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Effects of Heat Generation and Thermal Radiation on Unsteady Free Convective Flow Past an Accelerated Vertical Plate with Variable Temperature and Mass Diffusion

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ABSTRACT

In the present study, the numerical and exact solution of unsteady free convection flow past an accelerated motion of a vertical radiated plate with variable heat and mass transfer embedded in porous medium are studied and analyzed. Perturbation solutions in terms of the magnetic interaction parameter are obtained to a desired order of approximations. The governing differential equations are transformed into a set of non-linear differential equations and solved using similarity analysis with Runge-Kutta-Gill integration scheme. The numerical values obtained are then compared with the exact solution obtained by repeated integrals of complementary error function. The effects of various physical parameters on the dimensionless velocity, temperature and concentration profiles are presented graphically. In addition, the local values of the Skin-friction coefficient, Nusselt number and Sherwood number are also derived.

Keywords: Free convection, Porous medium, Radiation, Heat generation.

1. INTRODUCTION

Heat transfer with convection is very important in view of several physical problems. Boundary layer behavior over an accelerated plate is an important type of flow occurring in number of engineering processes. The heating of rooms and buildings by the use of radiators is a familiar example of heat transfer by free convection. MHD convection flow problems are also very important in the field of steller and planetary magnetospheres, aeronautics, electronics and space vehicle propulsion. Convective flow through porous medium has application in the field of chemical engineering for filtration and purification processes. The effects of radiation on heat transfer flows play important role in designing various devices and on adding chemical reaction effects having practical applications in chemical and hydrometallurgical industries. Dave et al.[1] and Tak and Pathak[2] have studied the heat, momentum and mass transfer in unsteady free convection flow past an accelerated plate. Raptis[3] studied the unsteady two-dimensional flow of viscous fluid through a porous medium bounded by infinite porous plate with constant suction and variable temperature. Raptis and Perdikis[4] then study the same problem when the temperature of porous plate oscillates in time about a constant mean. Acharya et al.[5] has analyzed free convection and mass transfer in steady flow through porous medium with constant suction in presence of magnetic field. Takhar et al.[6] considered the effect of radiation on free convective flow along semi-infinite vertical plate in presence of transverse magnetic field. Damseh et al.[7] has studied the similarity analysis of magnetic field and thermal radiation effects on forced convection flows. Taking an impulsively started infinite vertical plate, Tak and Maharshi[8], Ganeshan et al.[9] and Muthucumaraswamy and Vijayalakshmi[10] have studied radiation effects in free convection flow with variable heat flux. Pathak and Sisodia[11] have studied the radiation effects on free convection flow bounded by an impulsively started infinite vertical plate embedded in porous medium. The unsteady MHD flow past a vertical plate with chemical reaction parameter and radiation parameter was studied by many authors [12]-[15]. The thermal-diffusion and diffusion-thermo effects on the heat and mass transfer characteristics of free convection past a moving vertical plate embedded in a porous medium in the presence of magnetic field, blowing/suction and thermal radiation is investigated by Olanrewaju and Adeniyan [16]. The combined effects of Soret and Dufour on unsteady hydromagnetic free convective flow of a Newtonian, viscous, electrically conducting fluid on a continuously fluid past a vertical porous plate subjected to variable suction in presence of radiation absorption, mass diffusion, chemical reaction and heat source parameter have been studied by Babu et al. [17]. The unsteady two dimensional hydromagnetic forced convection boundary layer flow of a viscous incompressible fluid along flat plates with thermophoresis is studied by Uddin and Ali [18].

However, the combined effects of radiation and chemical reaction parameter on accelerated plate with variable mass and temperature are less studied in the literature. It is therefore, proposed to study heat generation/absorption and radiation effects on unsteady free convection flow through porous medium bounded by an accelerated plate with variable mass and temperature.

2. MATHEMATICAL FORMULATION AND ANALYSIS

Consider an unsteady free convection flow of an incompressible viscous radiating fluid, through a porous medium bounded by an accelerated heated plate of infinite extent in a uniform magnetic field, which is assumed to be applied transversely to the plate and fixed relative to the fluid. Initially it is assumed that the plate and the fluid are at a constant temperature and concentration $T_\infty *$ and $C_\infty *$ at all points. For $t* > 0$, the plate temperature and species concentration temperature at the plate are instantaneously raised to $T_w *$ and $C_w *$. The plate is assumed to be suddenly accelerated in the upward direction with uniform acceleration ${u_0^{*3}}/{v}$. The $x*$ axis is taken along the vertical plate in upward direction and $y*$ axis normal to it see Figure 1.

