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TRANSIENT FREE CONVECTIVE FLOW PAST A MOVING VERTICAL CYLINDER WITH CONSTANT MASS FLUX

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ABSTRACT

An exact solution to one dimensional unsteady free convective flow past an infinite moving vertical cylinder is investigated, taking mass flux into account. The dimensionless governing equations are solved by the Laplace Transform technique. The velocity, temperature and concentration profiles are studied for various physical parameters namely, Prandtl number, Schmidt number, thermal Grashof number, mass Grashof number and time. Also, skin friction and Nusselt number are obtained and discussed.

Keywords: *Free convection, Mass flux, Heat transfer, Vertical cylinder, Laplace transformation.*

1. INTRODUCTION

Free convection heat and mass transfer near a moving cylinder has a wide range of applications in the field of science and technology such as heat exchangers, nuclear reactors and solar collectors etc. There are few papers that deal with the analysis of simultaneous heat and mass transfer along a vertical cylinder. Bottemanne and Gbo [1] had studied the combined effect of heat and mass flux conditions both experimentally and theoretically. Chen and Yuh [2] studied steady heat and mass transfer effects for both conditions of uniform wall temperature, concentration, uniform heat and mass flux. Ganesan and Rani [3] dealt with unsteady natural convection boundary layer flow over a semi-infinite vertical cylinder with combined variable heat and mass flux. Goldstein and Briggs [4] carried out the one dimensional study of transient free convection from cylinders. They presented analytical solutions for the infinite cylinders. Ganesan and Rani [5] studied the transient free convection flow over a vertical cylinder under the combined buoyancy effects of heat and mass transfer. Venkatachalappa et *al.* [6] carried out the combined effects of rotation and buoyancy in a vertical annulus with both cylindrical walls rotating at different speeds. Ganesan and Loganathan [7] analyzed the effects of heat and mass transfer on the natural convection of an incompressible viscous fluid past a semi-infinite isothermal vertical cylinder. Evans *et al.* [8] and Velusamy and Garg [9] studied some transient results for the flow past cylinder. Suneetha and Reddy [10] analyzed the radiation and mass transfer effects on MHD free convection flow of a viscous incompressible fluid past a moving vertical cylinder in a porous medium. To solve the non-linear coupled equations, they used finite difference scheme of Crank-Nicolson type. Ganesan and Loganathan [11] presented the development of the free convection boundary layer flow of a viscous and incompressible fluid past an impulsively started semi-infinite vertical cylinder with uniform heat and mass flux and chemically reactive species. Zueco *et al.* [12] presented laminar axisymmetric convective heat and mass transfer in boundary layer flow over a vertical thin cylindrical configuration in the presence of significant surface heat and mass flux. Recently, Deka and Paul [13,14] have studied unsteady natural convective flow past an infinite vertical cylinder with combined effects of heat and mass transfer. And they also present an analytical treatment for the unsteady one-dimensional natural convective flow past an infinite moving vertical cylinder in the presence of thermal stratification. They use Laplace transform technique to solve the governing boundary layer equations.

The present investigation namely, an exact solution to the transient free convective flow past a moving vertical cylinder with constant mass flux has not received any attention in the literature. Hence, we have presented an analytical solution of unsteady free convective flow past an infinite vertical cylinder with constant mass flux. The solutions are obtained by Laplace transform technique for the velocity, temperature and concentration fields and these are presented in graphs. Skin friction and Nusselt number are also obtained and illustrated graphically.

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2. MATHEMATICAL ANALYSIS

We consider the problem of unsteady free convective flow of a viscous incompressible laminar flow over a moving infinite vertical cylinder of radius r_0. The x-axis is taken along the axis of the cylinder and radial coordinate r is normal to it. Initially, it is assumed that the cylinder and the fluid are at the same temperature T'_∞ and concentration C'_∞. At time $t' > 0$, the cylinder starts to move in the vertical direction with constant velocity u_0.The temperature on the surface of the cylinder is also raised to T'_w and a constant mass flux is maintained at the surface of the cylinder. All physical properties are assumed to be constant except for the density in the buoyancy terms, which is given by the usual Boussinesq approximation. The governing boundary layer equations for momentum, energy and concentration for free convective flow are as follows:

$$\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}+\frac{g\beta\left(T'-T'_\infty\right)}{\nu}+\frac{g\beta^*\left(C'-C'_\infty\right)}{\nu}=\frac{1}{\nu}\frac{\partial u}{\partial t'} \tag{1}$$

