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Unsteady Flow Past an Exponentially Accelerated Vertical Plate With Ramped Plate Heat Flux

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***Abstract*: An exact solution of an unsteady flow past an exponentially accelerated vertical plate with ramped plate heat flux has been studied. The governing coupled differential equations describing the flow are solved analytically by using Laplace transform technique. The influences of the various type of parameters on the velocity field, temperature distribution, shear stress and rate of heat transfer at the moving plate have been analyzed either graphically or in tabular form. It is found that both the velocity as well as the temperature of the fluid decrease with an increase in Prandtl number whereas they increase as time progresses. Prandtl number reduce the shear stress but enhance the rate of heat transfer at the moving plate.**

Keywords: Exponentially Accelerated Plate, Ramped Wall Heat Flux, Prandtl Number and Grashof Number.

1. INTRODUCTION

Heat transfer is the area that deals with the mechanism responsible for transferring energy from one place to another when a temperature difference exists. Natural convection is one of the most economical and practical methods of cooling and heating. Natural convection is caused by temperature or concentration induced density gradient within the fluid. Natural convection flow occurs as a result of influence of gravity forces on fluids in which density gradients have been thermally established. With the growing sophistication in technology and with the increasing concern with energy and the environment, the study of heat transfer has, over the past several years, been related to a very wide variety of problems, each with its own demands of precision and elaboration in the understanding of the particular processes of interest. Areas of study range from atmospheric, geophysical and environmental problems to those in heat rejection, space research and manufacturing systems. In a wide class of natural convection processes, heat transfer occurs from a heated vertical surface placed in a quiescent medium at a uniform temperature. If the plate surface temperature is greater than the ambient temperature, the fluid adjacent to the vertical surface gets heated, becomes light and rises. Heavier fluid from the neighboring areas rushes into take the place of the rising fluid. Similarly the flow for a cooled surface is downwards. Gupta et al. [1] have studied free convective effects on the flow past an accelerated vertical plate in an incompressible vertical plate. Isachenko [2] has reviewed the problems of heat transfer. Singh and Naveen [3] have investigated free convection flow past an exponentially accelerated vertical plate. Hossain and Shayo [4] have studied analytically the skin friction in the unsteady free convection flow past an accelerated plate. The mass transfer effects on the flow past an exponentially accelerated vertical plate with constant heat flux have been considered by Jha et al.[5]. Chandran et al.[6] have studied the unsteady hydromagnetic free convective flow with heat flux and accelerated boundary motion. Barletta [7] has presented an analysis on the heat transfer by fully developed flow and viscous heating in a vertical channel with prescribed wall heat fluxes. The transient free convection flow past an infinite vertical plate with periodic temperature variation has been discussed by Das et al. [8]. Narahari et al.[9] have considered the transient free convection flow between infinitely long vertical parallel plates with constant heat flux at one boundary. Chandran et al.[10] have studied the natural convection near a vertical plate with ramped wall temperature. The developing flow near a semi-infinite vertical wall with ramped temperature has been investigated by Singh et al. [11]. Muthucumaraswamy et al.[12] have studied the heat transfer effects on the flow past an exponentially accelerated vertical plate with variable temperature. Singh and Singh [13] have presented the transient HHD free convective near a semi infinite vertical wall having ramped temperature. The effects of heat transfer and viscous dissipation on MHD free convection flow past an exponentially accelerated vertical plate with variable temperature have been investigated by Kishore et al.[14]. Chandrakala [15] has studied thermal radiation effects on moving infinite vertical plate with uniform Heat flux. Chandrakala and Bhaskar [16] have considered the effects of heat transfer on flow past an exponentially accelerated vertical plate with uniform Heat flux. Asogwa et al.[17] have investigated the flow past an exponentially accelerated infinite vertical plate and temperature with variable mass diffusion. Chandrakala [18] has studied effects of radiation on flow past an impulsively started infinite vertical plate with uniform Heat and mass flux. Das et al.[19] have investigated an unsteady free convection flow past a vertical plate with heat and mass fluxes in the presence of thermal radiation. Unsteady slip flow past an infinite vertical plate with ramped plate temperature and concentration in the presence of thermal radiation and buoyancy has been studied by Maiti and Mandal [20]. Reddy et al.[21] have presented the radiation and heat absorption effects on an unsteady MHD boundary layer flow along an accelerated infinite vertical plate with ramped plate temperature. Recently, an unsteady flow past an accelerated vertical plate with variable temperature has been investigated by Kalita et al.[22].

