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HEAT AND MASS TRANSFER EFFECTS ON LINEARLY ACCELERATED ISOTHERMAL INCLINED PLATE

K.S. Balamurugan[a,*] N. Udaya Bhaskar Varma[b], J.L. Ramaprasad[c], J. Prakash[d]

[a] *Department of Mathematics, R.V.R. & J.C. College of Engineering, Guntur, Andhra Pradesh, 522019, India*
[b] *Department of Basic Sciences & Humanities, DNR College of Engineering & Technology Bhimavaram, Andhra Pradesh, 534202, India*
[c] *Department ofMathematics, PB Siddhartha College of Arts and Science, Vijayawada, Andhra Pradesh, 520010, India*
[d] *Department of Mechanical Engineering Science, University of Johannesburg, South Africa*

ABSTRACT

Current work reports heat and mass transfer effects on unsteady free convection flow past a linearly accelerated isothermal inclined plate with variable temperature and mass diffusion with thermal radiation. The fluid is gray and non-scattering medium. When time t>0, the plate is accelerated with velocity u_0t, the plate temperature is raised linearly with respect to time and the mass is diffused from the plate linearly with time. The Mathematical equations represent the present flow problem are solved by Laplace transform method. The influences of significant involved parameters on velocity, temperature and concentration are tested. The rate of heat transfer in terms of Nusselt number and the rate of mass transfer in terms of Sherwood number have also been computed and their impacts for various parameters are discussed through the graphs. Fluid velocity is reduced by radiation parameter R, Prandtl number Pr and inclined angle parameter ϕ. Also the rate of change of heat transfer for water is higher than that of air.

Keywords: *Inclined plate, isothermal, accelerated, radiation, heat and mass transfer*

1. INTRODUCTION

The effects of heat and mass transfer in the occurrence of thermal radiation play an significant part in industrial productions in the design of nuclear power plants, steel rolling, air turbines and numerous momentum devices for aircraft, design of furnace and combustion, processing of material, utilization of energy, measurements of temperature, remote sensing for space exploration and astronomy, processing of food and cryogenic manufacturing as well as many health, agricultural and military applications. The effects of radiation play an important role if surrounding fluid temperature is high and this state does occur in space technology. In such circumstances, combined influence of radiation and mass diffusion one has to yield into account.

Hossain and Takhar (1996) investigated the radiation effect on forced convection flow of dense viscous incompressible fluid over a vertical heated flat plate with uniform Roselland diffusion. To solve the equations of boundary layer authors employed both methods Keller box and implicit finite difference. Partha and Raja Sekhar (2005) presented heat and mass transfer effects in thermal and mass boundary layer over a semi-infinite vertical plate embedded in porous medium with thermal radiation. Makinde and Ogulu (2008) investigated the thermal radiation and temperature dependent viscosity effect on free convective flow with constant Prandtl number over a vertical plate. Stanford Shateyi and Sandile Sydney Mosta (2009) studied numerically an unsteady heat and mass transfer using Chebyshey pseudo-spectral method over a stretching sheet. Muthucumaraswamy and Visalakshi (2011) studied the unsteady flow of viscous incompressible fluid past an exponentially enhanced vertical plate with variable temperature and thermal radiation in the presence of uniform mass diffusion. Noor et al. (2012) examined a thermophoretic free convection hydro magnetic radiative flow over an inclined surface with heat sink. Authors employed method of shooting to yield the solutions of flow problem. Kishore et al. (2012) investigated the effects of dissipation and radiation on viscous incompressible fluid flow with porous medium and variable mass diffusion. Patil et al. (2013) investigated the buoyance effects and thermal diffusion of Newtonian fluid. Alessandra Adrover and Augusta Pedacchia (2014) presented a heat and mass transfer solution for laminar forced convection flow with fixed wall temperature and concentration and high peclet numbers. Mittermaier et al. (2014) analyzed the heat and mass transfer of a laminar fluid film flow with homogeneous velocity over a vertical isothermal plate. Balamurugan et al. (2015) investigated the impacts of heat and mass transfer on unsteady flow past a vertical porous plate with slip conditions jump in temperature and concentration. Adeyemi Isaiah Fagbade and Adeola John Omowaye (2016) studied a problem of free convective transient flow of Newtonian fluid past a vertical oscillating isothermal porous plate with heat generation. Jinhu Zhao et al (2016) investigated unsteady heat and mass transfer effects of fractional visco elastic fluid in the presence of porous medium and dufour effect. Ramaprasad et al. (2016) studied an unsteady 2-D laminar boundary layer flow of heat absorbing electrically conducting fluid past an inclined surface with buoyancy effects. Sergey Leblea, and Lewandowski (2017) presented an analytical solution of Navier-Stokes equations relating free convective heat transfer from an isothermal plate somewhat inclined from the vertical. Zueco et al. (2017) presented the numerical solution of two dimensional unsteady free convective heat and mass transfer flow over a moving infinite porous vertical plate with magnetic field, heat dissipative taking into account the soret effect and induce magnetic field. Aranyak Chakravarty et al. (2018) carried out a steady state analysis with the supposition of laminar flow regime. Adamu Cizachew and Bandari Shankar (2018) developed a model to study the impact of

