Effects of Thermophoresis and Chemical Reaction on Unsteady Hydro Magnetic Free Convection and Mass Transfer Flow Past an Impulsively Started Infinite Inclined Porous Plate in the Presence of Heat Generation/Absorption

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Abstract

In this paper, the effects of thermophoresis and chemical reaction on an unsteady hydro magnetic free convection and mass transfer flow past an impulsively started infinite inclined porous plate in the presence of heat generation or absorption is studied numerically. The similarity solution is used to transform the problem under consideration into a boundary value problem of coupled non-linear ordinary differential equations which are solved numerically by applying the Runge-Kutta sixth-order integration scheme together with Nachtsheim-Swigert shooting iteration technique. Dimensionless velocity, temperature and concentration profiles are displayed graphically for different physical parameters entering into the problem. Numerical results for the local skin-friction coefficient, wall heat transfer and particle deposition rate are obtained and presented graphically for various parametric conditions to show interesting aspects of the local similar solutions.

Keywords: Unsteady flow, Suction/injection, Thermophoresis, Chemical reaction, Heat generation/absorption.

1. Introduction

Thermophoresis is the term describing the phenomenon wherein small size particles, such as soot particles, aerosols or the like, when suspended in a gas in which there exists a temperature gradient, experience a force in the direction opposite to that of the temperature gradient. The velocity acquired by the particles is called the thermophoretic velocity and the force experienced by the suspended particles due to the temperature gradienf is known as the thermophoretic force. A common example of this phenomenon is the blackening of the glass globe of a kerosene lantern; the temperature gradient established between the flame and the globe drives the carbon particles produced in the combustion process towards the globe, where they deposit. Thermophoresis is of practical importance in many industrial applications, such as in thermal precipitators, which are sometimes more effective than electrostatic precipitators in removing submicron-sized particles from gas streams. Epstein et al. [1] analyzed the thermophoretic deposition of particles from a vertical plate in free convection boundary layer flow. The thermophoretic transport of small particles in forced convection flow over inclined plates was studied by Garg and Jayaraj [2]. Chiou [3] analyzed the effect of thermophoresis

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on submicron particle deposition from a forced laminar boundary layer flow onto an isothermal moving plate through similarity solutions. Recently, Chamkha and Pop [4] investigated the effect of thermophoresis particle deposition in a free convection boundary layer from a vertical flat plate embedded in a porous media. Very recently, Wang [5] studied the combined effects of inertia, diffusion and thermophoresis on particle deposition from a stagnation point flow onto an axisymmetric wavy wafer.

However, in many industrial processes involving heat and mass transfer over a moving surface, the diffusion species can be generated or absorbed due to chemical reaction with ambient fluid. Das et al. [6] studied the effect of a homogeneous first order chemical reaction on the flow past an impulsively started infinite vertical plate with uniform heat flux and mass transfer. A similarity solution for a mixed convection with diffusion and chemical reaction over a horizontal moving plate was studied by Fan et al. [7]. Recently, Seddeek [8] studied the effects of chemical reaction, thermophoresis and variable viscosity on steady hydro magnetic flow with heat and mass transfer over a flat plate in the presence of heat generation/absorption. Very recently, Muthucumaraswamy et al. [9] studied the first order chemical reaction on the radiative heat and mass transfer flow past an impulsively started infinite isothermal vertical plate.

Therefore, the objective of the present paper is to study the effects of thermophoresis and first order chemical reaction on an unsteady hydro magnetic free convection and mass transfer flow past an impulsively started infinite inclined plate in the presence of heat generation or absorption.

2.Governing equations and similarity analysis

An unsteady hydro magnetic free convection and mass transfer flow of an electrically conducting incompressible viscous fluid past an infinite inclined porous flat plate with an acute angle α to the vertical is considered. The flow is assumed to be in the x-direction, which is taken along the inclined plate and y-axis normal to it. A magnetic field of uniform strength B_0 is introduced normal to the direction of the flow. Initially ($t = 0$) the plate and the fluid are at rest. But for time t>0, the plate starts moving impulsively in its own plane with a velocity U_0, its temperature is raised to T_w which is higher than the ambient temperature T_∞. The species concentration at the surface is maintained uniform at C_w, which is taken to be zero, and that of the ambient fluid is assumed to be C_∞. The physical model and coordinate system are shown in Fig.1.