The motivation of our present investigation is to study the unsteady free convection flow of a viscous incompressible fluid past an exponentially accelerated vertical plate with ramped wall heat flux. Initially, at time $t \le 0$, the plate and fluid are at the same constant temperature T_∞ in a stationary condition. At time $t > 0$, the plate starts to move with exponential accelerated velocity $u_0 e^{\lambda^* t}$, where u_0 and λ^* are constants. The heat flux at the plate changes rampedly with time. The flow related

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dimensionless governing equations have been solved analytically with the help of Laplace transform technique. The effects of pertinent flow parameters on the fluid velocity, temperature, shear stress and heat transfer rate at the moving plate have been discussed with the help of graphs and table.

2 FORMULATION OF THE PROBLEM AND ITS SOLUTIONS

Consider an unsteady viscous incompressible flow of a fluid past an exponentially accelerated infinite vertical plate with ramped wall heat flux. A graphic view of the flow model and physical coordinate system is shown in Fig.1. Choose a Cartesian co-ordinates system in such a way that x-axis is taken along the plate in a vertically upward direction and y-axis is is assumed to be normal to the plate. At time $t \le 0$, both the fluid and plate are at rest with constant temperature T_∞. At time $t > 0$, the plate starts to move in its own plane with exponential accelerated velocity $u_0 e^{\lambda^* t}$ (where u_0 is the mean velocity of the plate and λ^* is the accelerating parameter) and the heat flux at the plate changes rampedly with time. Since the plate is infinitely long in the x- direction, all the physical variables are the functions of y and t only.

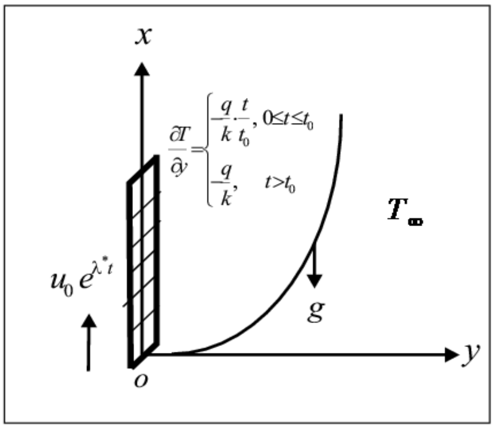

Fig.1 : Geometry of the problem.

The basic flow in the medium is entirely due to buoyancy force caused by temperature difference between the plate and the fluid. Under Boussinesq approximation, the the fully developed fluid flow be governed by the following system of equations

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

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p} \frac{\partial^2 T}{\partial y^2}, \qquad (2)$$

where u is the velocity in the x-direction, T the temperature of the fluid, g the acceleration due to gravity, β the coefficient of thermal expansion, ν the kinematic coefficient of viscosity, ρ the fluid density, k the thermal conductivity and c_p the specific heat at constant pressure.

The velocity and temperature boundary conditions are

$$u = 0, T = T_\infty \text{ for } y \text{ and } t \le 0,$$

$$u = u_0 e^{\lambda^* t}, \quad \frac{\partial T}{\partial y} = \begin{cases} -\dfrac{q}{k} \cdot \dfrac{t}{t_0} & \text{for } 0 < t \le t_0 \\ -\dfrac{q}{k} & \text{for } t > t_0 \end{cases} \quad \text{at } y = 0, \qquad (3)$$

$$u \to 0, T \to T_\infty \text{ as } y \to \infty \text{ for } t > 0,$$

where q is the constant heat flux.

We introduce the non-dimensional variables

$$\eta = \frac{y u_0}{\nu}, \quad \tau = \frac{t}{t_0}, t_0 = \frac{\nu}{u_0^2}, u_1 = \frac{u}{u_0}, \theta = \frac{u_0 k (T - T_\infty)}{q \nu}, \qquad (4)$$

On the use of (4), equations (1) and (2) become

$$\frac{\partial u_1}{\partial \tau} = \frac{\partial^2 u_1}{\partial \eta^2} + Gr\theta, \qquad (5)$$

$$Pr \frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial \eta^2}, \qquad (6)$$

where the non-dimensional parameters, specified based on the properties of the pure fluid are taken as $Pr = \frac{\rho \nu c_p}{k}$ the Prandtl number and $Gr = \frac{g\beta \nu^2 q}{k u_0^4}$ the Grashof number.

