Effect of radiation on Casson fluid flow of heat transfer over an unsteady stretching surface with suction/injection

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Abstract: **The unsteady two-dimensional flow of a non-Newtonian fluid over a stretching surface having a prescribed surface temperature in the presence of radiation and suction/injection is investigated. The Casson fluid model is used to characterise the non-Newtonian fluid behaviour. Similarity transformations are employed to transform the governing partial differential equations into ordinary differential equations. The transformed equations are then solved numerically by Bvp4cMatlab solver. The flow features and heat transfer characteristics for different values of the governing parameters viz. unsteadiness parameter, Casson parameter, radiation parameter, Prandtl number and suction/injection parameter are analyzed and discussed in detail. Fluid velocity initially decreases with increasing unsteadiness parameter and temperature as well as concentration decreases significantly due to unsteadiness. The effect of increasing values of the Casson parameter is to suppress the velocity field. But the temperature and concentration is enhanced with increasing Casson parameter. Both the momentum and thermal boundary layer thickness decreases in an increasing suction/injection parameter. Magnitude of skin-friction reduces, but the rate of heat transfer increases with raising the suction/injection parameter.**

IndexTerms **- Casson Fluid, Heat Transfer, Radiation, Suction/injection, Stretching Sheet .**

I. INTRODUCTION

The study of flow and heat transfer over a stretching/shrinking sheet receives considerable attention from many researchers due to its variety of application in industries such as extrusion of plastic sheets, wire drawing, hot rolling and glass fiber production. First of all Sakiadis etc [1, 2] performed the pioneering work of boundary layer flow over a continuous moving surface and similarity solutions were obtained for the governing equations. Crane [3] studied the flow over a linearly stretching sheet in an ambient fluid and gave a closed-form solution for stead two-dimensional flow of an incompressible viscous fluid caused by the stretching of an elastic sheet, which moves in its own plane with a velocity which varies linearly with distance from a fixed point.

In recent times, due to increasing industrial applications the flows involving non-Newtonian fluids grab significant attention of modern day researchers. Many materials in real field, like, melts, muds, condensed milk, glues, printing ink, emulsions, soaps, sugar solution, paints, shampoos, tomato paste etc. show properties which differs from those of Newtonian fluids. But, the main difficulty is to construct a single constitutive equation which follows all properties of such non-Newtonian fluids. Fox et al. [4] investigated the laminar boundary layer on a moving continuous flat sheet immersed in a non-Newtonian fluid. Djukic [5] discussed the Hiemmz magnetic Bow of power-law fluids. Rajagopal [6] investigated the viscometric flows of third grade fluids. Rajagopal and Gupta [7] studied a class of exact solutions to the equations of motion of a second grade fluid. Rajagopal et al. [8] investigated the flow of a viscoclastic fluid over a stretching sheet. Andersson and Dandapat [9] studied the flow of a power-law fluid over a stretching sheet. The governing equations of non-Newtonian fluids are highly non-linear and much more complicated than the governing equations of Newtonian fluids. Bhattacharyya et al.[10] investigated the heat transfer in the boundary layer flow of Maxwell fluid over a permeable shrinking sheet. Mukhopadhyaya etal [11] presented the effects of transpiration on the unsteady two-dimensional boundary layer flow of non-Newtonian fluid passing through a stretching sheet in the presence of a first order constructive/destructive chemical reaction and also conclude that the fluid velocity decreases as the magnetic parameter increases; however, the concentration increases in this case. Mukhopadhyay et al. [12] investigated the unsteady two-dimensional flow of a non-Newtonian fluid over a stretching surface having a prescribed surface temperature and conclude that the fluid velocity initially decreases with increasing unsteadiness parameter and temperature decreases significantly due to unsteadiness.

In many cases, mass transfer through a wall slot (i.e, mass transfer occurs in a small porous section of the body surface while there is no mass transfer in the remaining part of the body surface) into the boundary layer is of interest for the various potential applications including thermal protection, energizing of the inner portion of boundary layer in adverse pressure gradient, and skin friction reduction on control surfaces. Moreover, mass transfer through a slot strongly influences the development of a boundary layer along a surface and in particular can prevent or at least delay separation of the viscous region. Jat and Navin Kumar [13] studied the unsteady two-dimensional magnetohydrodynamics (MHD) stagnation point flow and heat transfer over a stretching sheet with suction/injection and also conclude that the velocity increases with the increasing values of unsteady parameter. Poornima et al. [14] studied the effect of slot suction (injection) into steady; MHD non-similar boundary layer flow over a sphere has been studied in the presence of variable. Uwanta and Hamza [15] studied the effect of suction/injection on transient hydromagnetic convective flow of viscous reactive fluid between vertical porous plates in the presence of transverse magnetic field and thermal diffusion and also conclude that suction/injection, thermal diffusion, reaction consumption, and thermal and solutal buoyancy play an important role in controlling the transport phenomena. The discontinuities can be avoided by choosing a non-uniform mass transfer distribution along a stream wise slot as has been discussed in Minkowycz et al. [16].