$$\frac{\partial^2 T'}{\partial r^2}+\frac{1}{r}\frac{\partial T'}{\partial r}=\frac{1}{\alpha}\frac{\partial T'}{\partial t'} \tag{2}$$

$$\frac{\partial^2 C'}{\partial r^2}+\frac{1}{r}\frac{\partial C'}{\partial r}=\frac{1}{D}\frac{\partial C'}{\partial t'} \tag{3}$$

with initial and boundary conditions:

$$\left.\begin{array}{l} t'\le 0,\ u=0,\ T'=T'_\infty,\ C'=C'_\infty\ \text{for all}\ r \\ t'>0,\ u=u_0,\ T'=T'_w,\ \dfrac{dC'}{dr}=-\dfrac{j}{2\pi r_0 D}\ \text{at}\ r=r_0 \\ u\to 0.\ T'\to T'_\infty,\ C'\to C'_\infty\ \text{as}\quad r\to\infty \end{array}\right\} \tag{4}$$

Introducing the non-dimensional quantities,

$$\begin{array}{l} R=\dfrac{r}{r_0},\ U=\dfrac{u}{u_0},\ t=\dfrac{t'\nu}{r_0^2},\ T=\dfrac{T'-T'_\infty}{T'_w-T'_\infty},\ C=\dfrac{2\pi d(C'-C'_\infty)}{j} \\ Sc=\dfrac{\nu}{D},\ Pr=\dfrac{\nu}{\alpha},\ Gr=\dfrac{g\beta r_0^2\left(T'_w-T'_\infty\right)}{u_0\nu},\ Gc=\dfrac{g\beta^* r_0^2\, j}{2\pi D u_0\nu} \end{array} \tag{5}$$

reduces equations (1)-(3) to,

$$\frac{\partial^2 U}{\partial R^2}+\frac{1}{R}\frac{\partial U}{\partial R}+GrT+GcC=\frac{\partial U}{\partial t} \tag{6}$$

$$\frac{\partial^2 T}{\partial R^2}+\frac{1}{R}\frac{\partial T}{\partial R}-Pr\frac{\partial T}{\partial t}=0 \tag{7}$$

$$\frac{\partial^2 C}{\partial R^2}+\frac{1}{R}\frac{\partial C}{\partial R}-Sc\frac{\partial C}{\partial t}=0 \tag{8}$$

The corresponding initial and boundary conditions in non-dimensional form are given by,

$$\left.\begin{array}{l} t\le 0,\ U=0,\ T=0,\ C=0\ \text{for all}\ R \\ t>0,\ U=1,\ T=1,\ \dfrac{dC}{dR}=-1\ \text{at}\ R=1 \\ t>0,\ U\to 0,\ T\to 0,\ C\to 0\ \text{as}\quad R\to\infty \end{array}\right\} \tag{9}$$

3. SOLUTIONS

We use the Laplace transform technique to solve the equations (6)-(8) subject to initial and boundary conditions (9).

We obtain the Laplace transformation of equations (6)-(8) as,

$$\frac{d^2\overline{U}}{dR^2}+\frac{1}{R}\frac{d\overline{U}}{dR}-s\overline{U}+Gr\overline{T}+Gc\overline{C}=0 \tag{10}$$

$$\frac{d^2\overline{T}}{dR^2}+\frac{1}{R}\frac{d\overline{T}}{dR}-sPr\overline{T}=0 \tag{11}$$

$$\frac{d^2\overline{C}}{dR^2}+\frac{1}{R}\frac{d\overline{C}}{dR}-sSc\overline{C}=0 \tag{12}$$

where s is the parameter of Laplace transform, defined by $L\{f(t)\}=F(s)$, L being the Laplace operator and $\overline{U}$, $\overline{T}$ and $\overline{C}$ are the Laplace transforms of U, T and C respectively.