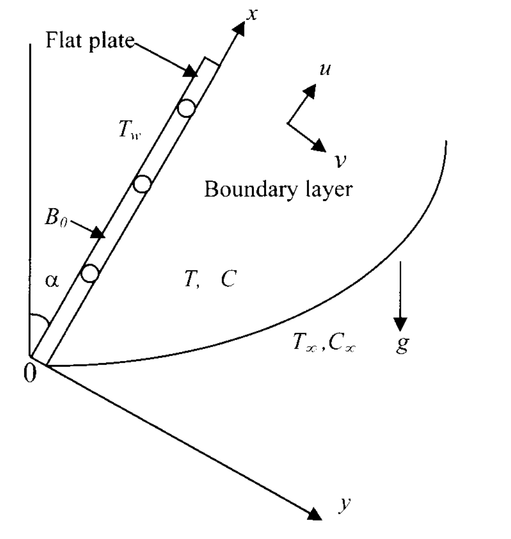


Fig. 1: Physical model and coordinate system.

Fluid suction or injection is imposed at the plate surface. A heat source or sink is placed within the flow to allow for possible heat generation or absorption effects. In addition, the effect of thermophoresis is taken into account as it helps in understanding mass deposition on a surface. We further assume that due to the boundary layer behavior the temperature gradient in the y direction is much larger than that in the x direction. Hence, only the thermophoretic velocity component which is normal to the surface is of importance, and there exists a homogeneous first order chemical reaction between the fluid and species concentration. Since the plate is infinite extended, all derivatives with respect to x are supposed to be zero. Hence, under the usual Boussinesq's and boundary-layer approximation, the governing equation for the conservation of mass, momentum, energy and concentration respectively are as follows:

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

$$\frac{\partial u}{\partial t}+v\frac{\partial u}{\partial y}=\upsilon\frac{\partial^2 u}{\partial y^2}+g\beta(T-T_\infty)\cos\alpha$$
$$-\frac{\sigma B_0^2}{\rho}u, \tag{2}$$
$$\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial y}=\frac{\lambda_g}{\rho c_p}\frac{\partial^2 T}{\partial y^2}+\frac{Q_0}{\rho c_p}(T-T_\infty)$$
$$+\frac{\mu}{\rho c_p}\left(\frac{\partial u}{\partial y}\right)^2+\frac{\sigma B_0^2}{\rho c_p}u^2, \tag{3}$$
$$\frac{\partial C}{\partial t}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-\frac{\partial}{\partial y}(V_T C)-K_l C, \tag{4}$$

with initial and boundary conditions:
for $t\le 0$: $u=v=0, T=T_\infty, C=C_\infty$ for all y.
for $t>0$:
$u=U_0, v=v(t), T=T_w, C=C_w=0$ at $y=0$,
$u=0, v=0, T=T_\infty, C=C_\infty$ as $y\to\infty$, (5)

where the variables and all physical quantities are defined in the nomenclature

In equation (4), the thermophoretic velocity V_T can be expressed in the following form:

$$V_T=-k\upsilon\frac{\nabla T}{T_r}=-\frac{k\upsilon}{T_r}\frac{\partial T}{\partial y} \tag{6}$$

where T_r is some reference temperature and k is the thermophoretic coefficient which is defined as (see Selim et al. [10]) :

$$k=\frac{2C_s(\lambda_g/\lambda_p+C_t Kn)[1+Kn(C_1+C_2 e^{-C_3/Kn})]}{(1+3C_m Kn)(1+2\lambda_g/\lambda_p+2C_t Kn)} \tag{7}$$

where C_1, C_2, C_3, C_m, C_s, C_t are constants, λ_g and λ_p are the thermal conductivities of the fluid and diffused particles, respectively and Kn is the Knudsen number.

Now in order to obtain a local similarity solution in time of the problem under consideration, we introduce a time dependent length scale δ as

$$\delta=\delta(t). \tag{8}$$

In terms of this length scale, a convenient solution of the equation (1) is considered to be in the following form:

$$v=v(t)=-v_0\frac{\upsilon}{\delta}, \tag{9}$$

where v_0 is the dimensionless wall mass transfer coefficient which is positive for suction and negative for injection or blowing.
We now introduce the following dimensionless variables:

$$\left.\begin{aligned}&\eta=\frac{y}{\delta}, u=U_0 f(\eta),\\ &\theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty}, \phi(\eta)=\frac{C}{C_\infty}.\end{aligned}\right\} \tag{10}$$

Introducing the relations (8)-(10) into the equations (2), (3) and (4), respectively, we obtain (by using the analysis of Hasimoto [11], Sattar and Hossain [12] and Alam et al. [13]) the following dimensionless non-linear ordinary differential equations which are locally similar in time but not explicitly time dependent:

$$f''+(2\eta+v_0)f'+Gr\theta\cos\alpha-Mf=0, \tag{11}$$

$$\theta''+\Pr(2\eta+v_0)\theta'+\Pr Q\theta+\Pr Ec f'^2$$
$$+\Pr Ec Mf^2=0, \tag{12}$$

$$\phi''+Sc(2\eta+v_0)\phi'-\tau Sc(\phi\theta''+\phi'\theta')$$
$$-ScK\phi=0, \tag{13}$$

and the corresponding boundary conditions for $t>0$ are obtained as:

$f=1, \theta=1, \phi=0$ at $\eta=0$,
$f=0, \theta=0, \phi=1$ as $\eta\to\infty$. (14)

where $\Pr=\dfrac{\rho c_p \upsilon}{\lambda_g}$ is the Prandtl number, $Sc=\dfrac{\upsilon}{D}$ is the Schmidt number, $M=\dfrac{\sigma B_0^2\delta^2}{\upsilon\rho}$ is the local magnetic field parameter, $Gr=\dfrac{g\beta(T_w-T_\infty)\delta^2}{\upsilon U_0}$ is the local Grashof number, $Q=\dfrac{Q_0\delta^2}{\upsilon\rho c_p}$ is the local heat generation/absorption parameter, $Ec=\dfrac{U_0^2}{c_p(T_w-T_\infty)}$ is the Eckert number, $\tau=-\dfrac{k(T_w-T_\infty)}{T_r}$ is the thermophoretic parameter and $K=\dfrac{K_l\delta^2}{\upsilon}$ is the chemical reaction parameter.

The physical quantities of most interest for engineering applications in the present problem are the local skin-friction coefficient (Cf), the local Nusselt number (Nu) and the local Stanton number (St) which can be defined by the following expressions:

$$Cf=\frac{\tau_w}{\rho U_0^2},\ Nu=\frac{\delta q_w}{\lambda_g(T_w-T_\infty)}$$

and $St=-\dfrac{J_s}{U_0 C_\infty}$ respectively. (15)

Now the wall shear stress on the surface τ_w, rate of heat transfer q_w and rate of transfer of species concentration J_s are given by:

$$\tau_w=\left[\mu\frac{\partial u}{\partial y}\right]_{y=0},\ q_w=-\lambda_g\left[\frac{\partial T}{\partial y}\right]_{y=0}$$

and $J_s=-D\left[\dfrac{\partial C}{\partial y}\right]_{y=0}$. (16)

Using (10) and (16), we can write the quantities of (15) in the following form:

$$Cf\,\mathrm{Re}=f'(0),\ \ Nu=-\theta'(0),$$
and $St Sc\,\mathrm{Re}=\phi'(0)$ (17)

where Re is the local Reynolds number which is defined by $\mathrm{Re}=\dfrac{U_0\delta}{\upsilon}$.

3. Numerical solution

The set of nonlinear and locally similar ordinary differential equations (11)-(13) with boundary conditions (14) have been solved numerically by applying the Nachtsheim-Swigert [14] shooting iteration technique (for detailed discussion of the method see Maleque and Sattar [15] and Alam et al. [16]) along with the sixth order Runge-Kutta integration scheme. A step size of $\Delta\eta$ = 0.01 was selected to be satisfactory for a convergence criterion of 10^{-6} in all cases. The value of η_∞ was found at each iteration loop by the statement $\eta_\infty=\eta_\infty+\Delta\eta$. The maximum value of η_∞, for each group of parameters v_0, Q, Pr, Sc, M, Gr, Ec, K, τ and α is determined when the value of the unknown boundary conditions at η = 0 does not change for a successful loop with error less than 10^{-6}.

In order to see the effects of step size ($\Delta\eta$), we ran the code for our model with three different step sizes as $\Delta\eta$ = 0.01, $\Delta\eta$ = 0.005, $\Delta\eta$ = 0.001. In each case we found very good agreement among them. Fig. 2 shows the velocity profiles for different step sizes ($\Delta\eta$). From this figure we also see that the obtained solution is independent of the grid sizes. This leads to confidence of the numerical computations to be reported in the next section.

4. Results and discussion

In this section, a comprehensive set of numerical results is displayed graphically in Figs. 3-14 to illustrate the influence of the various physical parameters on the locally similar solutions.

Figs. 3(a)-(c) illustrate the effect of varying the wall mass transfer coefficient v_0 on the velocity, temperature and concentration profiles, respectively. The imposition of wall fluid suction ($v_0>0$) for this problem has the effect of reducing the entire hydrodynamic, thermal, as well as concentration, boundary layers growth. But for the case of wall fluid injection or blowing ($v_0<0$), opposite effects are observed compared to that of wall fluid suction. The decreasing thickness of the concentration layer is caused by two effects; (i) the direct action of suction, and (ii) the indirect action of suction causing a thinner thermal boundary layer, which corresponds to higher temperature gradients, a consequent increase in the thermophoretic force and higher concentration gradients.