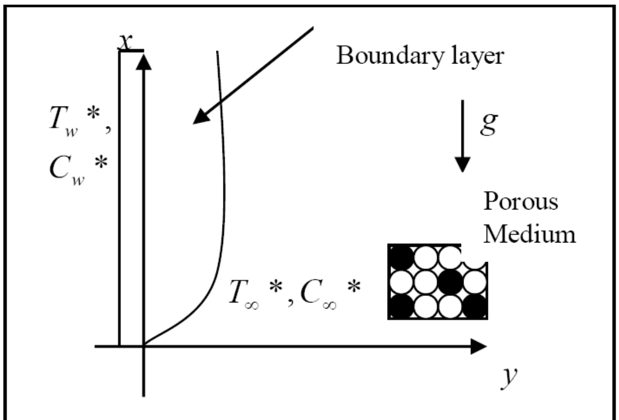

Fig. 1 Physical model and co-ordinate system

Since the motion is two-dimensional and length of the plate is large, therefore, all the physical variables are independent of $x*$ only. Then, under the usual Bousinesq's approximations, the governing equations can be expressed as:

Continuity equation:

$$\frac{\partial v*}{\partial y*} = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial u*}{\partial t*} + v*\frac{\partial u*}{\partial y*} = \upsilon \frac{\partial^2 u*}{\partial y*^2} + g\beta(T*-T_\infty*) + g\beta^*(C*-C_\infty*) - \frac{\upsilon}{K*}u* - \frac{\sigma B_0^2}{\rho}u* \tag{2}$$

Energy equation:

$$\frac{\partial T*}{\partial t*} + v*\frac{\partial T*}{\partial y*} = \frac{\kappa}{\rho c_P}\frac{\partial^2 T*}{\partial y*^2} - \frac{1}{\rho c_P}\frac{\partial q_r*}{\partial y*} + \frac{Q*}{\rho c_P}(T*-T_\infty*) \tag{3}$$

Concentration equation:

$$\frac{\partial C^*}{\partial t^*}+v^*\frac{\partial C^*}{\partial y^*}=D\frac{\partial^2 C^*}{\partial y^{*2}}-K_1C^* \tag{4}$$

where u^* and v^* are longitudinal and normal components of velocity along x^* and y^* directions, g the acceleration due to gravity, β the coefficient of thermal expansion , β^* the coefficient of species concentration expansion, T^* the temperature, C^* the concentration, υ the kinematic viscosity, ρ the density, κ the thermal conductivity, c_p the specific heat at constant pressure, σ the electrical conductivity, B_0 is magnetic field intensity, D the coefficient of mass diffusion, K_1 the rate of chemical reaction, Q^* the volumetric rate of heat generation/absorption, K^* and $q_r{}^*$ are permeability and heat flux respectively.

The radiative heat flux $q_r{}^*$ is given by Cogley et al.[19]:

$$\frac{\partial q_r{}^*}{\partial y^*}=4\,(T^*-T_\infty{}^*)\;I^* \tag{5}$$

where $I^*=\int_0^\infty K_{\lambda w}.\frac{\partial e_{b\lambda}}{\partial T^*}d\lambda$, $K_{\lambda w}$ is the absorption coefficient at the wall and $e_{b\lambda}$ is plank function

The initial and boundary conditions are as follows:

$$\left.\begin{array}{l}
t^*\le 0: u^*=0,\ T^*=T_\infty{}^*,\ C^*=C_\infty{}^*\ \ \forall\, y^* \\
t^*>0\ : u^*=\dfrac{u_0{}^{*3}}{v}t^*,\ \ T^*=T_\infty{}^*+(T_w{}^*-T_\infty{}^*)At^*, \\
\qquad\qquad C^*=C_\infty{}^*+(C_w{}^*-C_\infty{}^*)At^*\quad at\ y^*=0 \\
u^*=0\ ,\ T^*=T_\infty{}^*\ ,\ C^*=C_\infty{}^*\ \ as\ \ y^*\to\infty\qquad \text{where } A=\dfrac{u_0{}^{*2}}{v}.
\end{array}\right\} \tag{6}$$