The studies of thermal radiation and heat transfer are important in electrical power generation, astrophysical flows, solar power technology and other industries areas. A lot of extensive literature that deals with flows in the presence of radiation effects is now available. Hady et al. [17] investigated the flow and heat transfer characteristics of a viscous nanofluid over a nonlinearly stretching sheet in the presence of thermal radiation and also conclude that an increase in the thermal radiation parameter N_R and the nonlinear stretching sheet parameter n yields a decrease in the nanofluid's temperature, which leads to an increase in the heat transfer rates. Manjunatha et al. [18] considered the boundary layer flow and heat transfer analysis of an unsteady viscous dusty fluid over a porous stretching surface and momentum boundary layer equation considers the effect of transverse magnetic field whereas thermal boundary layer equation considers the effect of thermal radiation. Rani Titus and Annamma Abraham [19] investigated the heat transfer in Ferro fluid flow over a stretching sheet with radiation. Pop et al. [20] investigated the radiation effects (Rosseland model) on the flow of an incompressible viscous fluid over a flat sheet near the stagnation point and showed that a boundary layer is formed and its thickness increases with the radiation, velocity and temperature parameters and decreases when the Prandtl number is increased. Gopi Chand and Jat [21] investigated the viscous dissipation and radiation effects on MHD flow and heat transfer over an unsteady stretching surface in a porous medium. Mustafa et al. [22] studied the nonlinear radiation heat transfer effects in the natural convective boundary layer flow of nanofluid past a vertical plate.

However, the interactions of the unsteady two-dimensional flow of a non-Newtonian fluid over a stretching surface having a prescribed surface temperature in the presence of radiation and suction/injection is considered. The governing boundary layer equations have been transformed to a two-point boundary value problem in similarity variables and the resultant problem is solved numerically using bvp4c MATLAB solver. The effects of various governing parameters on the fluid velocity, temperature, skin-friction and the rate of heat transfer are shown in figures and analyzed in detail.

2. MATHEMATICAL FORMULATION

Consider laminar boundary layer two-dimensional flow and heat transfer of an incompressible, electrically conducting and radiative non-Newtonian Casson fluid over an unsteady stretching sheet. The unsteady fluid and heat flows start at t = 0. The sheet emerges out of a slit at origin (x = 0, y = 0) and moves with non-uniform velocity $U_w(x,t) = cx/(1-\alpha t)$ [23] where $c > 0, \alpha \geq 0$ are constants with dimensions (time)$^{-1}$, c is the initial stretching rate. The rheological equation of state for an isotropic and incompressible flow of a Casson fluid is [24, 25]

$$\tau_{ij} = \begin{cases} \left(\mu_B + \frac{p_y}{\sqrt{2\pi}}\right) 2e_{ij}, & \pi > \pi_c \\ \left(\mu_B + \frac{p_y}{\sqrt{2\pi_c}}\right) 2e_{ij}, & \pi < \pi_c \end{cases} \tag{2.1}$$

where μ_B is plastic dynamic viscosity of the non-Newtonian fluid, p_y is the yield stress of fluid, π is the product of the component of deformation rate with itself, namely, $\pi = e_{ij}e_{ij}$, e_{ij} is the $(i, j)^{th}$ component of the deformation rate, and π_c is critical value of π based on non-Newtonian model.

So, if a shear stress less than the yield stress is applied to the fluid, it behaves like a solid, whereas if a shear stress greater than yield stress is applied, it starts to move.

The governing equations of motion, the energy equation may be written in usual notation as

Continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2.2}$$

Momentum equation

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\left(1 + \frac{1}{\beta}\right)\frac{\partial^2 u}{\partial y^2} \tag{2.3}$$

Energy equation

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \kappa\frac{\partial^2 T}{\partial y^2} - \frac{\partial q_r}{\partial y} \tag{2.4}$$

The boundary conditions are

$$u = U_w, v = V_w, T = T_w \quad \text{at} \quad y = 0$$
$$u \to 0, T \to T_\infty \quad \text{as} \quad y \to \infty \tag{2.5}$$

where u and v are the velocity components in x and y directions, respectively, ν is the kinematic fluid viscosity $\beta = \mu_B\sqrt{2\pi_c}/p_y$ is the non-Newtonian or Casson parameter, q_r is the radiative heat flux, κ is the thermal conductivity,

$T_w(x,t) = T_\infty + cx^2 T_0 (1-\alpha t)^{-\frac{3}{2}} /(2\nu)$; where T_0 is a (positive or negative; heating or cooling) reference temperature (slit temperature at x=0) and T_∞ is the constant free stream temperature, the expressions for $U_w(x,t), T_w(x,t)$ are valid for time $t < \alpha^{-1}$