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[*] Corresponding author Email: muruganbalaks@gmail.com

heat source and slip parameter on heat and mass transfer of a Jeffery fluid with temperature and concentration in power low form. Thomas et al. (2018) examined how gas composition influences differential heat and mass transfer with in a laminar flow. Bano et al. (2018) studied the characteristics of heat and mass transfer of natural convection radiating fluid from a horizontal surface embedded in a porous medium. Salimipour (2019) investigated numerically the characteristics of heat transfer of a circular cylinder in a laminar incompressible vertical stream. Parashar and Ahmed (2019) studied MHD flow of electrically conducting fluid past an inclined plate with ramped parabolic velocity and Rossland thermal radiation. Michael Schaub and Stefan Brandt (2019) presented an analytical procedure to predict the heat transfer through unsteady natural convection at vertical flat plates in air. Rajakumar et al. (2019) analyzed the effects of thermal radiation and hall current on unsteady MHD free convective flow over a vertical semi-infinite oscillatory plate in the presence of ion slip. Yufei Huang et al. (2019) established a mathematical model to analyze the characteristics of heat and mass transfer of the heat source tower in low temperature environment. Using cubic B-spline method Abu Zeid et al. (2019) studied the mass transfer and thermal radiation effects of free convection flow over a moving vertical plate. Dharmaiah et al. (2019) studied the effects of viscous dissipation and transient aligned magnetic field on free convective flow past an inclined moving plate. Koushik, and Arul Prakash (2020) analyzed the characteristics of heat transfer in 180^0 bend domain with a bypass in the divider section using Garlerkin Finite Element Method. Paul Errera et al. (2020) developed a model of predictive coupling base on the Godunov-Ryabenkil regular mode study theory for stead state heat transfer problems with radiative boundary conditions. Dipak Sarma and Silpisikha Goswami (2020) studied analytically an unsteady heat and mass transfer flow over a vertical plate with porous medium. Myers and Font (2020) developed a mathematical model for the mass transfer process from a flowing fluid by a packed column. Balamurugan et al. (2020) investigated the temperature gradient heat source effects on MHD permeable base in the presence of viscous and joules dissipation. Govindaraju et al. (2020) analyzed the numerical study of fluid flow over stretching sheet with temperature dependent properties induced by mixed convection. Santhi Kumari et al. (2021) studied numerically the effects of heat and mass transfer on unsteady MHD free convective flow past an infinite vertical plate. Kranthi Kumar et al. (2021) presented MHD Casson fluid flow along inclined plate with hall and aligned magnetic effects.