To reduce the above equations into non-dimensional form, introducing the following dimensionless quantities:

$$y=\frac{y^*u_0{}^*}{\upsilon},\quad t=\frac{t^*u_0{}^{*2}}{\upsilon},\ u=\frac{u^*}{u_0{}^*},\ v=\frac{v^*}{u_0{}^*},\ \theta=\frac{(T^*-T_\infty{}^*)}{(T_w{}^*-T_\infty{}^*)},\ C=\frac{(C^*-C_\infty{}^*)}{(C_w{}^*-C_\infty{}^*)}$$

the above equations reduced to

$$\frac{\partial v}{\partial y} = 0 \tag{7}$$

$$\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + Gr\cdot\theta + Gc\cdot C - \frac{u}{K_0} - mu \tag{8}$$

$$\frac{\partial \theta}{\partial t} + v\frac{\partial \theta}{\partial y} = \frac{1}{Pr}\frac{\partial^2 \theta}{\partial y^2} - F.\theta + Q.\theta \tag{9}$$

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} - kC \tag{10}$$

and the initial and boundary conditions in non-dimensional form are

$$\left.\begin{array}{l} t \le 0 : u = 0,\ \theta = 0,\ C = 0 \quad \forall\, y \\ t > 0 : u = t,\ \theta = t,\ C = t \quad at\ y = 0 \\ \qquad u = 0,\ \theta = 0,\ C = 0 \quad as\ y \to \infty \end{array}\right\} \tag{11}$$

where

$$Gr = \frac{\upsilon g \beta (T_w^* - T_\infty^*)}{u_0 *^3}\ (Grashof\ number),\quad K_0 = \frac{u_0 *^2 K*}{\upsilon^2}\ (Permeability\ parameter),$$

$$Gc = \frac{\upsilon g \beta^* (C_w^* - C_\infty^*)}{u_0 *^3}\ (Modified\ Grashof\ number),\quad Pr = \frac{\mu c_p}{\kappa}\ (Prandtl\ number),$$

$$F = \frac{4\upsilon I*}{\rho c_P u_0 *^2}\ (Radiation\ parameter),\quad Q = \frac{4\upsilon Q_0 *}{\rho c_P u_0 *^2}\ (Heat\ generation\ /\ absorption\ parameter)$$

$$k = \frac{K_1 v}{u_0 *^2}(Chemical\ reaction\ paramter),\quad m = \frac{\sigma B_0^2 \upsilon}{\rho u_0 *^2}\ (Magnetic\ parameter),$$

$$Sc = \frac{v}{D}(Schmidt\ number).$$

Integrating equation (7), we obtain

$$v = -\frac{a}{\sqrt{t}} \tag{12}$$

where a is suction/injection parameter. It may be noted that for suction $a > 0$, for injection $a < 0$ and for impermeable plate $a = 0$.

For solution of momentum equation (8), energy equation (9) and concentration equation (10), the similar solution is not feasible and therefore we see a series solution by expanding u, θ and C in terms of power series (Mt), called magnetic interaction parameter, which is considered to be small i.e. Mt <<1]:

$$\left.\begin{aligned} u(y,t) &= t\cdot\sum_{i=0}^{\infty}(Mt)^i f_i(\eta), \quad \theta(y,t) = t\cdot\sum_{i=0}^{\infty}(Mt)^i\theta_i(\eta) \\ C(y,t) &= t\cdot\sum_{i=0}^{\infty}(Mt)^i C_i(\eta), \qquad \eta = \frac{y}{2\sqrt{t}} \end{aligned}\right\} \tag{13}$$

