{erfc}\left(\sqrt{i\omega t}\right)\right]\end{array}\right]$$

$$-\frac{a_3}{a_2}\left(\sqrt{\mathrm{Pr_{eff}}}-\sqrt{a_1}\right)\left[e^{a_2{}^2t}\left(2-\operatorname{erfc}\left(a_2\sqrt{t}\right)\right)-1\right] \tag{18}$$

$$+2a_3\sqrt{\frac{t}{\pi}}\left(\sqrt{\mathrm{Pr_{eff}}}-\sqrt{a_1}\right)+\frac{1}{\sqrt{\pi ta_1}}.$$

The Nusselt number for Casson fluid defined as

$$\mathrm{Nu}=-\frac{\nu}{U_0(T-T_\infty)}\frac{\partial T}{\partial y}|_{y=0}=\frac{1}{\theta(0,t)}+1,$$

$$=a_2\sqrt{\mathrm{Pr_{eff}}}\left(1+\frac{1}{e^{a_2{}^2t}\left[1+\operatorname{erf}\left(a_2\sqrt{t}\right)\right]-1}\right). \tag{19}$$

It should be noted that the obtained solutions for velocity and temperature satisfy all the boundary conditions. Moreover, if we consider $\alpha\to\infty$, the solution for velocity (17) reduce to the solution for viscous fluid.

3.1 Special Case

By considering $\omega=0$, we get the results of Stokes first problem as

$$u(y,t)=\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{a_1}{t}}\right)-\frac{a_1a_3}{a_2}\left[2\sqrt{\frac{t}{\pi}}e^{-\frac{y^2a_1}{4t}}-y\sqrt{a_1}\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{a_1}{t}}\right)\right]$$

$$+\frac{a_1a_3}{a_2^2}\left[e^{\left(a_2^2t-ya_2\sqrt{a_1}\right)}\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{a_1}{t}}-a_2\sqrt{t}\right)-\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{a_1}{t}}\right)\right]$$

$$-a_1a_3\left[\left(t+\frac{y^2a_1}{2}\right)\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{a_1}{t}}\right)-y\sqrt{a_1}\sqrt{\frac{t}{\pi}}e^{-\frac{y^2a_1}{4t}}\right]$$

$$-\frac{a_1a_3}{a_2^2}\left[e^{\left(a_2^2t-ya_2\sqrt{\mathrm{Pr_{eff}}}\right)}\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{\mathrm{Pr_{eff}}}{t}}-a_2\sqrt{t}\right)-\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{\mathrm{Pr_{eff}}}{t}}\right)\right]$$

$$+a_1a_3\left[\left(t+\frac{y^2\mathrm{Pr_{eff}}}{2}\right)\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{\mathrm{Pr_{eff}}}{t}}\right)-y\sqrt{\mathrm{Pr_{eff}}}\sqrt{\frac{t}{\pi}}e^{-\frac{y^2\mathrm{Pr_{eff}}}{4t}}\right]$$

$$+\frac{a_1a_3}{a_2}\left[2\sqrt{\frac{t}{\pi}}e^{-\frac{y^2\mathrm{Pr_{eff}}}{4t}}-y\sqrt{\mathrm{Pr_{eff}}}\operatorname{erfc}\left(\frac{y}{2}\sqrt{\frac{\mathrm{Pr_{eff}}}{t}}\right)\right]. \tag{20}$$

4.0 GRAPHICAL RESULTS AND DISCUSSION

To explore the physics of the problem, the obtained analytical results for temperature and velocity are computed numerically and then plotted graphically for different flow parameters. The interesting flow parameters include Casson parameter α, conjugate parameter γ, Grashof number Gr, radiation parameter R, Prandtl number Pr and phase angle ωt

The velocity field are plotted in Figure 2 for different values of α. As Casson parameter increases, the velocity of the fluid decreases. The velocity field are plotted in Figure 2 for various values of Pr. It is found that velocity decreases with increased in Pr. It is true because fluids with large Prandtl number have small thermal conductivity and high viscosity, so it makes the fluid thick and hence fluid motion decreased. The velocity are shown in Figure 4 for different values of the radiation parameter R in case of pure convection and also in presence of radiation. The velocity increases as the radiation parameter R increases.