The effect of heat generation or absorption coefficient Q on the velocity and temperature distributions is displayed in Figs. 4(a)-(b), respectively. As shown, increasing the values of Q produces increases in the velocity and temperature distributions of the fluid. This is expected since heat generation (Q>0) causes the thermal boundary layer to become thicker and the fluid to become warmer. In the case that

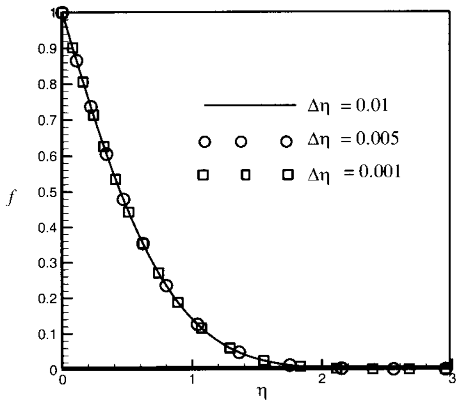
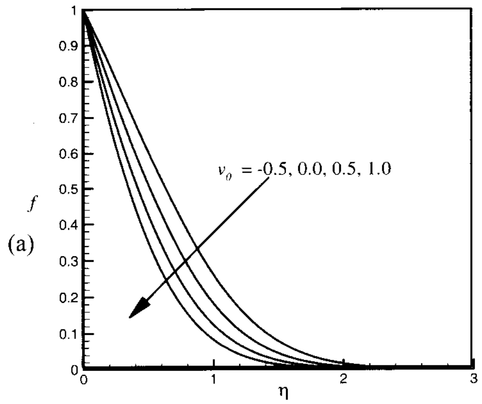
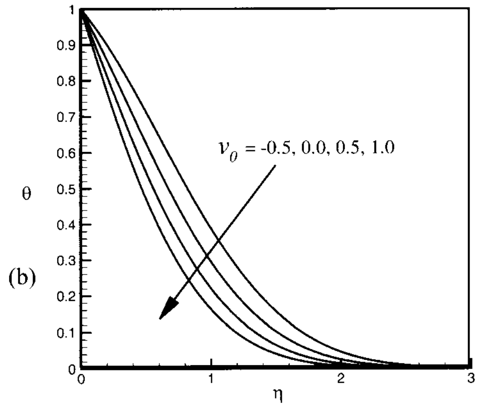


Fig. 2: Velocity profiles for different $\Delta\eta$.





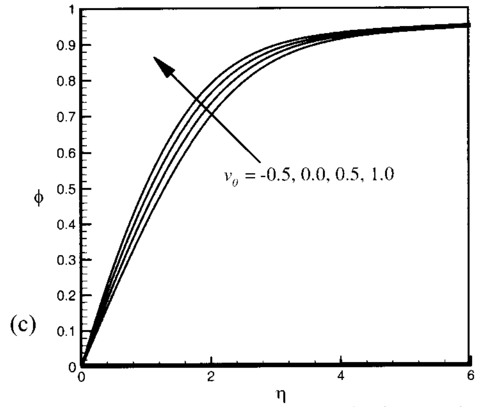
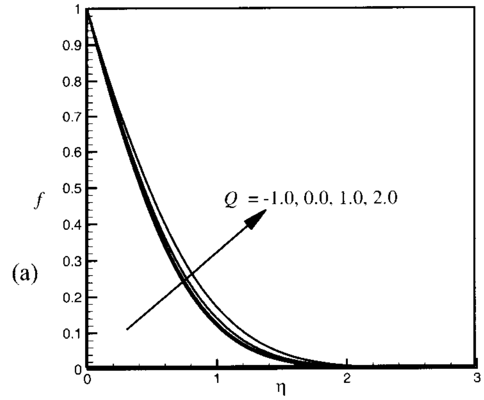


Fig. 3(a)-(c): Variation of dimensionless velocity, temperature and concentration profiles respectively for different values of v_0 and for Gr=6, Pr=0.71, Sc=0.30, M=0.5, Q=0.75, K=0.1, Ec=0.01, τ=1 and α=30^0.