Solutions of these equations (10)-(12) subject to the transformed initial and boundary conditions for T and C in (9), we get

$$\overline{T}=\frac{K_0\left(R\sqrt{sPr}\right)}{sK_0\left(\sqrt{sPr}\right)} \tag{13}$$

$$\overline{C}=\frac{K_0\left(R\sqrt{sSc}\right)}{s^{3/2}Sc^{1/2}K_1\left(\sqrt{sSc}\right)} \tag{14}$$

$$\overline{U}=\frac{K_0(R\sqrt{s})}{sK_0(\sqrt{s})}+\frac{Gr}{s^2(\Pr-1)}\left[\frac{K_0(R\sqrt{s})}{K_0(\sqrt{s})}-\frac{K_0(R\sqrt{sPr})}{K_0(\sqrt{sPr})}\right]+\frac{Gc}{s^{5/2}Sc^{1/2}(Sc-1)}\left[\frac{K_0(\sqrt{sSc})K_0(R\sqrt{s})}{K_1(\sqrt{sSc})K_0(\sqrt{s})}-\frac{K_0(R\sqrt{sSc})}{K_1(\sqrt{sSc})}\right] \tag{15}$$

and for $Pr = 1$, $Sc = 1$

$$\overline{U}=\frac{K_0\left(R\sqrt{s}\right)}{sK_0\left(\sqrt{s}\right)}+\frac{Gr}{2s^{3/2}}\left[R\frac{K_1(R\sqrt{s})}{K_0(\sqrt{s})}-\frac{K_0(R\sqrt{s})K_1(\sqrt{s})}{K_0(\sqrt{s})K_0(\sqrt{s})}\right]+\frac{Gc}{2s^2}\left[R\frac{K_1(R\sqrt{s})}{K_1(\sqrt{s})}-\frac{K_0(R\sqrt{s})}{K_0(\sqrt{s})}\right] \tag{16}$$

Now, using the theorem of inverse Laplace transform for equations (13)-(16), we obtain,

$$T=1+\frac{2}{\pi}\int_0^\infty e^{-(V^2t/Pr)}\Gamma_1\left(R,V\right)\frac{dV}{V} \tag{17}$$

$$C=-\frac{2}{\pi}\int_0^\infty(1-e^{-(V^2t/Sc)})\Gamma_5\left(R,V\right)\frac{dV}{V^2} \tag{18}$$

$$\begin{aligned}U=1+\frac{2}{\pi}\int_0^\infty e^{-V^2t}\Gamma_1(R,V)\frac{dV}{V}+\frac{2GrPr}{(Pr-1)\pi}\int_0^\infty(1-e^{-(V^2t/Pr)})\Gamma_4(R,\frac{V}{\sqrt{Pr}})\frac{dV}{V^3}\\+\frac{2Gc}{(Sc-1)\pi}\int_0^\infty[V^2t+Sc(e^{-(V^2t/Sc)}-1)]\xi(R,V,Sc)\frac{dV}{V^4}\end{aligned} \tag{19}$$

and for $Pr = 1$, $Sc = 1$,

$$U=1+\frac{2}{\pi}\int_0^\infty e^{-V^2t}\Gamma_1\left(R,V\right)\frac{dV}{V}+\frac{Gr}{\pi}\int_0^\infty(1-e^{-V^2t})\Gamma_2\left(R,V\right)\frac{dV}{V^2}+\frac{Gc}{\pi}\int_0^\infty(1-e^{-V^2t})\Gamma_3\left(R,V\right)\frac{dV}{V^3} \tag{20}$$

Non-dimensional skin friction, $\tau = -\left.\frac{\partial U}{\partial R}\right]_{R=1}$ can be obtained from the equations (19) and (20) for $Pr \neq 1$, $Sc \neq 1$ and $Pr = Sc = 1$ respectively as,

$$\tau = \frac{2}{\pi}\int_0^\infty e^{-V^2 t}\Gamma_6(V)dV + \frac{2GrPr}{(Pr-1)\pi}\int_0^\infty (1-e^{-V^2 t/Pr})\Gamma_9(\frac{V}{\sqrt{Pr}})\frac{dV}{V^2} + \frac{2Gc}{(Sc-1)\sqrt{Sc}}\int_0^\infty [V^2 t + Sc(e^{-V^2 t/Sc}-1)]\Gamma_{10}(\frac{V}{\sqrt{Sc}})\frac{dV}{V^3} \tag{21}$$

$$\tau = \frac{2}{\pi}\int_0^\infty e^{-V^2 t}\Gamma_6(V)dV + \frac{Gr}{\pi}\int_0^\infty (1-e^{-V^2 t})\Gamma_7(V)\frac{dV}{V^2} + \frac{Gc}{\pi}\int_0^\infty (1-e^{-V^2 t})\Gamma_8(V)\frac{dV}{V^2} \tag{22}$$