Physically, the higher radiation occurs when temperature is higher and hence velocity raises. The velocity profiles for different values of the conjugate parameter γ are shown in Figure 5, which shows that the velocity increases with increasing values of γ. The velocity for different phase angle ωt are presented in Figure 6. The velocity shows an oscillating behavior. The velocity close to the wall is maximum and decreasing with increasing distance from the wall, eventually tends to zero as $y \to \infty$. It is also clearly seen from this figure, that the velocity satisfies the given boundary conditions (12) which provide a useful mathematical check on our calculi.

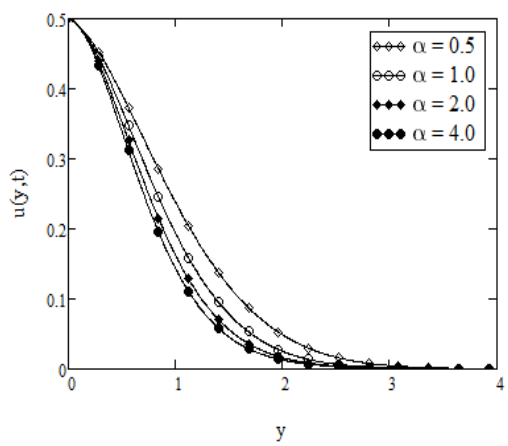


Figure 2 Velocity graph for α, when $\Pr = 0.7, Gr = 3,$ $R = 2, \gamma = 0.5, t = 0.2, \omega t = \frac{\pi}{3}.$

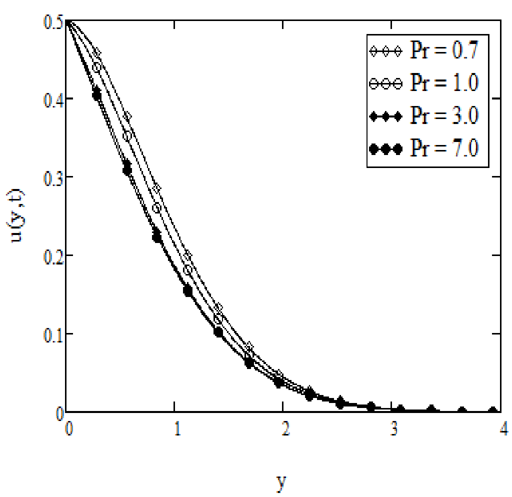


Figure 3 Velocity graph for $\Pr$, when $\alpha = 0.5, Gr = 5,$ $R = 1, \gamma = 0.5, t = 0.2, \omega t = \frac{\pi}{3}.$

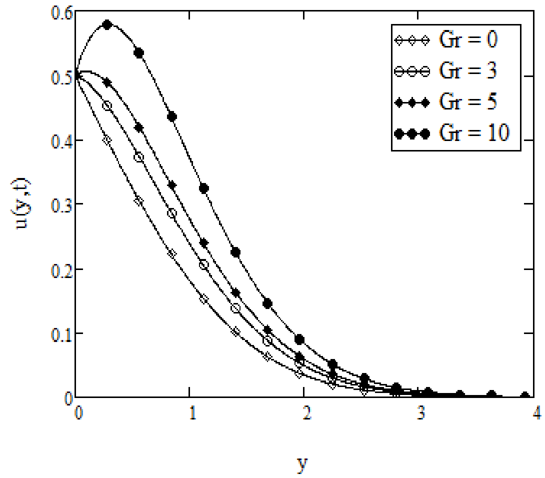


Figure 4 Velocity graph for Gr, when $\alpha = 0.5, \Pr = 0.7,$ $R = 2, \gamma = 0.5, t = 0.2, \omega t = \frac{\pi}{3}.$

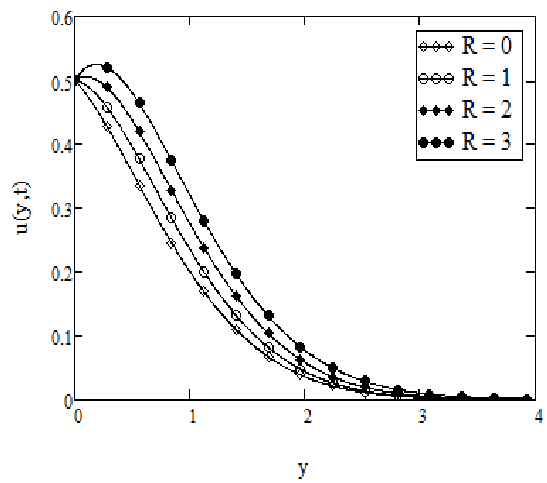


Figure 5 Velocity graph for R, when $\alpha = 0.5, \Pr = 0.7,$ $Gr = 5, \gamma = 0.5, t = 0.2, \omega t = \frac{\pi}{3}.$