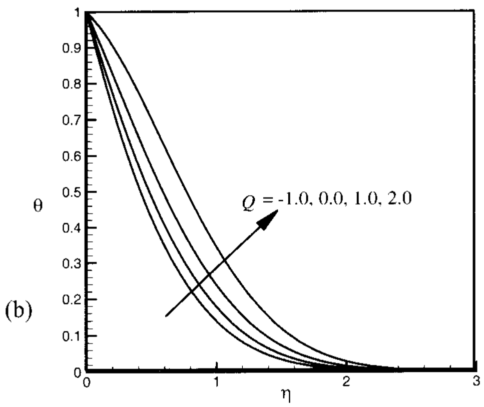


Fig. 4(a)-(b): Variation of dimensionless velocity, temperature and concentration profiles respectively for different values of Q and for Gr=6, Pr=0.71, Sc=0.30, M=0.5, v_0=0.75, K=0.1, Ec=0.01, τ=1 and α=30^0.

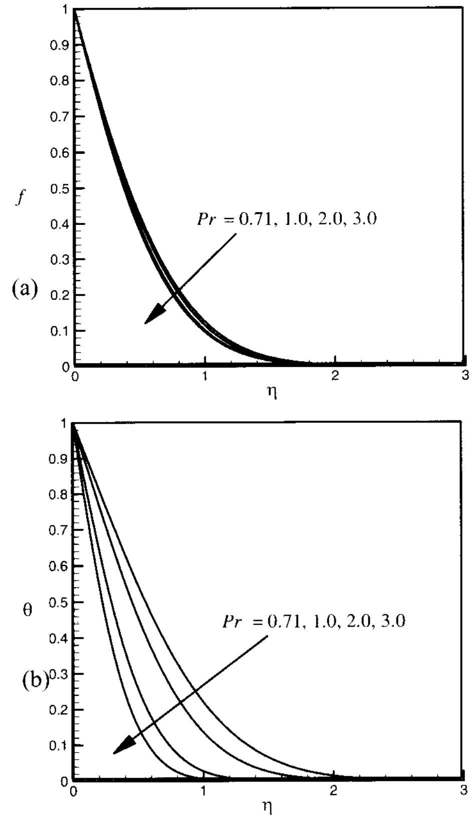


Fig. 5(a)-(b): Variation of dimensionless velocity, temperature and concentration profiles respectively for different values of Pr and for Gr=6, Q=0.75, Sc=0.30, M=0.5, v_0=0.50, K=0.1, Ec=0.01, τ=1 and α=30^0.

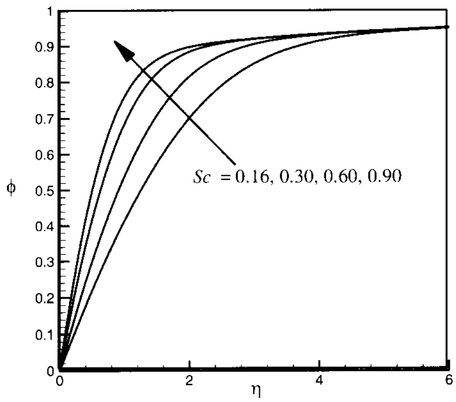


Fig. 6: Variation of dimensionless concentration profiles for different values of Sc and for Gr=6, Pr=0.71, Q=0.75, M=0.50, v_0=0.50, K=0.1, Ec=0.01, τ =1 and α=30^0.

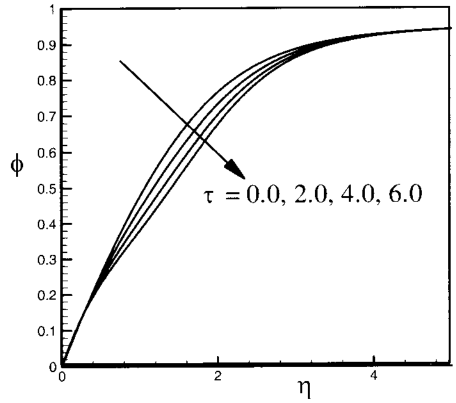


Fig. 7: Variation of dimensionless concentration profiles for different values of τ and for Gr=6, Pr=0.71, Sc=0.30, M=0.5, v_0=0.75, K=0.1, Ec=0.01, Q =0.75 and α=30^0.

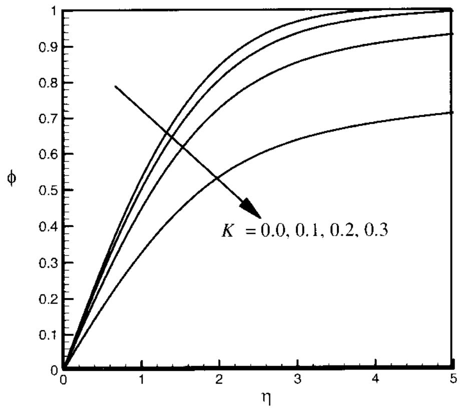


Fig. 8: Variation of dimensionless concentration profiles for different values of K and for Gr=6, Pr=0.71, Q=0.75, M=0.50, v_0=0.50, Sc=0.30, Ec=0.01, τ = 1 and α = 30^0.