By using the Rosseland approximation the radiative heat flux q_r is given by

$$q_r = -\frac{4\sigma_1}{3k*}\frac{\partial T^4}{\partial y} \qquad (2.6)$$

Where σ_1 is the Stefan -Boltzmann constant and $k*$ is the mean absorption coefficient. It should be noted that by using the Rosseland approximation, the present analysis is limited to optically thick fluids. If temperature differences within the flow are significantly small, then equation (2.4) can be linearised by expanding T^4 into the Taylor series about T_∞, which after neglect higher order terms takes the form:

$$T^4 \cong 4T_\infty^3 T - 3T_\infty^4 \qquad (2.7)$$

In view of equations (2.8) and (2.9), eqn. (2.6) reduces to

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \left(\kappa + \frac{16\sigma_1 T_\infty^3}{3k*}\right)\frac{\partial^2 T}{\partial y^2} \qquad (2.8)$$

We introduce also a stream functions ψ is defined by

$$u = \frac{\partial \psi}{\partial y} \quad \text{and} \quad v = -\frac{\partial \psi}{\partial x} \qquad (2.9)$$

Introducing the similarity variables as

$$\eta = \sqrt{\frac{c}{\nu(1-\alpha t)}}\,y, \psi = \sqrt{\nu c/(1-\alpha t)}\,xf(\eta), \theta = \frac{T-T_\infty}{T_w - T_\infty}$$

$$T = \left[T_\infty + T_0 cx^2 (1-\alpha t)^{\frac{-3}{2}} /(2\nu)\right]\theta(\eta)$$

(2.10)

The mass transfer velocity V_w can take the form.

$$V_w(t) = -\left(\frac{c\nu}{1-\alpha t}\right)^{1/2} f_w \qquad (2.11)$$

where $f(\eta)$ is the dimensionless stream function, $\theta(\eta)$ is the dimensionless temperature, η is the similarity variable

Substituting equations (2.9) to (2.11) in (2.3) & (2.8), we have

$$\left(1+\frac{1}{\beta}\right)f''' + ff'' - f'^2 - A\left(\frac{\eta}{2}f'' + f'\right) = 0 \qquad (2.12)$$

$$\frac{1}{\Pr}(1+N)\theta'' + f\theta' - 2f'\theta - \frac{A}{2}(\eta\theta' + 3\theta) = 0 \qquad (2.13)$$

The transformed boundary conditions can be written as

$$f = fw, f' = 1, \theta = 1 \quad \text{at} \quad \eta = 0$$
$$f' \to 0, \theta \to 0 \quad \text{as} \quad \eta \to \infty \qquad (2.14)$$

where primes denote differentiation with respect to η, $A = \alpha / c$ is the velocity ratio parameter, $\Pr = \nu/\kappa$ is the Prandtl number, $N = \frac{16\sigma_1 T_\infty^3}{3k*\kappa}$ is the radiation parameter.

The physical quantities of interest are the wall skin friction coefficient C_{fx}, and the local Nusselt number Nu_x which are defined as

$$C_{fx} = \frac{\tau_w}{\rho U_w^2(x)}, Nu_x = \frac{xq_w}{\alpha(T_w - T_\infty)} \qquad (2.15)$$

where τ_w is the shear stress or skin friction along the stretching sheet and q_w is the heat flux from the sheet and those are defined as

$$\tau_w = \left(\mu_B + \frac{p_y}{\sqrt{2\pi}}\right)\left(\frac{\partial u}{\partial y}\right)_{y=0}$$
$$q_w = \alpha\left(\frac{\partial T}{\partial y}\right)_{y=0} \tag{2.16}$$

Thus, we get the wall skin friction coefficient C_{fx}, and the local Nusselt number Nu_x as follows:

$$C_{fx}\sqrt{\mathrm{Re}_x} = \left(1+\frac{1}{\beta}\right) f''(0)$$
$$\frac{Nu_x}{\sqrt{\mathrm{Re}_x}} = -\theta'(0) \tag{2.17}$$

where $\mathrm{Re}_x = \frac{U_w x}{\upsilon}$ is the local Reynolds number.

3 SOLUTION OF THE PROBLEM

The set of equations (2.12) to (2.14) were reduced to a system of first-order differential equations and solved using a MATLAB boundary value problem solver called **bvp4c**. This program solves boundary value problems for ordinary differential equations of the form $y' = f(x, y, p), a \le x \le b$, by implementing a collocation method subject to general nonlinear, two-point boundary conditions $g(y(a), y(b), p)$. Here $\boldsymbol{p}$ is a vector of unknown parameters. Boundary value problems (BVPs) arise in most diverse forms. Just about any BVP can be formulated for solution with **bvp4c**. The first step is to write the *ODEs* as a system of first order ordinary differential equations. The details of the solution method are presented in Shampine and Kierzenka[26].

4 RESULTS AND DISCUSSION

The abovementioned numerical scheme is carried out for various values of physical parameters, namely, the unsteadiness parameter (*A*), the Casson parameter (β), the Prandtl number (Pr), radiation parameter (N) and the suction/injection parameter (fw) to obtain the effects of those parameters on dimensionless velocity and temperature distributions. The obtained computational results are presented graphically in Figures 1a-5.