Then, equating the like powers of (Mt) equations (7) to (10) are reduced to the following set of ordinary differential equations

$$Sc^{-1}.C_0'' + 2(a+\eta)C_0' - 4C_0 = 0, \tag{14}$$

$$Pr^{-1}.\theta_0'' + 2(a+\eta)\theta_0' - 4\theta_0 = 0, \tag{15}$$

$$f_0'' + 2(a+\eta) f_0' - 4 f_0 = 0, \tag{16}$$

$$Pr^{-1}\theta_1'' + 2(a+\eta)\theta_1' - 8\theta_1 - \frac{4\cdot F}{m}\theta_0 + \frac{4\cdot Q}{m}\theta_0 = 0, \tag{17}$$

$$Sc^{-1}C_1'' + 2(a+\eta)C_1' - 8C_1 - \frac{4\cdot k}{m}C_0 = 0, \tag{18}$$

$$f_1'' + 2(a+\eta) f_1' - 8 f_1 + \frac{4\cdot Gr}{m}\theta_0 + \frac{4\cdot Gc}{m}C - 4\left(1+\frac{1}{mK_0}\right) f_0 = 0, \tag{19}$$

$$Pr^{-1}\theta_i'' + 2(a+\eta)\theta_i' - 4\cdot(i+1)\cdot\theta_i - \frac{4\cdot F}{m}\theta_{i-1} + \frac{4\cdot Q}{m}\theta_{i-1} = 0, \quad i \ge 2 \tag{20}$$

$$Sc^{-1}C_i'' + 2(a+\eta)C_i' - 4\cdot(i+1)\cdot C_i - \frac{4\cdot k}{m}C_{i-1} = 0, \quad i \ge 2 \tag{21}$$

$$f_i'' + 2(a+\eta) f_i' - 4\cdot(i+1)\cdot f_i + \frac{4\cdot Gr}{m}\theta_{i-1} + \frac{4\cdot Gc}{m}C_{i-1} - 4\left(1+\frac{1}{mK_0}\right) f_{i-1} = 0, \quad i \ge 2 \tag{22}$$

with the initial conditions

$$\left.\begin{aligned} &\eta = 0 \quad : \theta_0 = 1, C_0 = 1, \ f_0 = 1, \ \theta_i = 0, \ C_i = 0, \ f_i = 0, \quad \forall \ i \ge 1 \\ &\eta \to \infty : \ \theta_i = 0, \ C_i = 0, \ f_i = 0, \ \forall \ i \ge 0 \end{aligned}\right\} \tag{23}$$

The main physical quantity of interest is skin-friction coefficient C_f, Nusselt number *Nu* and Sherwood number *Sh* which are defined as

$$C_f = \sqrt{t}\ \sum_{i=0}^{\infty}(Mt)^i\ f_i{}'(0),\ Nu = -\sqrt{t}\ \sum_{i=0}^{\infty}(Mt)^i\ \theta_i{}'(0) \text{ and } C_f = -\sqrt{t}\ \sum_{i=0}^{\infty}(Mt)^i\ C_i{}'(0)$$

3. SOLUTION OF THE PROBLEM

In order to obtain analytical solutions of the system of differential equations we are using repeated integrals of complementary error functions. The homogenous parts of the above system of differential equation admit solutions in terms of repeated integrals of complementary error functions (See Abramowitz and Stegun[20]). For non-homogenous part of equation (14) and (21), the particular integrals are calculated by the method of undetermined coefficients. The equations (14) to (21), subject to the boundary conditions (22) are derived as follows:

$$C_0(\xi) = \frac{i^2 .erf_c(\sqrt{Sc}.\xi)}{i^2 erf_c(\sqrt{Sc}.a)}, \qquad \xi = \eta + a$$

$$\theta_0(\xi) = \frac{i^2 .erf_c(\sqrt{Pr}.\xi)}{i^2 erf_c(\sqrt{Pr}.a)},$$

$$f_0(\xi) = \frac{i^2 erf_c(\xi)}{i^2 erf_c(a)},$$

$$\theta_1 = \left(\frac{F}{m} + \frac{Q}{m}\right)\left(\frac{i^4 erf_c(\sqrt{Pr}\cdot\xi)}{i^4 erf_c(\sqrt{Pr}\cdot a)} - \frac{i^2 erf_c(\sqrt{Pr}\cdot\xi)}{i^2 erf_c(\sqrt{Pr}\cdot a)}\right),$$

$$C_1 = \frac{k}{m}\left(\frac{i^4 erf_c(\sqrt{Sc}\cdot\xi)}{i^4 erf_c(\sqrt{Sc}\cdot a)} - \frac{i^2 erf_c(\sqrt{Sc}\cdot\xi)}{i^2 erf_c(\sqrt{Sc}\cdot a)}\right),$$