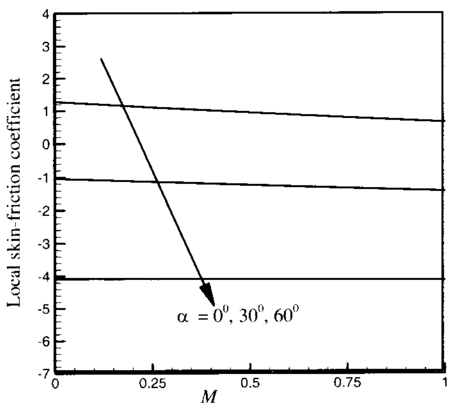


Fig. 9: Effects of M and α on the local skin-friction coefficient for Gr=6, Pr=0.71, Q=0.75, v_0=0.50, Sc=0.30, Ec=0.01, K= 0.1 and τ = 1.

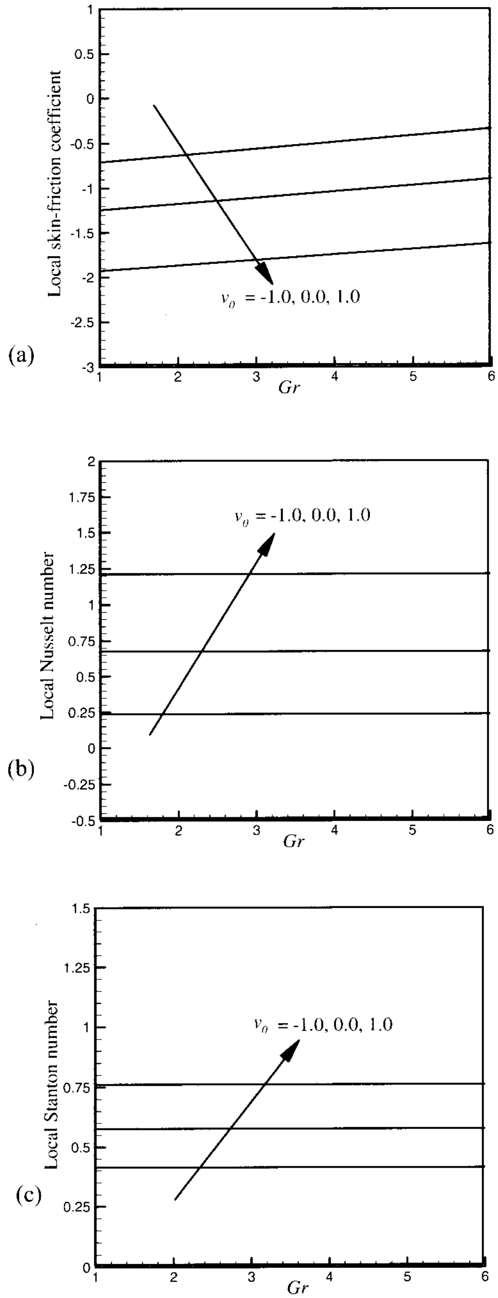


Fig. 10 (a)-(c): Effects of v_0 and Gr on local skin-friction coefficient, local Nusselt number and local Stanton number respectively for M=0.50, Pr=0.71, Q=0.75, Sc=0.30, Ec=0.01, K= 0.1, τ=1 and α=30^0.

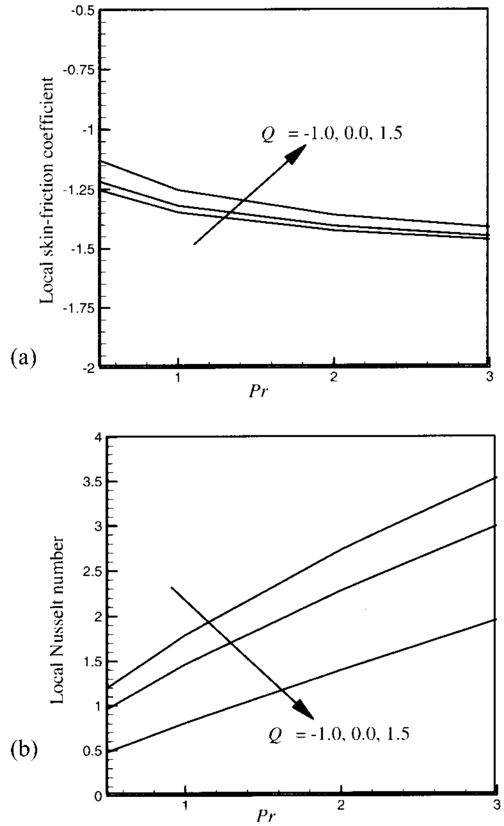


Fig. 11 (a)-(b): Effects of Pr and Q on local skin-friction coefficient and local Nusselt number respectively for Gr=6, v_0=0.50, M=0.50, Sc=0.30, Ec=0.01, K= 0.1, τ =1 and α=30^0.