In order to validate the method used in this study and to judge the accuracy of the present analysis, comparison with available results of Sharidan et al. [27], Chamkha et al. [28] and Mukhopadyay et al. [12] corresponding to the skin-friction coefficient $f''(0)$ for unsteady flow of viscous incompressible fluid is made (Table 1) and found in excellent agreement.

Fig. 1a exhibits the velocity profiles for several values of unsteadiness parameter A. It is seen that the velocity along the sheet decreases initially with the increase in unsteadiness parameter A, and this implies an accompanying reduction of the thickness of the momentum boundary layer near the wall but away from the wall, fluid velocity increases with increasing unsteadiness i.e. away from the wall, the velocity field and the corresponding boundary layer are found to increase with an increase in A. Same type of behaviour has been reported by Mukhopadhyay et al.[12]. A= 0 indicates the steady case. Fig. 1b represents the effects of unsteadiness parameter on the temperature distribution. From this figure, it is noticed that the temperature at a particular point is found to decrease significantly with increasing unsteadiness parameter. Same observation can be found from Refs. [27, 29, 12]. Rate of heat transfer (from the sheet to the fluid) decreases with increasing A (see also Fig. 7). As the unsteadiness parameter A increases, less heat is transferred from the sheet to the fluid; hence, the temperature decreases (Fig. 1b).

Effects of Casson parameter β on velocity and temperature profiles for both steady and unsteady motion are clearly exhibited in Fig. 2a and b, respectively. For both steady and unsteady motion, same type of behaviour of velocity with increasing β is noted. The effect of increasing values of β is to reduce the velocity, and hence, the boundary layer thickness decreases (Fig. 2a). Same type of behaviour has been reported by Mukhopadhyay et al.[20]. The effect of increasing β leads to enhance the temperature field for both steady and unsteady motion (Fig. 2b). This effect is more pronounced for steady motion. The thickening of the thermal boundary layer occurs due to increase in the elasticity stress parameter.

Effects of suction/injection parameter fw on velocity and temperature profiles for both steady and unsteady motion are clearly exhibited in Fig. 3a and b respectively. For both steady and unsteady motion, same type of behaviour of velocity with increasing fw is noted. The effect of increasing values of fw is to reduce both the velocity and temperature, and hence, the momentum and thermal boundary layer thickness decreases (Fig. 3a & 3b).

The temperature profiles for the variation of radiation parameter N can be found from Fig. 4. It is noted that the temperature increases with increasing N (Fig. 4). Moreover, the thermal boundary layer thickness increases by increasing radiation ramameter.

The temperature profiles for the variation of Prandtl number can be found from Fig. 5. It is noted that the temperature decreases with increasing Pr (Fig. 5). Moreover, the thermal boundary layer thickness decreases by increasing Prandtl numbers.

An increase in Prandtl number reduces the thermal boundary layer thickness. Prandtl number signifies the ratio of momentum diffusivity to thermal diffusivity..

Furthermore, the effects of unsteadiness parameter A, Casson parameter β and suction/injection parameter fw on velocity gradient at the wall and heat transfer coefficient are presented in Fig. 6 and 7. Magnitude of $f''(0)$ related to skin-friction coefficient decreases with an increasing unsteadiness parameter A and suction/injection parameter fw and also with Casson parameter β, but the magnitude of heat transfer rate at the surface decreases for β, increases with A and M.

5 CONCLUSIONS

The unsteady two-dimensional flow of a non-Newtonian fluid over a stretching surface having a prescribed surface temperature in the presence of radiation and suction/injection is investigated. Using similarity transformations, the governing equations are transformed to self-similar ordinary differential equations which are then solved using Bvp4c MATLAB solver. From the study, the following remarks can be summarized.

1. Fluid velocity initially decreases with increasing unsteadiness parameter and temperature decreases significantly due to unsteadiness.
2. Both the momentum and thermal boundary layer thickness decreases in an increasing suction/injection parameter fw.
3. Magnitude of skin-friction reduces, but the rate of heat transfer increases with raising the suction/injection parameter.
4. The skin-friction decreases with increasing unsteadiness parameter and the rate of heat and mass transfer increases significantly due to unsteadiness.
5. The effect of increasing values of the Casson parameter is to suppress the velocity field. But the temperature and concentration is enhanced with increasing Casson parameter.
6. The effect of increasing values of the radiation parameter, thermal boundary layer increases.