$$f_1 = Z i^4 erf_c(\xi) - \left(1 + \frac{1}{m K_0}\right)\frac{i^2 erf_c(\xi)}{i^2 erf_c(a)} - \frac{4\cdot Gr\cdot i^4 erf_c(\sqrt{Pr}.\xi)}{m(Pr-1)\, i^2 erf_c(\sqrt{Pr}.a)} - \frac{4\cdot Gc\cdot i^4 erf_c(\sqrt{Sc}.\xi)}{m(Sc-1)\, i^2 erf_c(\sqrt{Sc}.a)},$$

where

$$Z = \frac{4\cdot Gr\cdot i^4 erf_c(\sqrt{Pr}.a)}{m(Pr-1)\, i^2 erf_c(\sqrt{Pr}.a)\, i^4 erf_c(a)} + \frac{4\cdot Gc\cdot i^4 erf_c(\sqrt{Sc}.a)}{m(Sc-1)\, i^2 erf_c(\sqrt{Sc}.a)\, i^4 erf_c(a)} + \left(1 + \frac{1}{m K_0}\right)\frac{1}{i^4 erf_c(a)}$$

An exact solution of all the equation is obtained when $Pr \neq 1$ and $Sc \neq 1$. In the case of Pr =1 and Sc =1, we take the limiting values and find

$$C_0 = \frac{i^2 erf_c(\xi)}{i^2 erf_c(a)},$$

$$\theta_0 = \frac{i^2 erf_c(\xi)}{i^2 erf_c(a)},$$

$$\theta_1 = \left(\frac{F}{m} + \frac{Q}{m}\right)\left(\frac{i^4 erf_c(\xi)}{i^4 erf_c(a)} - \frac{i^2 erf_c(\xi)}{i^2 erf_c(a)}\right),$$

$$C_1 = \frac{k}{m}\left(\frac{i^4 erf_c(\xi)}{i^4 erf_c(a)} - \frac{i^2 erf_c(\xi)}{i^2 erf_c(a)}\right),$$

$$f_1 = \left(1 + \frac{1}{mK_0} - \frac{Gr}{m} - \frac{Gc}{m}\right)\frac{i^4 erf_c(\xi)}{i^4 erf_c(a)} - \left(1 + \frac{1}{mK_0} - \frac{Gr}{m} - \frac{Gc}{m}\right)\frac{i^2 erf_c(\xi)}{i^2 erf_c(a)}$$

The function $i^n erf_c(\xi)$ is the repeated integral of complementary error function defined as:

$$i^n erf_c(\xi) = \frac{2}{\sqrt{\pi}}\int_{\xi}^{\infty}\frac{(t-\xi)^n}{n!}\, e^{-t^2}\, dt, \;\; n = 0,1,2......$$

$$= \sum_{K=0}^{\infty}\frac{(-1)^K \xi^K}{2^{n-K} K!\,\Gamma\left(1 + \frac{n-K}{2}\right)}$$

$$i^{-1} erf_c(\xi) = \frac{2}{\sqrt{\pi}} e^{-\xi^2}, i^n erf_c(\xi) = erf_c(\xi) \text{ and } \frac{\partial}{\partial \xi} i^n erf_c(\xi) = -i^{n-1} erf_c(\xi)$$

and the recurrence relation is

$$i^{n-2} erf_c(\xi) - 2\xi\, i^{n-1} erf_c(\xi) - 2n i^n erf_c(\xi) = 0$$

For the numerical solution of all equations, the unknown initial values are identified by the Runge-Kutta-Gill integration scheme method, with a step size of 0.01. To validate the results, the numerical solution is then compared with exact solution, which is obtained by repeated integrals of complementary error function we see that the results obtained by both the method are in a good agreement.

4. RESULTS AND DISCUSSION

Numerical results for the velocity, temperature and concentration functions with skin friction co-efficient, rate of heat and mass transfer are calculated for different values of the parameters. We have chosen the different values of Schmidt number *Sc* i.e. 0.30, 0.60 and 2.62 which represent the diffusing chemical species of most common interest in air, namely- He, H_2O and propyl benzene respectively (Perry [21]). The values of Prandtl number are chosen for air $Pr = 0.72$, electrolyte solution $Pr = 1.0$ and water $Pr = 7.0$. The chemical reaction parameter k has values either $k > 0$, $k < 0$ and $k = 0$ refers to destructive, generative and no reaction respectively.