The initial and boundary conditions given by equation (3) become

$$u_1 = 0, \theta = 0 \text{ for } \eta \text{ and } \tau \le 0,$$

$$u_1 = e^{\lambda \tau}, \quad \frac{\partial \theta}{\partial \eta} = \begin{cases} -\tau & \text{for } 0 < \tau \le 1 \\ -1 & \text{for } \tau > 1 \end{cases} \quad \text{at } \eta = 0, \qquad (7)$$

$$u_1 \to 0, \theta \to 0 \text{ as } \eta \to \infty \text{ for } \tau > 0,$$

where $\lambda = \frac{\lambda^* \nu}{u_0^2}$ is the non-dimensional accelerated parameter.

On the use of Laplace transformation technique, equations (5) and (6) become

$$s\bar{u}_1 = \frac{d^2 \bar{u}_1}{d\eta^2} + Gr\bar{\theta}, \qquad (8)$$

$$Prs\bar{\theta} = \frac{d^2 \bar{\theta}}{d\eta^2}, \qquad (9)$$

where

$$\bar{u}_1(\eta, s) = \int_0^\infty u_1(\eta, s) e^{-s\tau} d\tau \text{ and } \bar{\theta}(\eta, s) = \int_0^\infty \theta(\eta, s) e^{-s\tau} d\tau \qquad (10)$$

and s is the Laplace transform variable.

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The corresponding boundary conditions for $\bar{u}_1$ and $\bar{\theta}$ become

$$\bar{u}_1 = \frac{1}{s-\lambda}, \quad \frac{d\bar{\theta}}{d\eta} = -\frac{1-e^{-s}}{s^2} \quad \text{at} \quad \eta = 0,$$
$$\bar{u}_1 \to 0, \quad \bar{\theta} \to 0 \quad \text{as} \quad \eta \to \infty. \tag{11}$$

The solution of the equations (8) and (9) subject to the boundary conditions (11) can easily be obtained and are given by

$$\bar{u}_1(\eta, s) = \begin{cases} \dfrac{1}{s-\lambda} e^{-\sqrt{s}\,\eta} + \dfrac{Gr(1-e^{-s})}{s^{\frac{7}{2}}\sqrt{Pr}\,(Pr-1)}\left(e^{-\sqrt{s}\,\eta} - e^{-\sqrt{s\,Pr}\,\eta}\right) & \text{for } Pr \neq 1, \\ \dfrac{1}{s-\lambda} e^{-\sqrt{s}\,\eta} + \dfrac{Gr(1-e^{-s})}{2s^3}\,\eta e^{-\sqrt{s}\,\eta} & \text{for } Pr = 1, \end{cases} \tag{12}$$

$$\bar{\theta}(\eta, s) = \frac{(1-e^{-s})}{s^2\sqrt{sPr}}\, e^{-\sqrt{sPr}\,\eta}, \tag{13}$$

The inverse Laplace transform of the equations (12) and (13) gives the solution of velocity field and temperature distributions in terms of exponential and complimentary error function as

$$u_1(\eta, \tau) = \begin{cases} A_1(\xi,\tau) + \dfrac{Gr}{\sqrt{Pr}\,(Pr-1)}\left[B_1(\xi,\tau) - H(\tau-1)B_1(\xi,\tau-1)\right] & \text{for } Pr \neq 1, \\ A_1(\xi,\tau) + \dfrac{Gr}{2}\left[G_3(\xi,\tau) - H(\tau-1)G_3(\xi,\tau-1)\right] & \text{for } Pr = 1, \end{cases}$$
(14)