Table 1 Comparison for $f''(0)$ for *M=0* for Newtonian fluid

A	$f''(0)$			
	Present Study	Sharidan et al. [27]	Chamkha et al. [32]	Mukhopadhyay [48]
0.8	-1.261043	-1.261042	-1.261512	-1.261479
1.2	-1.377724	-1.377722	-1.378052	-1.377850

GRAPHS

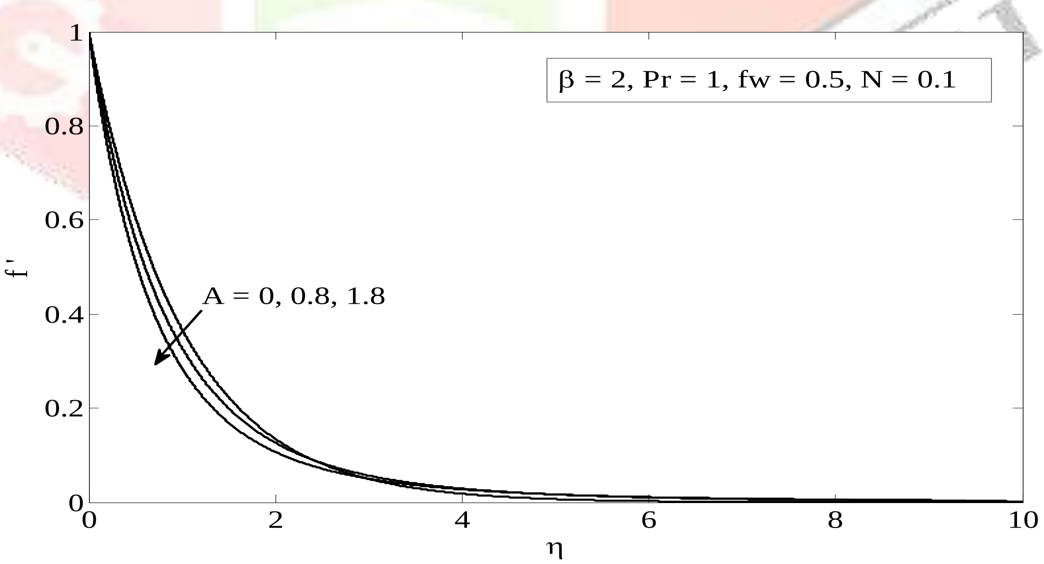