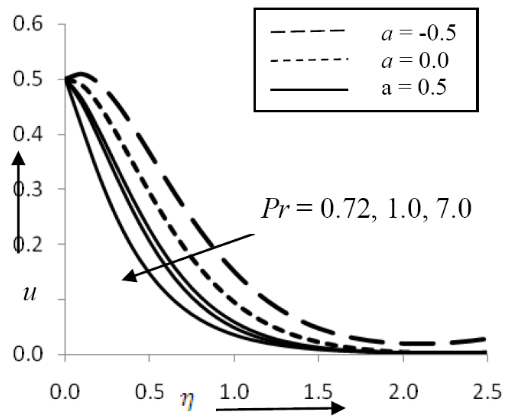

Fig. 1 Velocity profiles for different values of Prandtl number and suction/injection parameter

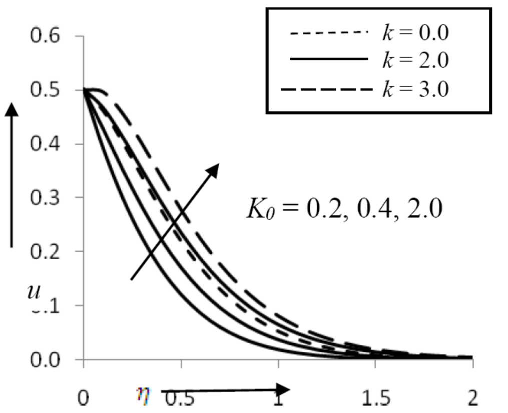

Fig. 2 Velocity profiles for different values of chemical reaction and permeability parameter

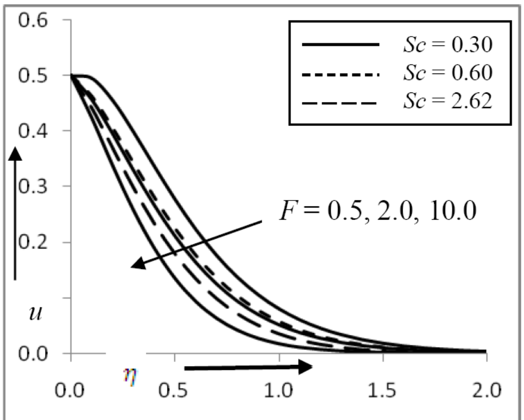

Fig. 3 Velocity profiles for different values of Schmidt number and radiation parameter

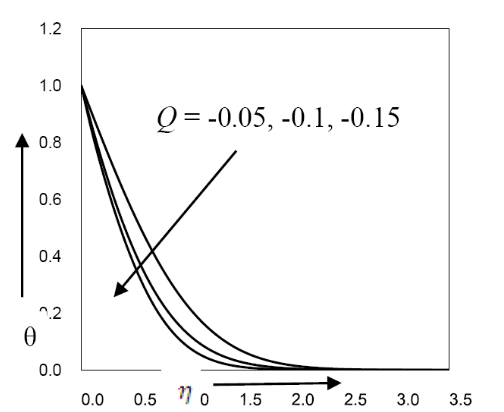

Fig. 4 Temperature profiles for different values of heat absorption/generation parameter

The effects of *Pr, a, Sc, F, k,* K_0 on velocity field *u* have been shown in the Fig. 1 to Fig. 3. It is observed from these figures that an increase in Prandtl number *Pr*, suction parameter *a*, Schmidt number *Sc* and radiation parameter *F* decreases the velocity when the plate is cooled by the free convection currents ($Gr > 0$). Further, it is interesting to note that velocity increases as chemical reaction parameter k or permeability parameter K_0 increases.

In Fig. 4 the temperature function θ is plotted against the variable η for different values of heat generation/absorption parameter Q taking other parameter fixed. It is observed that fluid temperature increases due to increase in the volumetric rate of heat generation, while it decreases in the case of volumetric rate of heat absorption or sink parameter.