$$\theta(\eta, \tau) = F_1(\xi,\tau) - H(\tau-1)F_1(\xi,\tau-1), \tag{15}$$

where

$$F_1(\xi,\tau) = \sqrt{\frac{\tau^3}{\pi Pr}}\left[\frac{4}{3}\left(1+Pr\xi^2\right)e^{-Pr\xi^2} - \frac{2}{3}\sqrt{\pi Pr}\,\xi\left(3+2Pr\xi^2\right)\mathrm{erfc}\left(\sqrt{Pr}\,\xi\right)\right], \tag{16}$$

$$G_1(\xi,\tau) = \frac{\tau^{\frac{5}{2}}}{15}\left[\left\{\frac{1}{\sqrt{\pi}}\left(16+36Pr\xi^2+8Pr^2\xi^4\right)e^{-Pr\xi^2}\right.\right.$$
$$\left.\left. -2\xi\sqrt{Pr}(15+20Pr\xi^2+4Pr^2\xi^4)\,\mathrm{erfc}(\sqrt{Pr}\,\xi)\right\}\right], \tag{17}$$

$$G_2(\xi,\tau) = \frac{\tau^{\frac{5}{2}}}{15}\left[\left\{\frac{1}{\sqrt{\pi}}\left(16+36\xi^2+8\xi^4\right)e^{-\xi^2} - 2\xi(15+20\xi^2+4\xi^4)\,\mathrm{erfc}(\xi)\right\}\right],$$

$$G_3(\xi,\tau) = 2\xi\left[\tau^{\frac{5}{2}}\left\{\mathrm{erfc}(\xi) - 2\xi\left[\frac{1}{\sqrt{\pi}}\xi^2 e^{-\xi^2} - \frac{1}{2}\xi\,\mathrm{erfc}(\xi)\right]\right\}\right. \tag{18}$$

$$\left. +\frac{1}{3}\tau^{\frac{3}{2}}\left\{\frac{1}{\sqrt{\pi}}\left(1-2\xi^2\right)e^{-\xi^2} + 2\xi^3\,\mathrm{erfc}\left(\xi\right)\right\}\right], \tag{19}$$

$$A_1(\xi,\tau) = \frac{1}{2}e^{\lambda\tau}\left[e^{2\xi\sqrt{\lambda\tau}}\,\mathrm{erfc}(\xi+\sqrt{\lambda\tau}) + e^{-2\xi\sqrt{\lambda\tau}}\,\mathrm{erfc}(\xi-\sqrt{\lambda\tau})\right], \tag{20}$$

$$B_1(\xi,\tau) = G_2(\xi,\tau) - G_1(\xi,\tau), \tag{21}$$

$$\xi = \frac{\eta}{2\sqrt{\tau}}, \tag{22}$$

and $\mathrm{erfc}(x)$ is the complementary error function and $H(\tau-1)$ the unit step function.

3 RESULTS AND DISCUSSION

In the following subsections, we highlights the effects of various thermophysical parameters such as Prandtl number Pr, Grashof number Gr, accelerating parameter λ and time τ on the velocity field, temperature distribution, shear stress and the rate of heat transfer at the exponentially accelerated moving plate $\eta = 0$ with the help of graphs and table. The value of the Prandtl number $Pr = 0.71$ is chosen to represent air at 20^0 C temperature and 1 atmospheric pressure. The Grashof number or buoyancy parameter Gr represents the effect of free convection current. Only positive values of the buoyancy parameter ($Gr > 0$) is considered (which corresponds to the cooling problem) here.

3.1 EFFECTS OF PARAMETERS ON THE VELOCITY PROFILES

The fluid velocity profiles are shown in Figs. 2-5. These figures show that the velocity field is maximum near the moving plate and gradually decreases away from the plate and finally tends to zero. It is observed from Fig.2 that the fluid velocity u_1 decreases with an increase in Prandtl number Pr. This is consistent with the physical point of view that the fluids with high Prandtl number have greater viscosity, which makes the fluid thick and hence move slowly. Fig.3 reveals that an increase in Grashof number Gr leads to rise in the fluid velocity u_1. This is due to the contribution from the buoyancy force near the plate. The Grashof number Gr signifies the relative effect of the thermal buoyancy force to the viscous hydrodynamic force in the boundary layer. The fluid velocity increases due to the enhancement of the thermal buoyancy force. It is seen from Fig.4 that the fluid velocity u_1 increases with an increase in accelerating parameter λ. It means that the increase of acceleration parameter increase the motion of exponentially accelerating moving plate at $\eta = 0$ which in turn increase the fluid motion also. It is observed from Fig.5 that the fluid velocity u_1 increases with time τ progresses. That means enhancement of time accelerates the fluid motion.