In the present study, the heat and mass transfer effects are analyzed on unsteady free convective flow past a linearly accelerated isothermal inclined plate with variable temperature and variable concentration in the occurrence of thermal radiation. The governing equations are solved by Laplace transform method and the solution is in terms of exponential and complementary error function.

2. MATHEMATICAL ANALYSIS

Consider an unsteady two dimensional viscous incompressible fluid past a linearly accelerated inclined plate with variable mass diffusion and temperature. The flow is assumed to be in the x-direction, which is taken along the inclined plate and y-axis normal to it. When time $t^* > 0$ the plate is linearly raised with a velocity $u_0 t^*$ in its own plane and the temperature from the plate is accelerated linearly with time and also the mass is diffused from the plate in a linear mode with respect to *t*. The fluid is non-scattering medium and gray emitting-absorbing radiation. The governing equations for this investigation are based on Boussinesq's approximation.

$$\frac{\partial u^*}{\partial t^*} = \frac{\partial^2 u^*}{\partial y^2} + g\cos\phi\beta(T^* - T_\infty^*) + g\cos\phi\beta^*(C^* - C_\infty^*) \tag{1}$$

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

$$\frac{\partial C^*}{\partial t^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} \tag{3}$$

Boundary conditions:

$$t^* > 0: u^* = u_0 t^*, \quad T^* = T_\infty^* + (T_w^* - T_\infty^*)At^*,$$
$$C = C_\infty^* + (C_w^* - C_\infty^*)At^* \; at \quad y^* = 0$$
$$u^* \to 0, T \;\to\; T_\infty^*, C \;\to C_\infty^* \quad as \quad y^* \to \; \infty \tag{4}$$

Where A=$\sqrt[3]{\frac{u_0^2}{v}}$. The local radiant for the case of an optically thin gray gas is given by $\frac{\partial q_r}{\partial y^*} = -4a^*\sigma(T_\infty^{*4} - T^{*4})$ (5)

It is assumed that the temperature differences are small within the flow and that T^{*4} may be expressed as a linear function of the temperature. This is attained by escalating T^{*4} in a Taylor series about T_∞^* and ignoring the higher order terms we get,

$$T^{*4} \cong 4T_\infty^{*3}T^* - 3T_\infty^{*4} \tag{6}$$

Using equations (5) and (6) equation (2) becomes

$$\frac{\partial T^*}{\partial t^*} = \frac{k}{\rho C_p}\frac{\partial^2 T^*}{\partial y^{*2}} + 16a^*\sigma T_\infty^{*3}(T_\infty^* - T^*) \tag{7}$$

The non-dimensional quantities are

$$y = y^*\sqrt[3]{\frac{u_0}{v^2}}, \quad u = \frac{u^*}{\sqrt[3]{vu_0}}, \quad t = t^*\sqrt[3]{\frac{u_0^2}{v}}, \quad C = \frac{C^* - C_\infty^*}{C_w^* - C_\infty^*},$$
$$R = -\frac{16a^*\sigma T_\infty^{*3}}{k}\sqrt[3]{\frac{v}{u_0^2}}, \quad Sc = \frac{\upsilon}{D}, \quad Gr = \frac{g\beta(T_w^* - T_\infty^*)}{u_0},$$
$$T = \frac{T^* - T_\infty^*}{T_w^* - T_\infty^*}, \; Gm = \frac{g\beta^*(C_w^* - C_\infty^*)}{u_0}, \, \Pr = \frac{\mu C_p}{k}, \tag{8}$$

Equations (1), (2) and (3) reduces to

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u^*}{\partial y^2} + Gr(\cos\phi)T + Gm(\cos\phi)C \tag{9}$$

$$\frac{\partial T}{\partial t} = \frac{1}{\Pr}\frac{\partial^2 T}{\partial y^2} - \frac{RT}{\Pr} \tag{10}$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} \tag{11}$$

Boundary conditions:

$$t^* > 0: u = t, \quad T = t, \; C = t \quad at \quad y = 0$$
$$u \to 0, \quad \theta \to 0, \quad C \to 0 \quad as \quad y \to \infty \tag{12}$$