Non-dimensional Nusselt number, $Nu = -\left.\frac{\partial T}{\partial R}\right]_{R=1}$ can be obtained from the equation (17) as

$$Nu = \frac{2}{\pi}\int_0^\infty e^{-(V^2 t/Pr)}\Gamma_6(V)dV \tag{23}$$

where,

$$\Gamma_1(R,V) = \frac{J_0(RV)Y_0(V) - Y_0(RV)J_0(V)}{J_0^2(V)+Y_0^2(V)}$$

$$\Gamma_2(R,V) = R\frac{J_1(RV)Y_0(V) - Y_1(RV)J_0(V)}{J_0^2(V)+Y_0^2(V)} - \left[\frac{\{J_0(RV)J_0(V)+Y_0(RV)Y_0(V)\}\{J_1(V)Y_0(V)-Y_1(V)J_0(V)\}}{[J_0^2(V)+Y_0^2(V)]^2} + \frac{\{J_1(V)J_0(V)+Y_1(V)Y_0(V)\}\{J_0(RV)Y_0(V)-Y_0(RV)J_0(V)\}}{[J_0^2(V)+Y_0^2(V)]^2}\right]$$

$$\Gamma_3(R,V) = R\frac{J_1(RV)Y_1(V) - Y_1(RV)J_1(V)}{J_1^2(V)+Y_1^2(V)} - \Gamma_1(R,V)$$

$$\Gamma_4(R,V/\sqrt{Pr}) = \frac{J_0(RV/\sqrt{Pr})Y_0(V/\sqrt{Pr}) - Y_0(RV/\sqrt{Pr})J_0(V/\sqrt{Pr})}{J_0^2(V/\sqrt{Pr})+Y_0^2(V/\sqrt{Pr})} - \Gamma_1(R,V)$$

$$\xi(R,V,Sc) = \Gamma_5(R,V) - \frac{\{J_1(V)J_0(V)+Y_1(V)Y_0(V)\}\{J_0(RV/\sqrt{Sc})Y_0(V/\sqrt{Sc}) - Y_0(RV/\sqrt{Sc})J_0(V)\}}{\{J_1^2(V)+Y_1^2(V)\}\{J_0^2(V/\sqrt{Sc})+Y_0^2(V/\sqrt{Sc})\}} + \frac{2}{\pi V}\frac{\{J_0(RV/\sqrt{Sc})J_0(V/\sqrt{Sc})+Y_0(RV/\sqrt{Sc})Y_0(V/\sqrt{Sc})\}}{\{J_1^2(V)+Y_1^2(V)\}\{J_0^2(V/\sqrt{Sc})+Y_0^2(V/\sqrt{Sc})\}}$$

$$\Gamma_5(R,V) = \frac{J_0(RV)Y_1(V) - Y_0(RV)J_1(V)}{J_1^2(V)+Y_1^2(V)}$$

$$\Gamma_6(V) = \frac{J_1(V)Y_0(V) - Y_1(V)J_0(V)}{J_1^2(V)+Y_1^2(V)}$$

$$\Gamma_7(V) = \frac{V\{J_2(V)Y_0(V) - Y_2(V)J_0(V)\}}{2[J_0^2(V)+Y_0^2(V)]} - \Gamma_6(V) - \frac{2V\{J_1(V)J_0(V)+Y_1(V)Y_0(V)\}\{J_1(V)Y_0(V)-Y_1(V)J_0(V)}{[J_0^2(V)+Y_0^2(V)]^2}$$

$$\Gamma_8(V) = \frac{\{J_2(V)Y_1(V) - Y_2(V)J_1(V)\} + \{J_1(V)Y_0(V) - Y_1(V)J_0(V)\}}{2[J_1^{\,2}(V) + Y_1^{\,2}(V)]} - \Gamma_6(V)$$

$$\Gamma_9(V/\sqrt{Pr}) = \frac{1}{\sqrt{P_r}}\frac{\{J_1(V/\sqrt{Pr})Y_0(V/\sqrt{Pr}) - Y_1(V/\sqrt{Pr})J_0(V/\sqrt{Pr})\}}{\{J_0^{\,2}(V/\sqrt{Pr}) + Y_0(V/\sqrt{Pr})\}} - \Gamma_6(V)$$

$$\Gamma_{10}(V/\sqrt{Sc}) = -\frac{\{J_1(V)J_0(V) + Y_1(V)Y_0(V)\}\{J_1(V/\sqrt{Sc})Y_0(V/\sqrt{Sc}) - Y_1(V/\sqrt{Sc})J_0(V)\}}{\{J_1^{\,2}(V) + Y_1^{\,2}(V)\}\{J_0^{\,2}(V/\sqrt{Sc}) + Y_0^{\,2}(V/\sqrt{Sc})\}} + \frac{2}{\pi V}\frac{\{J_1(V/\sqrt{Sc})J_0(V/\sqrt{Sc}) + Y_1(V/\sqrt{Sc})Y_0(V/\sqrt{Sc})\}}{\{J_1^{\,2}(V) + Y_1^{\,2}(V)\}\{J_0^{\,2}(V/\sqrt{Sc}) + Y_0^{\,2}(V/\sqrt{Sc})\}}$$