Fig. 1(a) Velocity for different *A*

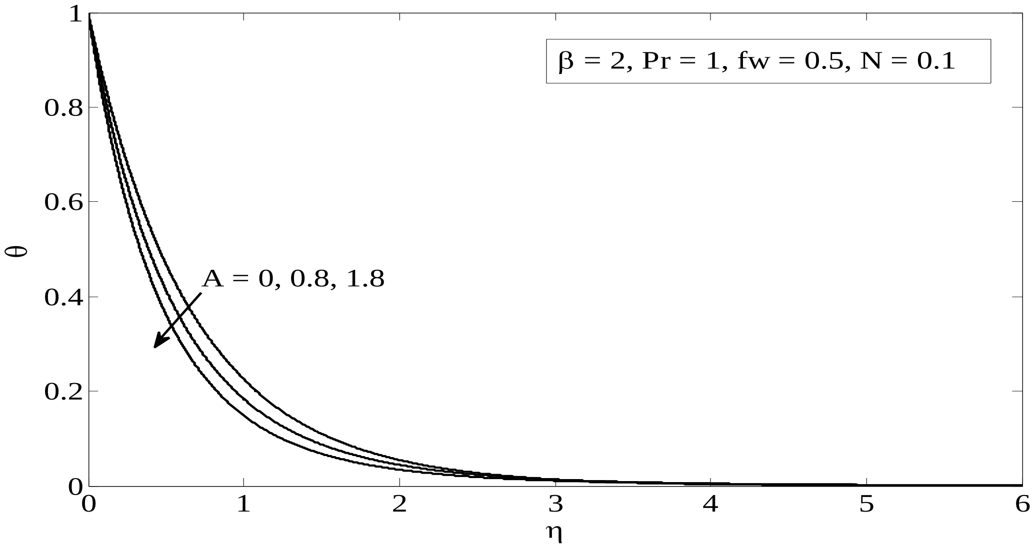

Fig. 1(b) Temperature for different *A*

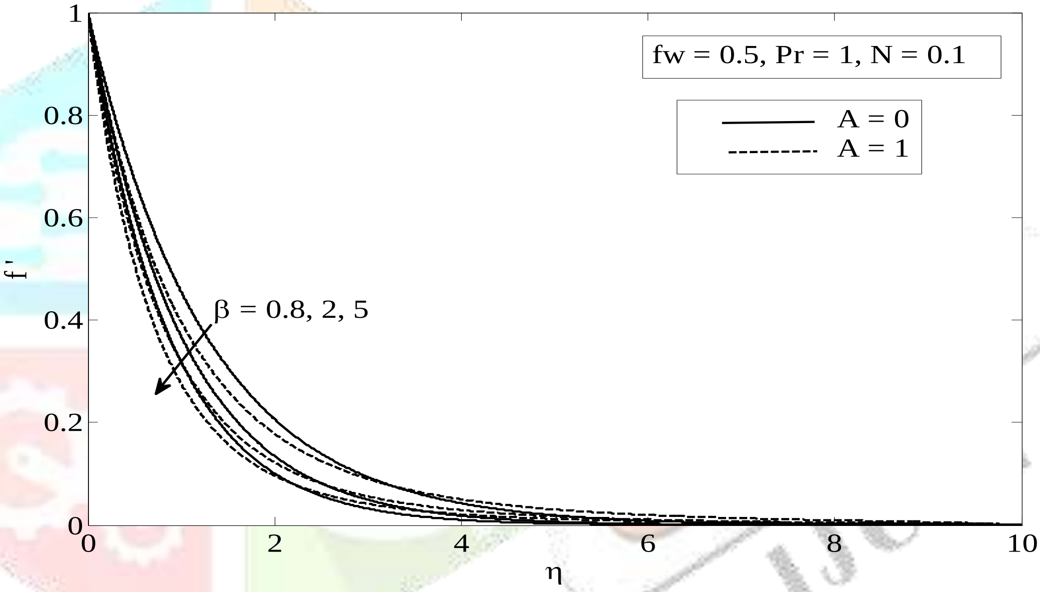

Fig.2(a) Velocity for different *A*

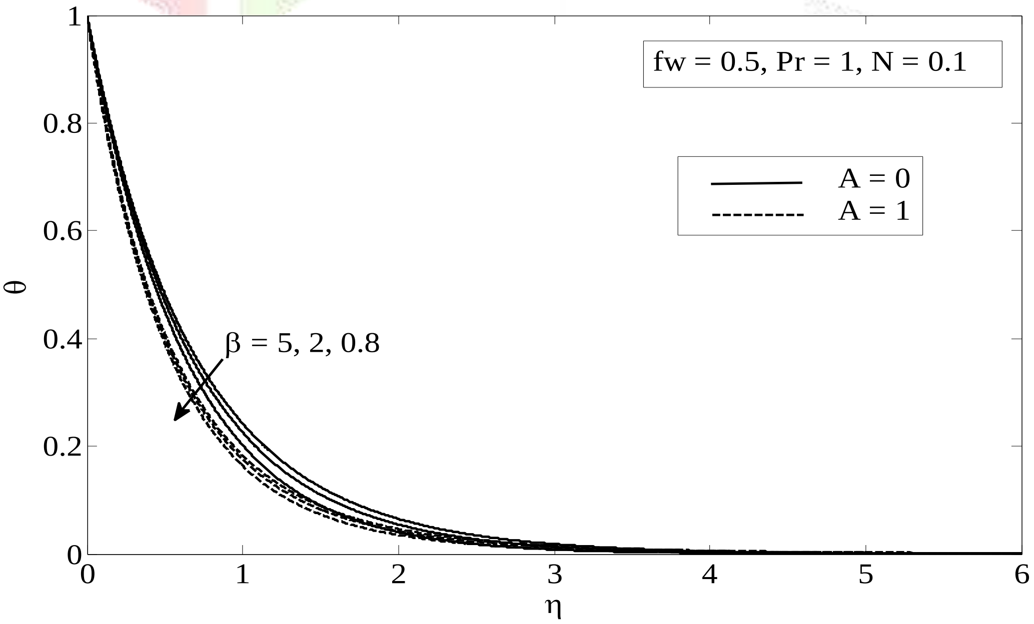

Fig.2(b) Temperature for different *β*