The solutions of the equations (9) to (11) with respect to the boundary conditions (12) are as follows:

$$\begin{aligned}
u(y,t) &= \left(1+\frac{Gr\cos\phi}{R}\right)\left[\left(t+\frac{y^2}{2}\right)erfc\left(\frac{y}{2\sqrt{t}}\right)-y\sqrt{\frac{t}{\pi}}e^{-\frac{y^2}{4t}}\right] \\
&-\frac{Gr\cos\phi(\Pr-1)}{R^2}erfc\left(\frac{y}{2\sqrt{t}}\right) \\
&+\left(e^{-ct}\,\frac{Gr\cos\phi(\Pr-1)}{2R^2}\right)\left[\begin{array}{l} e^{y\sqrt{-c}}erfc\left(\frac{y}{2\sqrt{t}}+\sqrt{-ct}\right) \\ +e^{-y\sqrt{-c}}erfc\left(\frac{y}{2\sqrt{t}}-\sqrt{-ct}\right)\end{array}\right] \\
&+\left(\frac{Gm\cos\phi}{24(Sc-1)}\right)\left[\begin{array}{l}(12t^2+12y^2t+y^4)erfc\left(\frac{y}{2\sqrt{t}}\right) \\ -(2y^3+20yt)\sqrt{\frac{t}{\pi}}e^{-\frac{y^2}{4t}}\end{array}\right] \\
&-\frac{Gr\cos\phi}{R}\left[\begin{array}{l}\left(\frac{t}{2}+\frac{y\Pr}{4\sqrt{R}}\right)erfc\left(\frac{y\sqrt{\Pr}}{2\sqrt{t}}+\sqrt{\frac{Rt}{\Pr}}\right)e^{y\sqrt{R}} \\ +\left[\left(\frac{t}{2}-\frac{y\Pr}{4\sqrt{R}}\right)erfc\left(\frac{y\sqrt{\Pr}}{2\sqrt{t}}-\sqrt{\frac{Rt}{\Pr}}\right)e^{-y\sqrt{R}}\right]\end{array}\right] \\
&-\frac{Gm\cos\phi}{24(Sc-1)}-\frac{Gr\cos\phi(\Pr-1)}{2R^2}e^{-ct} \\
&\left[\begin{array}{l}erfc\left(\frac{y\sqrt{\Pr}}{2\sqrt{t}}+\sqrt{\left(\frac{R}{\Pr}-c\right)t}\right)e^{y\sqrt{R-c\Pr}} \\ +erf\left(\frac{y\sqrt{\Pr}}{2\sqrt{t}}-\sqrt{\left(\frac{R}{\Pr}-c\right)t}\right)e^{-y\sqrt{R-c\Pr}}\end{array}\right] \\
&+\frac{Gr\cos\phi(\Pr-1)}{2R^2}\left[\begin{array}{l}erfc\left(\frac{y\sqrt{\Pr}}{2\sqrt{t}}+\sqrt{\frac{Rt}{\Pr}}\right)e^{y\sqrt{R}} \\ +erfc\left(\frac{y\sqrt{\Pr}}{2\sqrt{t}}-\sqrt{\frac{Rt}{\Pr}}\right)e^{-y\sqrt{R}}\end{array}\right] \\
&+\left[\begin{array}{l}(12t^2+12y^2tSc+Sc^2y^4)erfc\left(\frac{y\sqrt{Sc}}{2\sqrt{t}}\right) \\ -(2y^3Sc+20yt)\sqrt{\frac{Sct}{\pi}}e^{-\frac{y^2Sc}{4t}}\end{array}\right] \qquad (13)
\end{aligned}$$