4. RESULTS AND DISCUSSIONS

Numerical values for velocity (U), temperature (T), concentration (C), skin friction (τ) and Nusselt number (Nu) are calculated for different values of thermal Grashof number Gr, mass Grashof number Gc, Prandtl number Pr, Schmidt number Sc and time t and they are discussed with the help of graphical presentation. We restricted our observations for Pr = 0.71(air) and Pr = 7.0 (water) only.

Effects of thermal Grashof number and mass Grashof number on velocity profiles for Pr = 0.71, Sc = 0.6 and t = 1.2 are shown in Fig.1. The thermal Grashof number Gr signifies the relative effect of the buoyancy force to the hydrodynamic viscous force. The mass Grashof number Gc signifies the ratio of the species buoyancy force to the viscous hydrodynamic force. It is observed that the velocity slowly increases with increase in Gr and Gc. Fig. 2 shows the effects of Sc and Pr on velocity profiles for $Gr = Gc = 5$ and t = 1.2. The Prandtl number Pr physically relates the relative thickness of the hydrodynamic boundary layer and thermal boundary layer. The Schmidt number Sc physically relates the relative thickness of the hydrodynamic boundary layer and concentration boundary layer. It is seen that the velocity increases with decreases in Sc and Pr. Fig. 3 depicts the velocity profiles against time at Pr = 0.71, Sc = 0.6 and R = 1.4 for different values of Gr and Gc, which shows that velocity increases with the increases in Gr and Gc.

The transient temperature profiles for different Prandtl numbers and time are depicted in Fig. 4. The effect of Prandtl number is very important in temperature field. It is seen from this figure that the temperature decreases with increasing the values of Pr and increases with the increasing the values of time t. Fig. 5 depicts the effects of Prandtl number on temperature profiles with respect to time. Initially temperature increases rapidly with time but for large time it becomes steady.

In figure 6 concentration profiles are shown for different Sc and t. The figure shows that the concentration decreases with increasing the values of Sc and increases with increasing the values of t. Fig. 7 shows the concentration profiles for different Sc with respect to time t. Initially concentration increases with time but for large time it becomes steady.

The skin friction profiles for different values of Prandtl number and Schmidt number are plotted in figure 8. The skin friction decreases as t increases. It is also seen that the skin friction decreases with increasing Schmidt number and decreasing Prandtl number. Fig. 9 shows the rate of heat transfer for different values of Prandtl number. We observe that the Nusselt number i.e. rate of heat transfer increases with increase in Prandtl number and Schmidt number. An important observation is that the skin friction and Nusselt number approach fixed value at larger time.

5. CONCLUSIONS

The following conclusions are drawn from the above observations and discussions.

I. Velocity increases with the increase in Gr and Gc, but decreases with increase in Pr and Sc.

II. Temperature profiles are decreasing as Pr increases, but increases with time. Initially temperature increases sharply with time but for large time it becomes steady.

III. In case of Sc, the concentration profile is decreasing as Sc increases.

IV. Skin friction increases with decreasing value of Sc.

V. Nusselt number increases with increasing values of Prandtl number *Pr*, but decreases for smaller time and attains a fixed value for larger time.

Nomenclature

g acceleration due to gravity.
J_0 Bessel function of first kind and zero order.
J_1 Bessel function of first kind and order one.
K_0 modified Bessel function of order zero.
K_1 modified Bessel function of order one.
r radial distance from centre of the cylinder.
r_o radius of the cylinder.
Pr Prandtl number
t' time
t dimensionless time
u x- component of velocity.
u_0 vertical velocity of the cylinder.
U dimensionless velocity
Y_0 Bessel function of second kind and zero order.
Y_1 Bessel function of second kind and order one
α thermal diffusivity
β coefficient of thermal expansion
ν kinematic viscosity.
T' temperature
T dimensionless temperature
C' species concentration
C dimensionless species concentration
D mass diffusion coefficient
Gr thermal Grashof number
Gc mass Grashof number
β^* volumetric coefficient of expansion with concentration
j mass flux of the diffusing species.