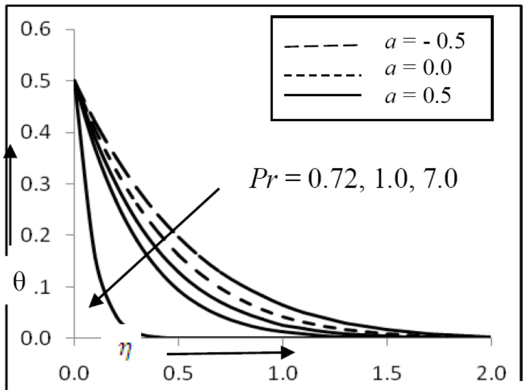

Fig. 5 Temperature profiles for different values of Prandtl number and suction/injection

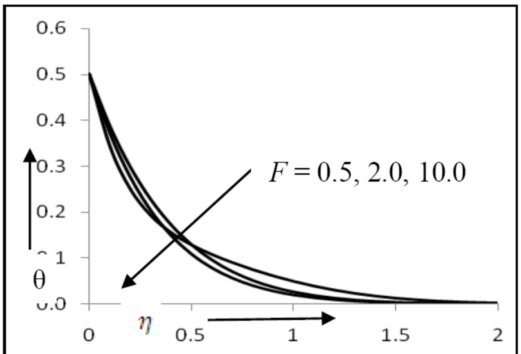

Fig. 6 Temperature profiles for different values of radiation parameter

In Fig. 5 the temperature function θ is plotted against the variable η for different values of suction/injection parameter a and Prandtl number Pr taking other parameter fixed. It may be noted that the temperature decreases as a or Pr increases. The effect of radiation parameter is important in temperature profiles. Fig. 6 shows that the temperature increases with decreasing radiation parameter. It is found that an increase in the thermal radiation leads to decrease in temperature boundary layer.

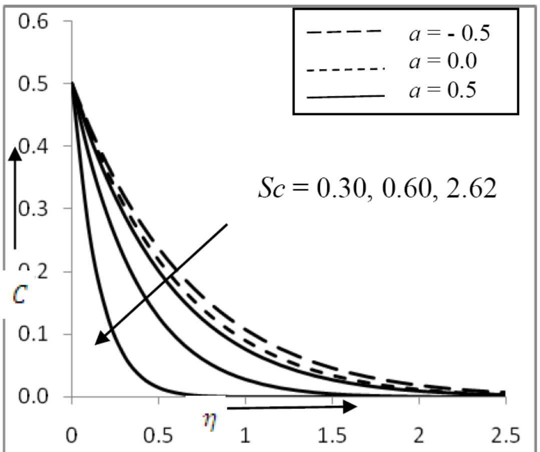

Fig. 7 Concentration profiles for different values of Schmidt number and suction/injection

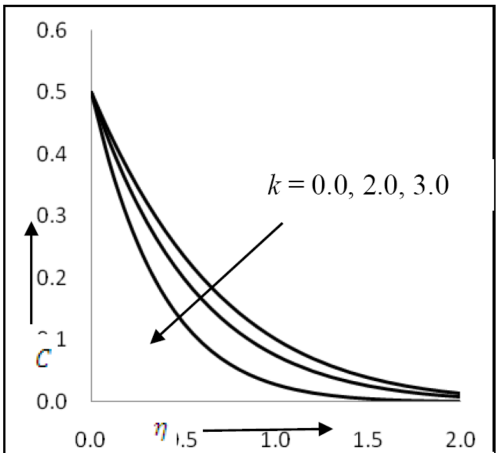

Fig. 8 Concentration profiles for different values of chemical reaction parameter

Figures 7 and 8 shows the concentration profiles against the variable η for different values of suction/injection parameter a, Schmidt number Sc and chemical reaction parameter *k* taking other parameter fixed. It may be noted that the concentration decreases as *a* or *Sc* increases. The effect of chemical reaction parameter is important in concentration profile. It is clearly seen from Fig. 8 that the concentration increases with decreasing chemical reaction parameter *k*. It is found that an increase in the rate of chemical reaction leads to decrease in the concentration boundary layer.