$$T(y,t)=\left[\begin{array}{l}\left(\frac{t}{2}+\frac{y\Pr}{4\sqrt{R}}\right)erfc\left(\frac{y\sqrt{\Pr}}{2\sqrt{t}}+\sqrt{\frac{Rt}{\Pr}}\right)e^{y\sqrt{R}} \\ +\left(\frac{t}{2}-\frac{y\Pr}{4\sqrt{R}}\right)erfc\left(\frac{y\sqrt{\Pr}}{2\sqrt{t}}-\sqrt{\frac{Rt}{\Pr}}\right)e^{-y\sqrt{R}}\end{array}\right] \qquad (14)$$

$$C(y,t)=\left(t+\frac{y^2Sc}{2}\right)erfc\left(\frac{y\sqrt{Sc}}{2\sqrt{t}}\right)-y\sqrt{\frac{tSc}{\pi}}e^{\frac{y^2Sc}{4t}} \qquad (15)$$

Nusselt Number

$$\begin{aligned}Nu=-\left(\frac{\partial T}{\partial y}\right)_{y=0} &= t\sqrt{R}erf\left(\sqrt{\frac{Rt}{\Pr}}\right)+\sqrt{\frac{t\Pr}{\pi}}e^{-\frac{Rt}{\Pr}} \\ &+\frac{\Pr}{2\sqrt{R}}erf\left(\sqrt{\frac{Rt}{\Pr}}\right)\end{aligned} \qquad (16)$$

Sherwood Number

$$Sh=-\left(\frac{\partial C}{\partial y}\right)_{y=0}=2\sqrt{\frac{tSc}{\pi}} \qquad (17)$$

3. RESULTS AND DISCUSSION

The problem of heat and mass transfer has been formulated, studied and explained analytically, numerical calculations were conceded out for physical analysis of the problem for different physical parameters. Graphs are plotted for velocity, temperature, concentration, Nusselt number and Sherwood number. The heating (Gr<0, Gm<0) and cooling (Gr>0, Gm>0) take place by setting up free convection current owing to temperature and concentration gradient. The result of velocity for different values of radiation parameter R, Prandtl number Pr, thermal Grashof number Gr and inclined angle parameter ϕ are presented in figures 1-3. It is noticed that the velocity of the fluid increases with increasing values of thermal Grashof number Gr and the velocity of the fluid decelerated with accelerating values of radiation parameter R or Prandtl number Pr or inclined angle parameter ϕ in the case of cooling of the plate. From these findings, it is clear that the fluid velocity reductions in the presence of high thermal radiation, Prandtl number and inclined angle. The temperature profiles are calculated for dissimilar values of thermal radiation parameter for air (Pr = 0.71) at time t = 0.5 and 1 and are showed in figures 4 and 5 respectively. It is noticed that the temperature falls as thermal radiation parameter R rises.

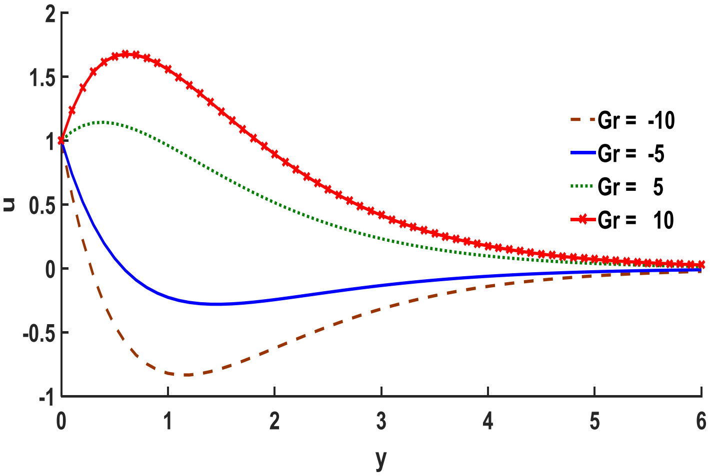

Fig. 1 Velocity profiles for for Gr when Pr = 0.71, R = 1, Sc = 0.60, Gm = 10, ϕ = π/6 and t = 1.