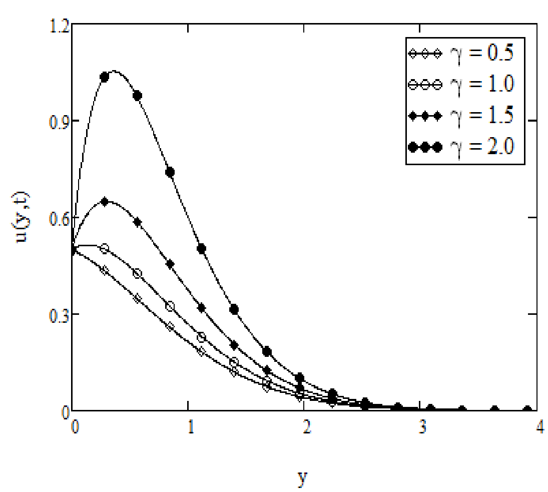


Figure 6 Velocity graph for γ, when $\alpha = 0.5, Gr = 3,$ $\Pr = 0.7, R = 1, t = 0.2, \omega t = \frac{\pi}{3}.$

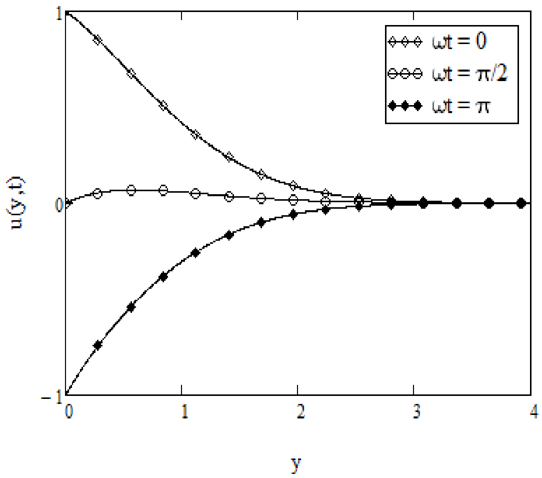


Figure 7 Velocity graph for ωt, when $\alpha = 0.5, \Pr = 0.7, Gr = 3, R = 2, \gamma = 0.5, t = 0.2.$

5.0 CONCLUSION

In this study, Casson fluid flow over an oscillating vertical plate subject to Newtonian heating is investigated analytically by using Laplace transform technique. The results obtained show that the velocity increases with increasing values of the Grashof number, radiation parameter and Newtonian heating parameter. However, it is decreased when Casson parameter and Prandtl number are increased. The velocity shows an oscillating behavior for different phase angle. Moreover the analytic solutions obtained in the present work are significant not only because they are solutions of some fundamental flows, but also serve as accuracy standards for approximate methods.

Nomenclature

$\mathbf{i}$	Unit vector
Gr	Grashof number
h_s	Heat transfer coefficient
k	Thermal conductivity
R	Radiation parameter
$\Pr$	Prandtl number
p_y	Yield stress
$\Pr_{\text{eff}}$	Effective Prandtl number
q_r	Radiative flux
C_p	Heat capacity at a constant pressure
T	Fluid temperature
T_∞	Ambient temperature
t	Time
U	Amplitude of plate oscillations
u	Velocity of the fluid
ωt	Phase angle
$H(t)$	Unit step function
erfc	Complementary error function

Greek symbols

α	Casson fluid parameter
τ	Shear stress
$\alpha^{\bullet}$	Shear rate
β	Volumetric coefficient of thermal expansion
γ	Conjugate parameter
ρ	Fluid density
μ	Dynamic viscosity
μ_B	Plastic dynamic viscosity
ν	Kinematic viscosity
π	Product of the component of deformation rate with itself
θ	Dimensionless temperature
ω	Frequency of oscillation

Subscripts

w	Near the plate
∞	Far away at infinity

Superscripts

$*$	Dimensional variables

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