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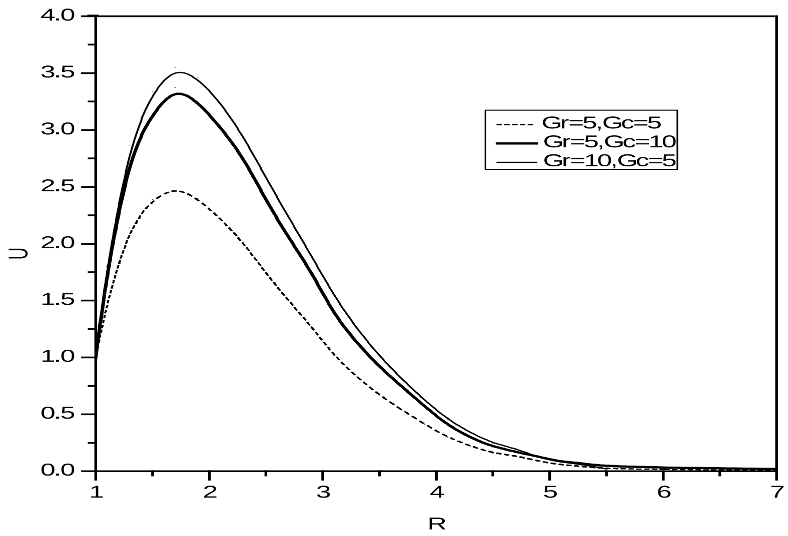

Fig.1: Velocity profiles for *Sc* = 0.6, *Pr* = 0.71 and *t* = 1.2

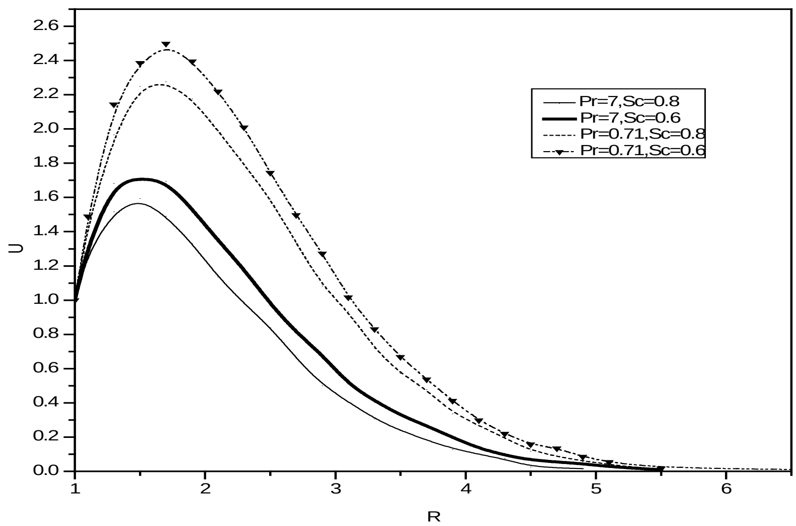

Fig. 2: Effects of *Sc* and *Pr* on velocity profiles for *Gr* = *Gc* = 5, *t* = 1.2