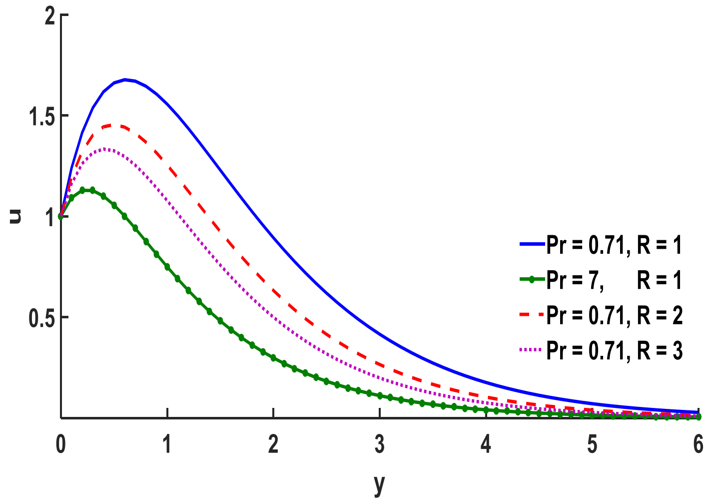

Fig. 2 Velocity profiles for Pr and R when Gr = 10, Sc = 0.60, $\phi = \pi/6$, Gm = 10 and t = 1.

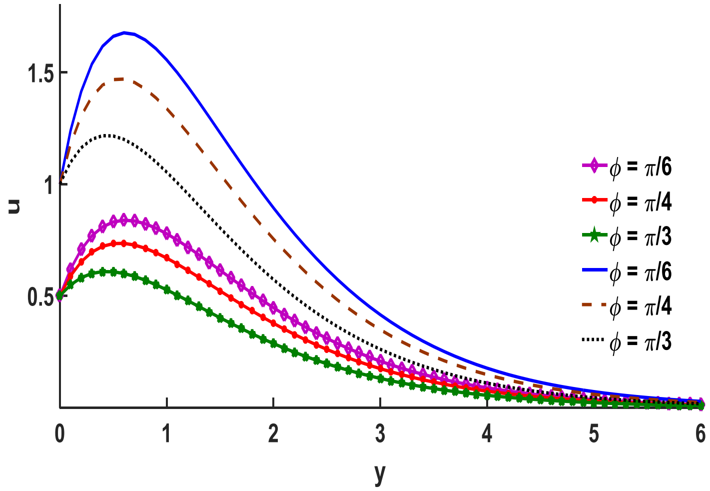

Fig. 3 Velocity profiles for ϕ when Gr = 10, Sc = 0.60, Gm = 10, Pr = 0.71 and R = 1.