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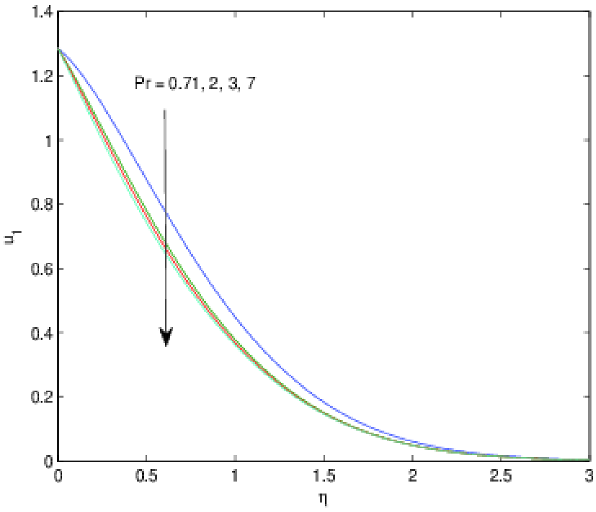

Fig.2: Velocity profiles for Pr when $Gr = 5$, $\lambda = 0.5$ and $\tau = 0.2$

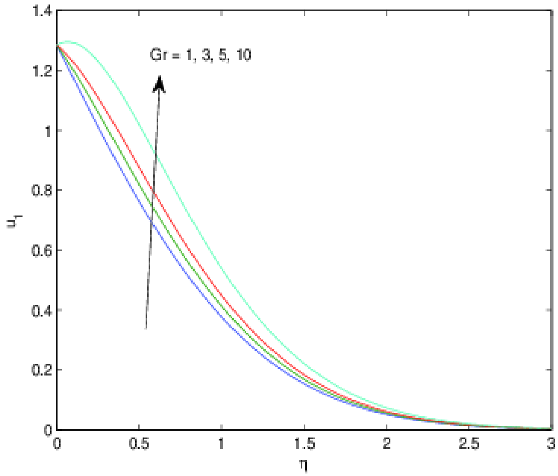

Fig.3: Velocity profiles for Gr when $Pr = 0.71$, $\lambda = 0.5$ and $\tau = 0.2$