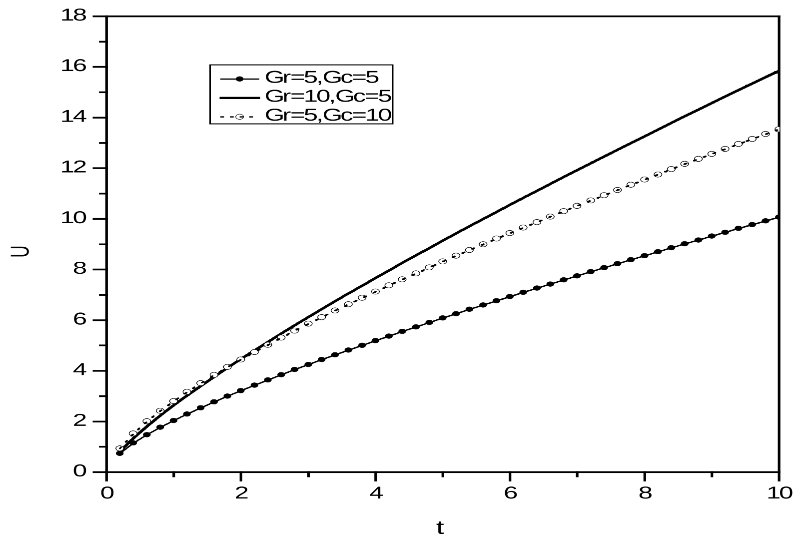

Fig. 3: Velocity profiles for *Sc* = 0.6 and *Pr* = 0.71 at *R*=1.4

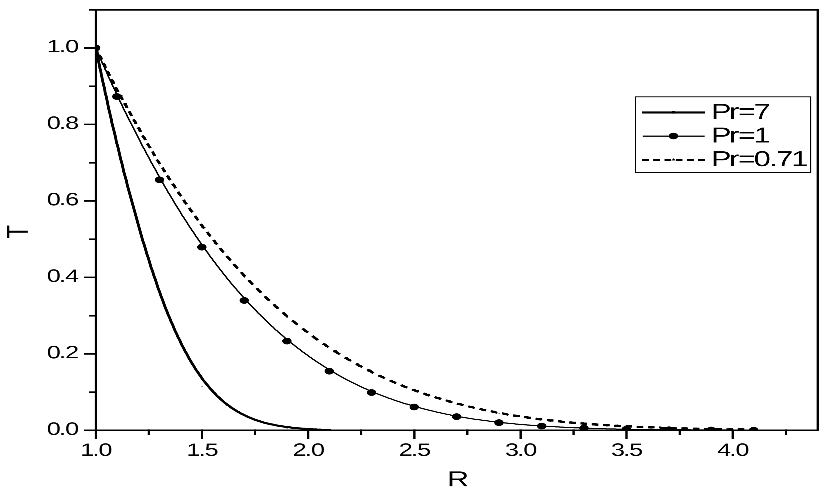

Fig. 4: Transient temperature profiles for different *Pr* and *t* = 0.4.