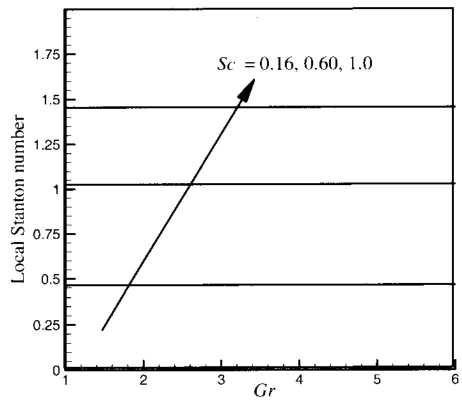


Fig. 12: Effects of Sc and Gr on local Stanton number for M=0.50, Pr=0.71, Q=0.75, v_0=0.50, Ec=0.01, K= 0.1, τ =1 and α=30^0.

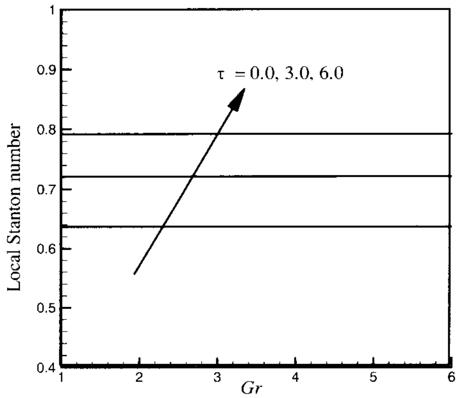


Fig. 13: Effects of τ and Gr on local Stanton number for M=0.50, Pr=0.71, Q=0.75, Sc=0.30, Ec=0.01, K= 0.1, v_0= 0.50 and α = 30^0.

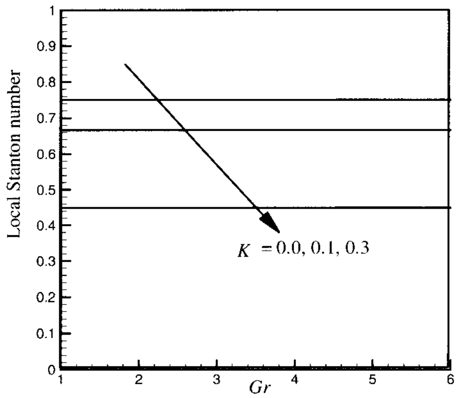


Fig. 14: Effects of K and Gr on local Stanton number for M=0.50, Pr=0.71, Q=0.75, Sc=0.30, Ec=0.01, v_0= 0.50, τ = 1 and α = 30^0.

the strength of the heat source is relatively large, the maximum fluid temperature does not occur at the wall, but rather in the fluid region close to it. Conversely, in the presence of a heat sink or heat absorption effect (Q< 0) there is a reduction in the thermal state of the fluid.

The effect of Prandtl number Pr on the velocity and temperature profiles is shown in Figs. 5(a)-(b) respectively. From these figures we observe that both the velocity and temperature profiles decrease monotonically with the increase of Pr.

The effects of the Schmidt number Sc , the thermophoretic parameter τ and the chemical reaction parameter K on the concentration profiles are shown in Figs. 6-8 respectively. It is clear from Fig. 6 that the concentration boundary layer thickness decreases as the Schmidt number Sc increases and this is analogous to the effect of increasing the Prandtl number on the thickness of a thermal boundary layer. For the parametric conditions used in Fig. 7, the effect of increasing the thermophoretic parameter τ is limited to increasing slightly the wall slope of the concentration profiles for η< 0.3, but decreasing the concentration for values of η> 0.3. From Fig. 8 we see that there is a fall in the concentration due to the increasing values of the chemical reaction parameter.

Fig. 9 reveals the combined effects of the magnetic field parameter M and the angle of inclination α to the vertical, on the local skin-friction coefficient. From this figure we observe that the local skin-friction coefficient is found to decrease due to an increase in the magnetic field strength when the angle of inclination α is fixed. This is expected, since the applied magnetic field tends to impede the flow motion and thus to reduce the surface friction force. From this figure we also observe that an increase in the angle of inclination produces a decrease in the buoyancy force and hence reduces the local skin-friction coefficient for all values of M.