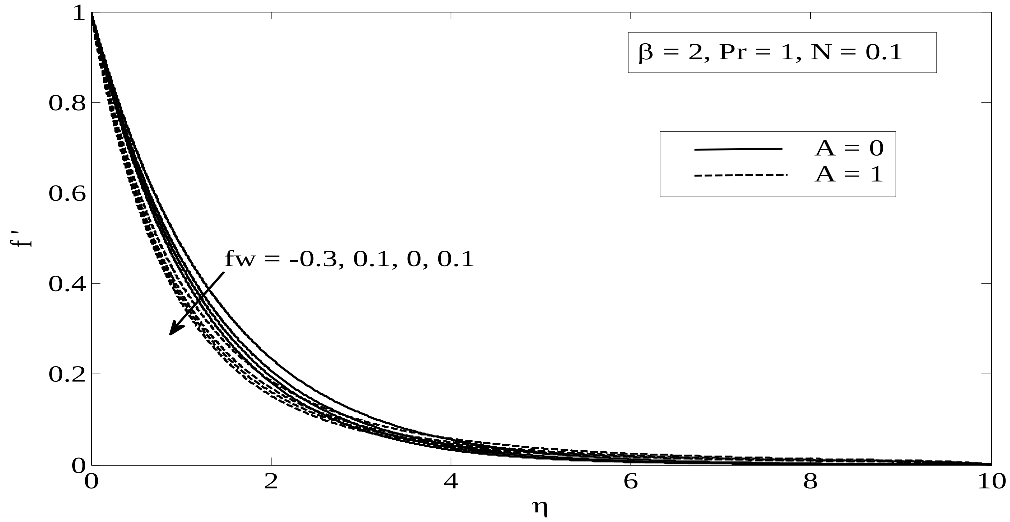

Fig.3(a) Velocity for different *fw*

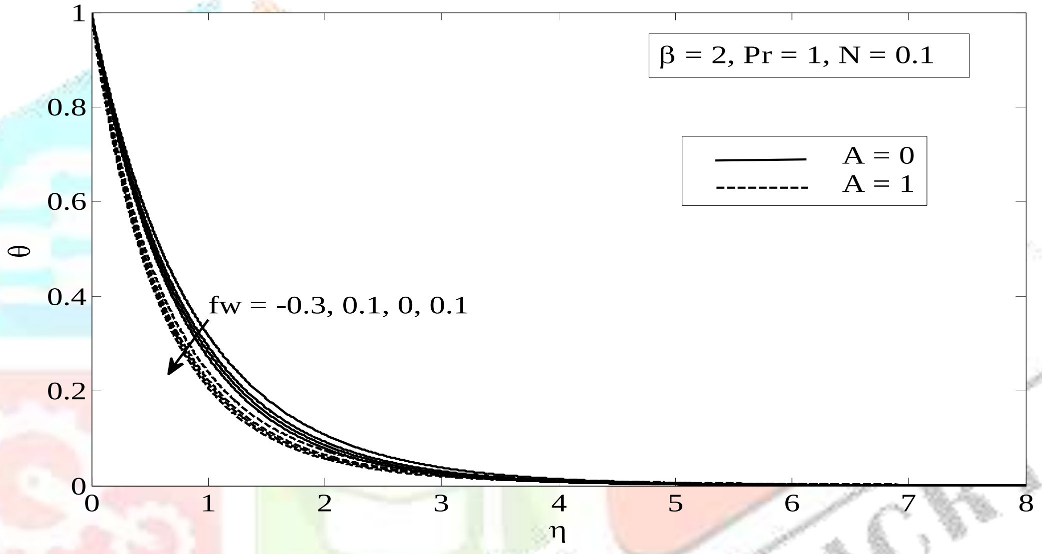

Fig.3(b) Temperature for different *fw*

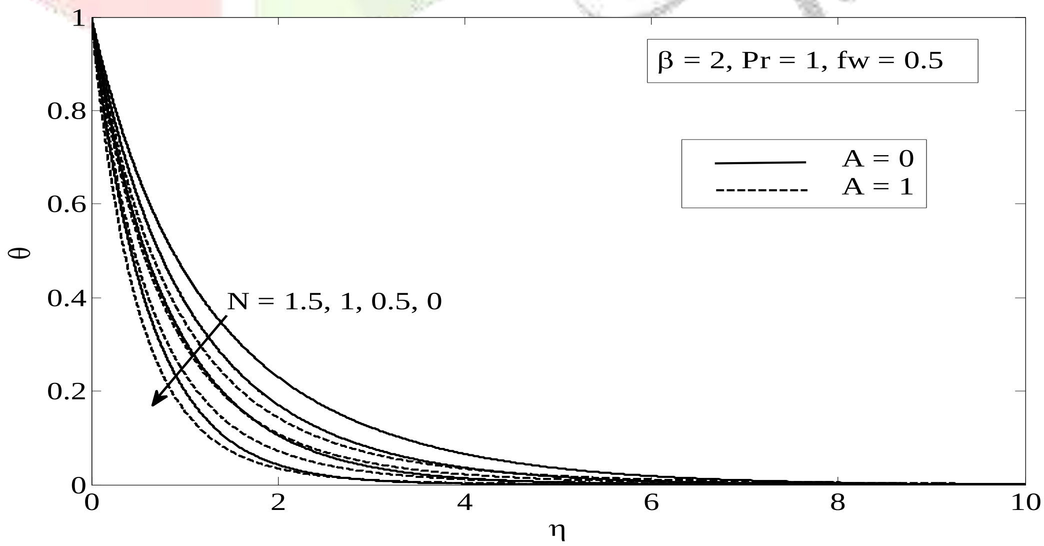

Fig.4 Temperature for different *N*

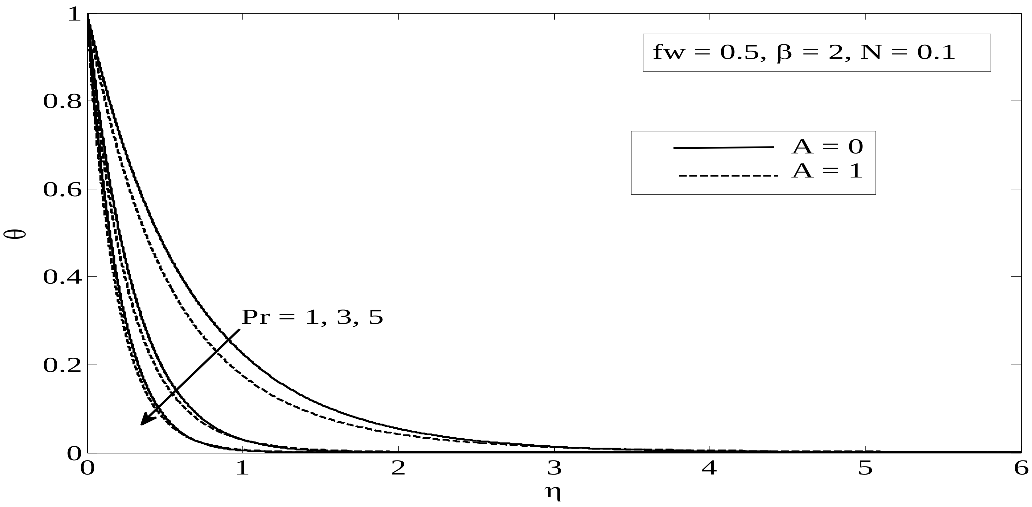