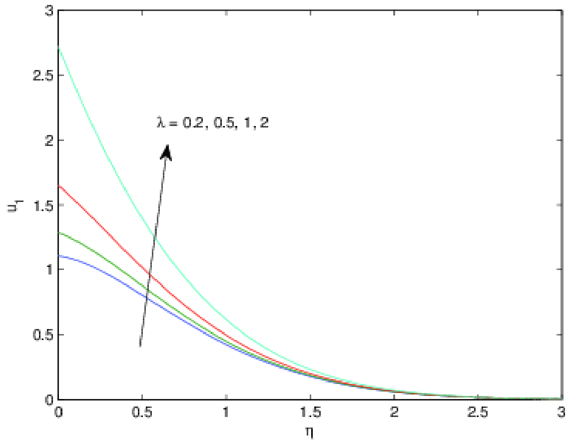

Fig.4: Velocity profiles for λ when $Pr = 0.71$, $Gr = 5$ and $\tau = 0.2$

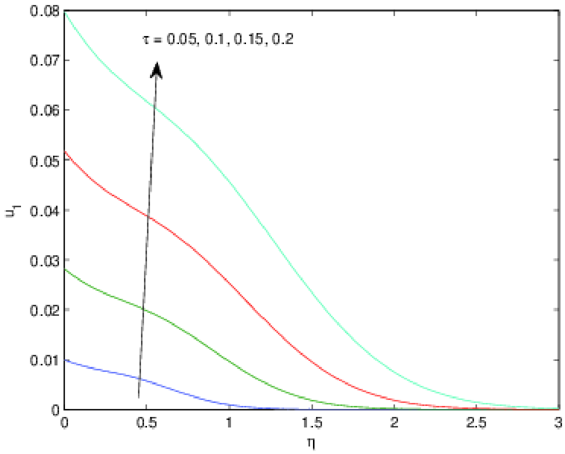

Fig.5: Velocity profiles for τ when $Pr = 0.71$, $Gr = 5$ and $\lambda = 0.5$

3.2 EFFECTS OF PARAMETERS ON THE TEMPERATURE DISTRIBUTION

The effects of Prandtl number Pr and time τ on the temperature distribution have been shown in Figs.6 and 7. The temperature is highest near the plate surface and decreases asymptotically to the free stream zero value far away from the plate. Fig.6 displays that the temperature decreases with an increase in Prandtl number Pr. It may be noted that an increase of Prandtl number causes the decrease of thermal boundary layer thickness that is why the temperature distribution across the thermal boundary layer decreases. It is observed from Fig.7 that the temperature increases with an increase in time τ.

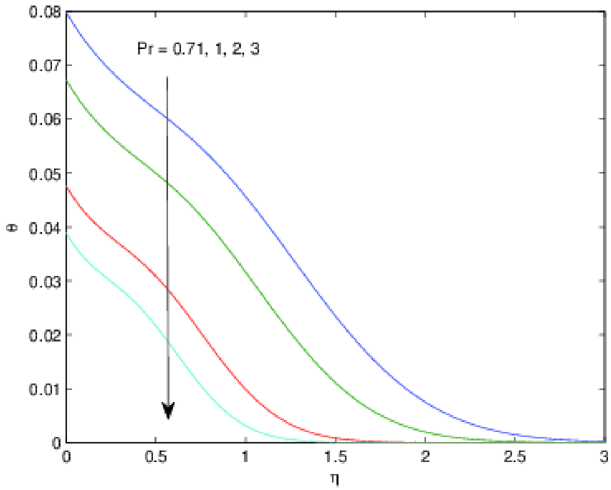

Fig.6: Temperature profiles for Pr when $\lambda = 0.5$ and $\tau = 0.2$

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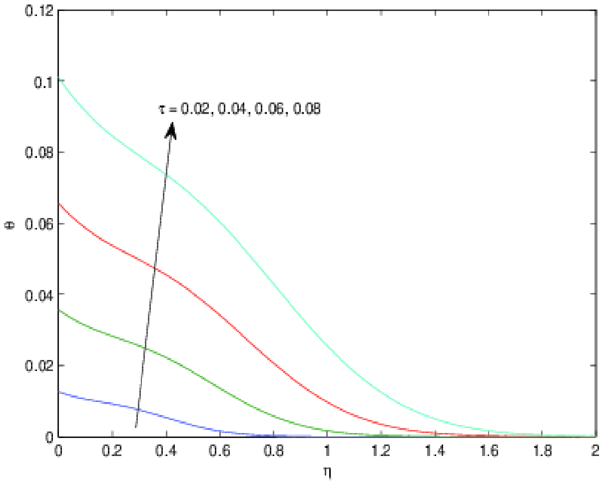

Fig.7: Temperature profiles for τ when $Pr = 0.71$ and $\lambda = 0.5$

3.3 EFFECTS OF PARAMETERS ON THE SHEAR STRESS AT THE PLATE

The non-dimensional shear stress τ_x at the moving plate $\eta = 0$ due to the flow is given by

$$-\tau_x = \begin{cases} \frac{1}{\sqrt{\pi\tau}}\left[1+\sqrt{\pi\lambda\tau}\,e^{\lambda\tau}\ erf\ (\sqrt{\lambda\tau})\right] \\ +\frac{Gr}{\sqrt{Pr}\ (\sqrt{Pr}+1)}\left[\tau^2-(\tau-1)^2\right] \quad \text{for } Pr \neq 1, \\ \frac{1}{\sqrt{\pi\tau}}\left[1+\sqrt{\pi\lambda\tau}\,e^{\lambda\tau}\ erf\ (\sqrt{\lambda\tau})\right] \\ +\frac{3Gr}{2\sqrt{\pi}}\left[\tau^{3/2}-(\tau-1)^{3/2}\right] \quad \text{for } Pr = 1, \end{cases} \tag{23}$$

Generally, increase of shear stress is a disadvantage in the different technical applications. Numerical values of the shear stress τ_x at the plate $\eta = 0$ due to the flow are presented in Table 1 for several values of Prandtl number Pr, Grashof number Gr, accelerating parameter λ and time τ. Table 1 shows that the magnitude of the shear stress τ_x at the plate $\eta = 0$ decreases with an increase in Prandtl number Pr while it increases with an increase in either Grashof number Gr or accelerating parameter λ for fixed values of time τ as it expected since the fluid velocity decreases with an increase in Prandtl number Pr and it increases with an increase in either Grashof number Gr or accelerating parameter λ. Further, it is seen that for fixed values of Prandtl number Pr, Grashof number Gr and accelerating parameter λ, the magnitude of τ_x decreases as time τ progresses.