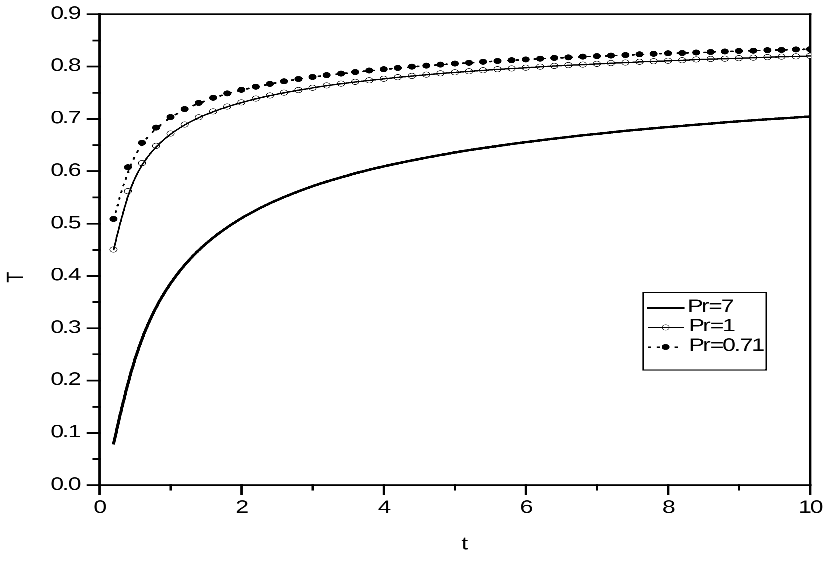

Fig. 5: Effects of *Pr* on temperature profiles with respect to time at *R*=1.4

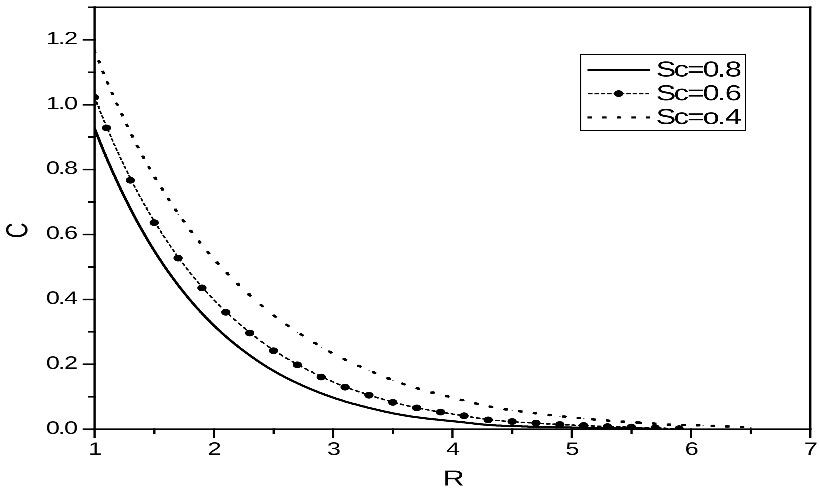

Fig. 6: Concentration profiles for different *Sc* at *t* = 1.2

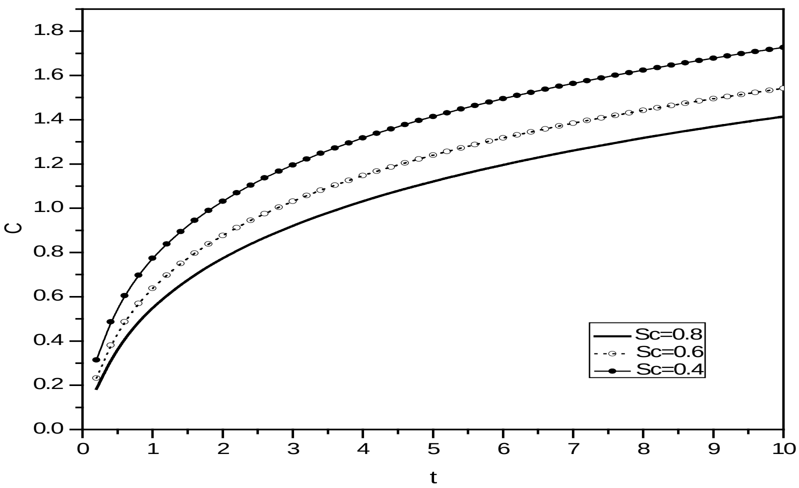

Fig. 7: Concentration profiles with respect to time *t* at *R*=1.4

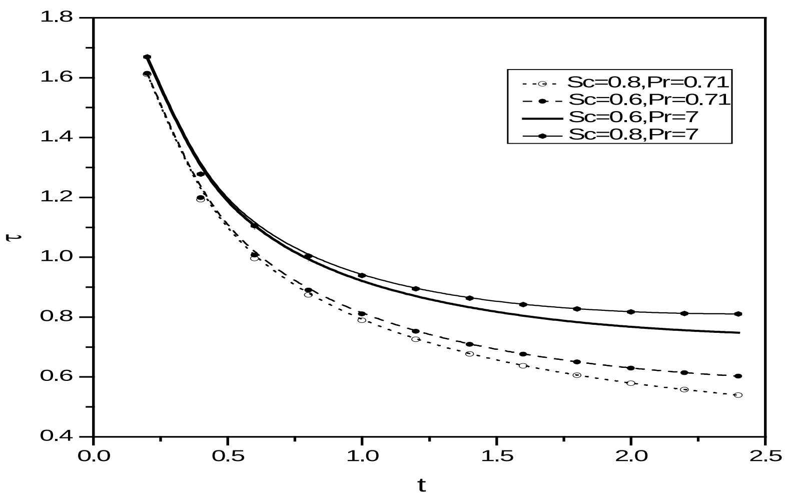

Fig. 8: Skin friction against time for different values of *Sc* at *Gr* = *Gc* = 0.4

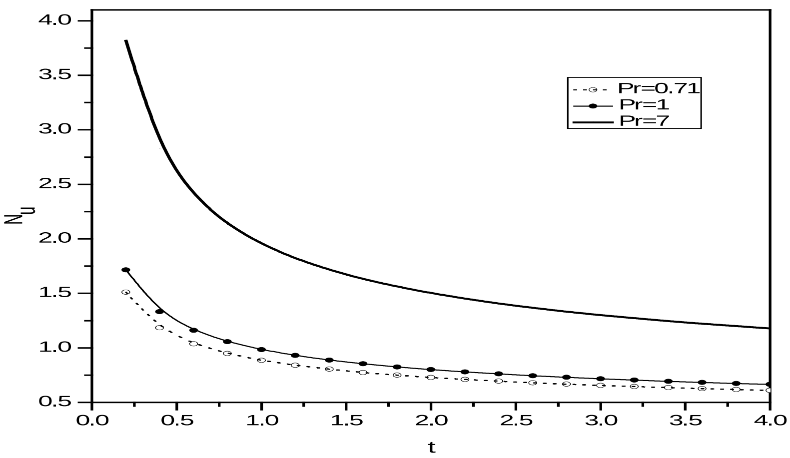

Fig. 9: Effects of *Pr* on Nusselt number.

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