Fig.5 Temperature for different *Pr*

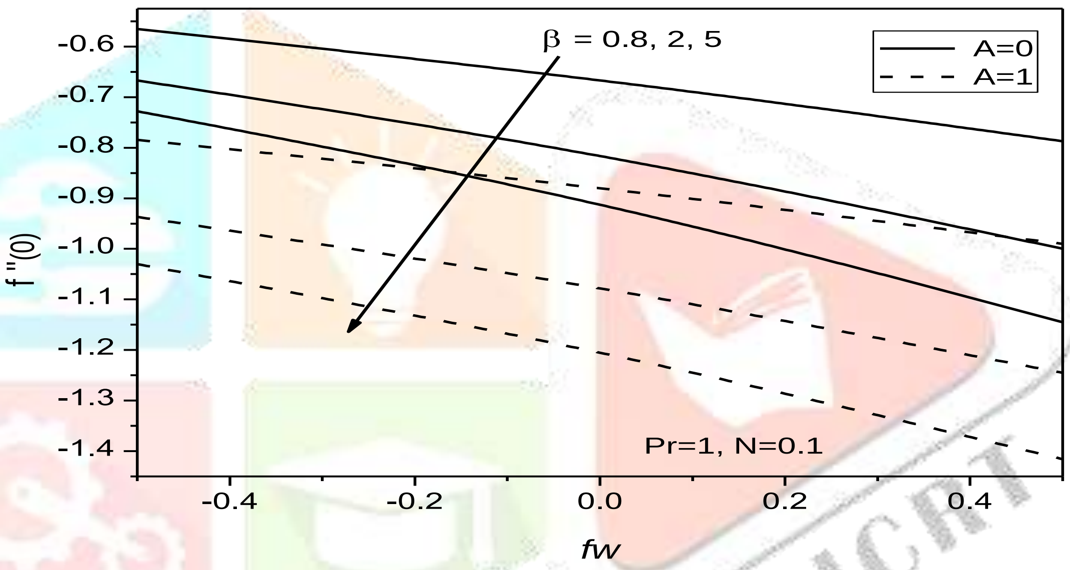

Fig.6 Skin-friction for different *β*, *fw* and A

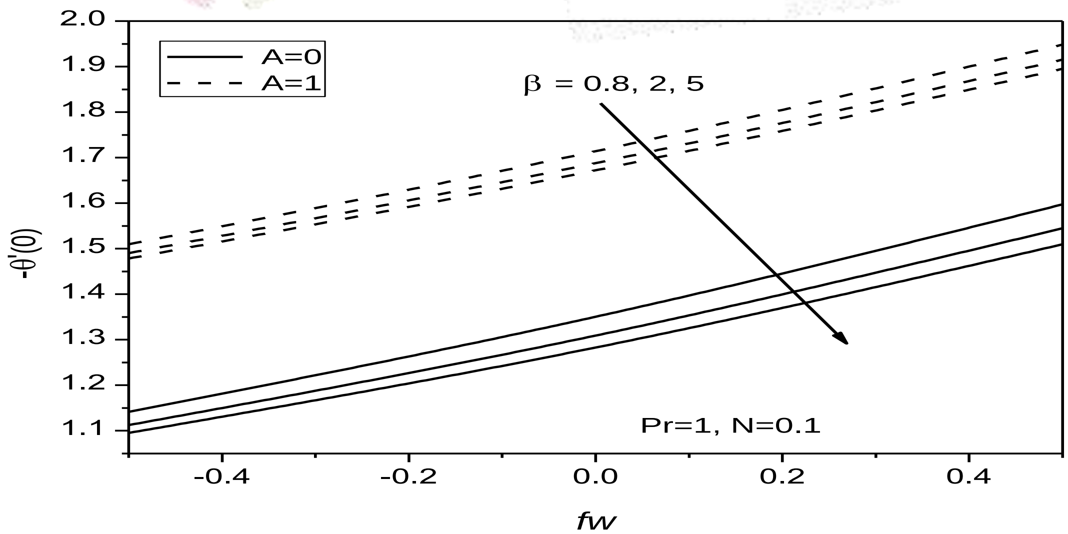

Fig.7 Local Nusselt number for different *β*, *fw* and *A*

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