Table 1. Shear stress $-\tau_x$ at the moving plate $\eta = 0$ for $\lambda = 0.5$, $Pr = 0.71$, $Gr = 5$

τ	Pr			Gr			λ		
	0.71	2	3	1	3	5	0.2	0.5	1.0
0.1	4.54490	3.14018	2.81390	2.48386	3.51438	4.54490	4.43275	4.54490	4.74201
0.2	3.46362	2.41007	2.16537	1.91784	2.69073	3.46362	3.29745	3.46362	3.77141
0.3	2.66007	1.95771	1.79457	1.62955	2.14481	2.66007	2.44689	2.66007	3.07606
0.4	1.94457	1.59339	1.51182	1.42931	1.68694	1.94457	1.68673	1.94457	2.47436

3.4 EFFECTS OF PARAMETERS ON THE HEAT TRANSFER RATE AT THE PLATE

The rate of Heat transfer at the plate $\eta = 0$ is given by

$$\theta' = \left(\frac{\partial\theta}{\partial\eta}\right)_{\eta=0} = F_2(\tau) - H(\tau-1)F_2(\tau-1), \qquad (24)$$

where

$$F_2(\tau) = \frac{4}{3}\tau\sqrt{\frac{\tau}{\pi Pr}} - \tau \qquad (25)$$

The numerical values of the rate of heat transfer at the plate $\eta = 0$ are depicted in Fig.8 for different values of Prandtl number Pr and time τ. It is seen from Fig.8 that the rate of heat transfer at the moving plate $\eta = 0$ increases with an increase in either Prandtl number Pr or time τ. The negative values of $\theta'(0)$ physically clarify that there is heat flow from the plate to the fluid.

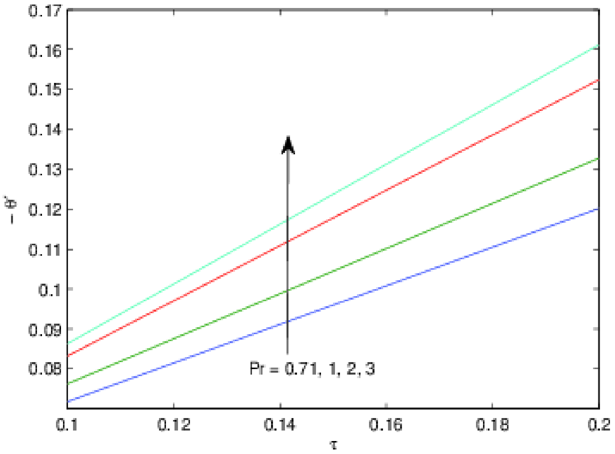

Fig.8: Rate of Heat transfer $-\theta'$ for Pr and τ

4 CONCLUSION

Effects of heat transfer on an unsteady flow past an exponentially accelerated vertical plate with ramped plate heat flux have been investigated theoretically. The flow related governing equations are solved analytically with the help of Laplace transform technique. Some conclusions of the study are as below:

- The velocity field and temperature distribution are maximum near the moving plate and gradually decrease asymptotically away from the plate and finally tends to zero.
- Increase of Prandtl number reduce the fluid velocity field. On the other hand, enhancement of either buoyancy parameter or accelerating parameter or time increases the fluid velocity field.
- It is seen that the temperature distribution decreases with an increase in Prandtl number where as it increases with an increase in time.
- The magnitude of shear stress at the moving plate due to the flow decreases with an increase in Prandtl number while it increases with an increase in either Grashof number or accelerating parameter.
- The rate of heat transfer at the moving plate increases with the enhancement of either Prandtl number or time.

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