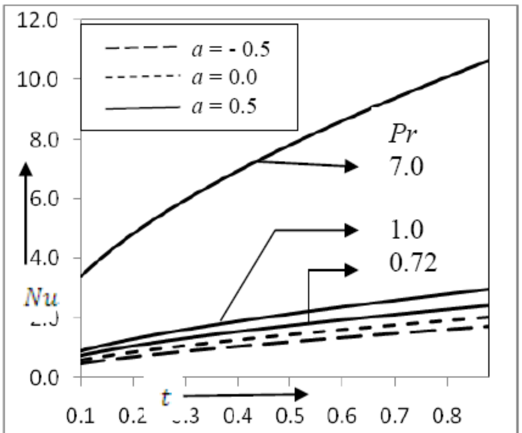

Fig. 9 Surface heat transfer graph for different values of Prandtl number and suction/injection

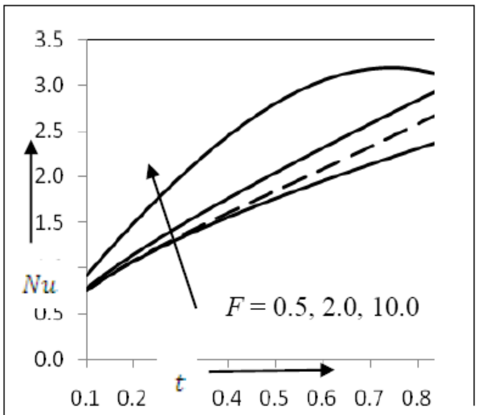

Fig. 10 Surface heat transfer graph for different values of magnetic and radiation parameter

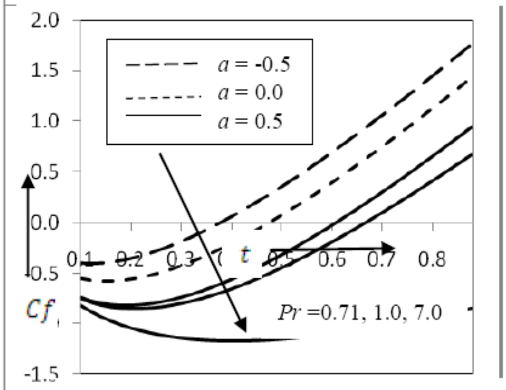

Fig. 11 Skin friction coefficient profiles for different values of Prandtl number and suction / injection parameter

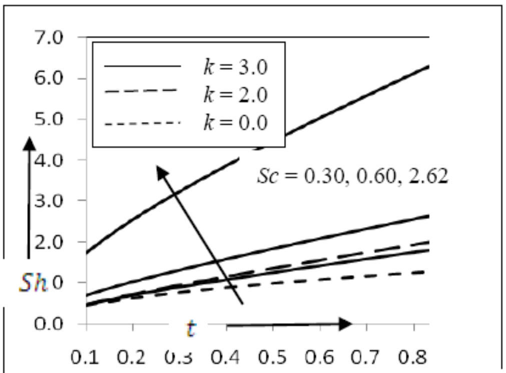

Fig. 12 Sherwood number profiles for different values of Schmidt number and chemical reaction

The dimensionless rate of heat transfer in terms of Nusselt number profiles for different values of *Pr, a, F* are shown in Figures 9 and 10. The rate of heat transfer increases with increasing Prandtl number or suction / injection or radiation parameter.

In figure 11, the skin-friction coefficient C_f profiles for different values of *a* and *Pr*, taking other parameters fixed. It is observed that C_f decreases with increase in the Prandtl number *Pr* or suction/injection parameter *a*. Figure 12 depict the dimensionless rate of mass transfer in terms of Sherwood number for different values of chemical reaction parameter, and Schmidt number. It is found that Sherwood number increases with increases of chemical reaction parameter or Schmidt number.

5. CONCLUSIONS

1. The skin-friction increases with decreasing radiation parameter and skin friction coefficient increase with increase in chemical reaction parameter.
2. The effect of radiation F is to decrease the velocity and temperature in the free convective boundary layer.
3. The rate of mass transfer in terms of Sherwood number increases as chemical reaction parameter or Schmidt number increases.
4. It is found that an increase in the thermal radiation leads to decrease in temperature boundary layer.
5. It is found that an increase in the rate of chemical reaction leads to decrease in the concentration boundary layer.
6. With the increase in permeability parameter K_0, increases the resistance of the porous medium, the velocity increases in the boundary layer.
7. The presence of heat absorption/generation parameter causes reduction in temperature profiles and hence reduces the thermal boundary layer thickness.

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