Figs.10 (a)-(c) reveals the effects of suction/injection parameter v_0 and Grashof number Gr on the local skin-friction coefficient, the local Nusselt number and the local Stanton number, respectively. These figures confirm that the local skin-friction coefficient decreases, whereas both the local Nusselt number and the local Stanton number increase when the values of v_0 increase.

In Figs.11(a)-(b), the combined effects of Q and Pr on the local skin-friction coefficient and the local Nusselt number are respectively presented. From these figures we see that for fixed value of Pr, the local skin-friction coefficient increases, whereas the local Nusselt number decreases with the increasing values of Q. It is also found from these figures that the local skin-friction coefficient decreases, whereas the local Nusselt number increases significantly with the increasing values of Pr for all values of Q.

Finally Figs. 12-14 depict respectively, the effects of Schmidt number Sc, thermophoretic parameter τ and chemical reaction parameter K on the local Stanton number. From these figures we observe that the local Stanton number increases with the increasing values of both the

Schmidt number and thermophoretic parameter, whereas it decreases with the increasing values of the chemical reaction parameter.

Conclusions

In this paper, the effects of thermophoresis and chemical reaction on an unsteady hydro magnetic free convection and mass transfer flow past an impulsively started infinite inclined porous plate in the presence of heat generation or absorption is studied theoretically. A set of similarity equations governing the fluid velocity, temperature and particle mass concentration was obtained by using an appropriate similarity transformation. The dimensionless locally similar and non-linear ordinary differential equations are solved numerically by using the Nachtsheim-Swigert shooting iteration method. From the present numerical investigation we may conclude that all the hydrodynamic, thermal as well as concentration boundary layers decrease with the increasing values of suction parameter v_0. Both the velocity and temperature distributions increase with the increasing values of the heat generation parameter Q but opposite effects are observed for the case of Prandtl number Pr. The concentration boundary layer decreases with the increasing values of both the Schmidt number Sc and thermophoretic parameter τ, whereas it increases with the increasing values of the chemical reaction parameter K. The local skin-friction coefficient decreases with increasing values of magnetic field parameter, angle of inclination to the vertical, suction parameter as well as Prandtl number, whereas it increases with the increasing values of the Grashof number as well as heat generation parameter. The local Nusselt number increases with the increasing values of suction parameter as well as Prandtl number, whereas it decreases with the increasing values of the heat generation parameter. The local Stanton number increases with the increasing values of the suction parameter, Schmidt number, as well as, thermophoretic parameter whereas it decreases with the increasing values of the chemical reaction parameter. Finally it is expected that the present work can be used as a vehicle for understanding the thermophoresis particle deposition on heat and mass transfer produced in an unsteady laminar free convection boundary-layer flow past an infinite inclined porous plate in the presence of a magnetic field and a heat source.

Nomenclature

B_0 = applied magnetic field, [Wbm^{-2}]
C = concentration inside the boundary layer, [kgm^{-2}]
Cf = local skin-friction coefficient
c_p = specific heat at constant pressure, [$Jkg^{-1}K^{-1}$]
D = molecular diffusivity, [m^2s^{-1}]
f = dimensionless velocity, [ms^{-1}]
g = acceleration due to gravity, [ms^{-2}]
Gr = local Grashof number
k = thermophoretic coefficient
K_l = reaction rate constant
K = chemical reaction parameter
M = magnetic field parameter
Nu = local Nusselt number
Pr = Prandtl number
Q_0 = heat generation constant
Q = heat generation parameter
Sc = Schmidt number
St = local Stanton number
T = temperature inside the boundary layer, [K]
T_r = reference temperature, [K]
U_0 = uniform plate velocity, [ms^{-1}]
$v(t)$ = suction/injection velocity, [ms^{-1}]
V_T = thermophoretic velocity, [ms^{-1}]
u, v = velocity components in the x- and y-direction respectively, [ms^{-1}]
x, y = Cartesian coordinates along the plate and normal to it, [m]

Greek Symbols:

η = similarity variable
α = angle of inclination to the vertical
β = coefficient of thermal expansion
δ = time dependent length scale, [m]
λ_g = thermal conductivity of fluid, [$Wm^{-1}K^{-1}$]
τ = thermophoretic parameter
σ = electrical conductivity, [$m\,\Omega\,m^{-1}$]
ρ = density of the fluid, [kgm^{-3}]
μ = viscosity of the fluid, [Pa.s]
υ = kinematic viscosity, [m^2s^{-1}]
θ = dimensionless temperature
ϕ = dimensionless concentration

Subscripts:

w = condition at wall

∞ = condition at infinity

Superscript:

$'$ differentiation with respect to η

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