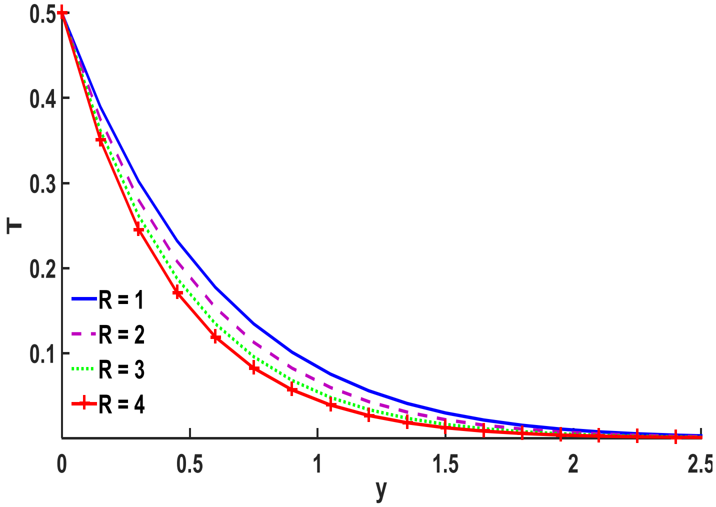

Fig. 4 Temperature profiles for R when Pr = 0.71 and t = 0.5

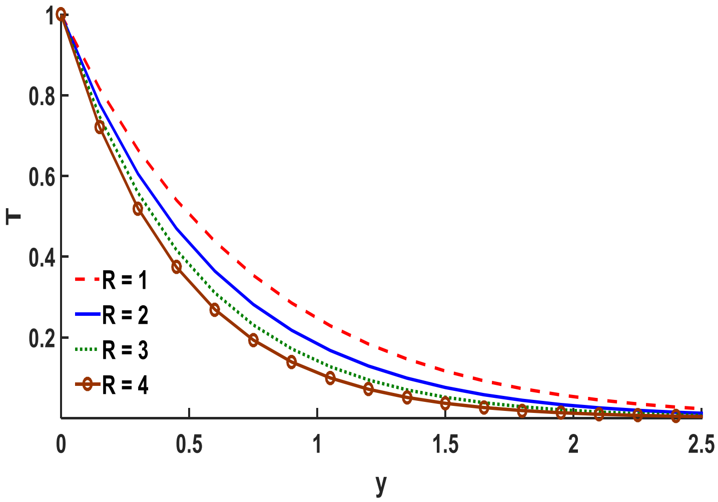

Fig. 5 Temperature profiles for R when Pr = 0.71 and t = 1

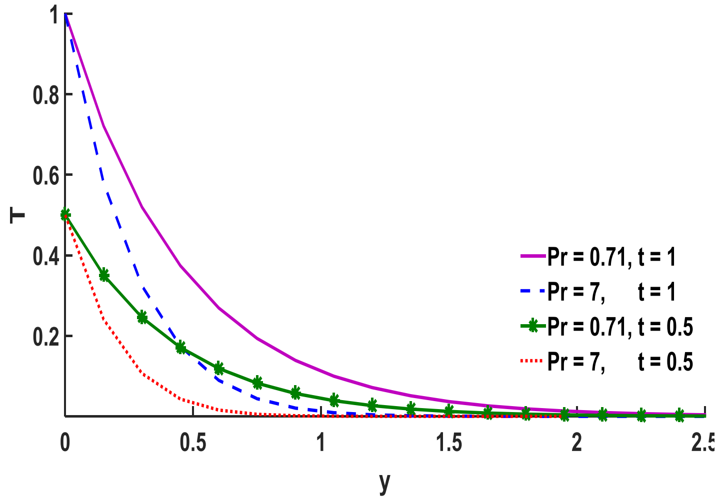

Fig. 6 Temperature profiles for Pr when R=4

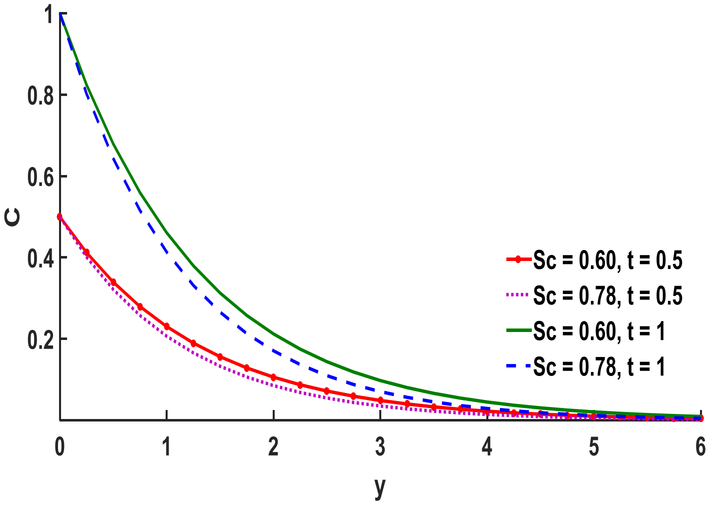

Fig. 7 Concentration profiles for Sc

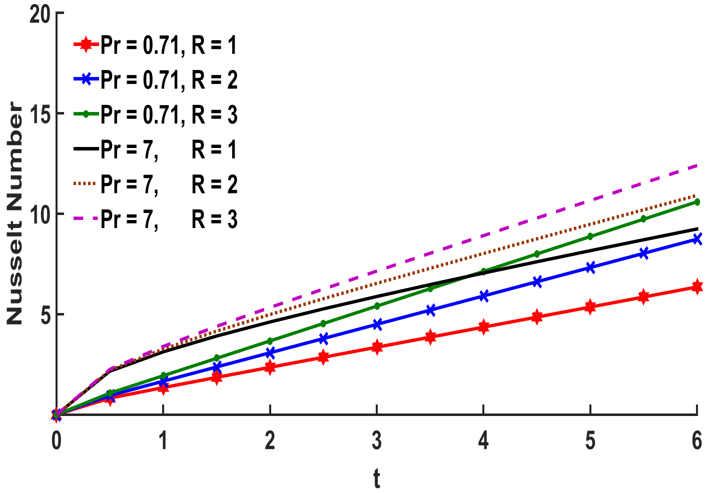

Fig. 8 Nusselt number

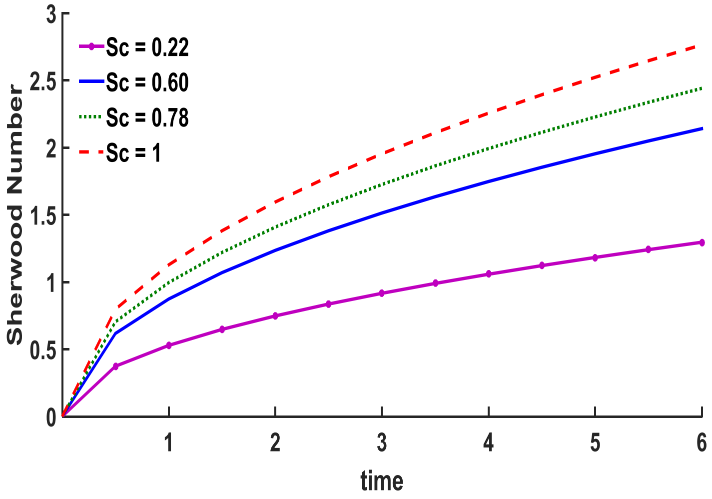

Fig. 9 Sherwood number

Figure 6 proves that the temperature for water (Pr = 7) is lower than that of air (Pr = 0.71). This is owed to fact that fluid thermal conductivity diminutions with increasing Pr causing a decrease in thickness of thermal boundary layer. Figure 7 shows the effect of concentration profiles for different values of Schmidt number Sc at time t = 0.5 and 1. It is noticed that the concentration decreases with increasing Schmidt number. Figure 8 shows the Nusselt number for air (Pr = 0.71) is lower than that of water (Pr = 7). The reason is that higher values of Pr are to decrease the thermal conductivities and hence the heat is able to diffuse away from the plate and further rapidly than higher values of Pr. So that rate of heat transfer is reduced. Finally from figure 9 it is noticed that the Sherwood number accelerates with rise in Schmidt number.

4. CONCLUSIONS

An analytical solution for hydrodynamic flow past a viscous incompressible fluid past a linearly accelerated isothermal inclined plate with variable temperature and mass diffusion with thermal radiation has been investigated. The mathematical equations are solved by the Laplace transform method. The impacts of various physical parameters are presented through graphs. The conclusions of the investigation are as follows:

- Fluid velocity is reduced by radiation parameter R, Prandtl number Pr and inclined angle parameter ϕ.
- Temperature falls by rising values of thermal radiation parameter R.
- Schmidt number Sc reduces the wall concentration.
- The Nusselt number for water is higher than air.
- Schmidt number Sc tends to increase the Sherwood number.

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