Similarity Solutions for Hydromagnetic Free Convective Heat and Mass Transfer Flow along a Semi-Infinite Permeable Inclined Flat Plate with Heat Generation and Thermophoresis

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Abstract. The problem of steady, two-dimensional, laminar, hydromagnetic flow with heat and mass transfer over a semi-infinite, permeable inclined flat plate in the presence of thermophoresis and heat generation is studied numerically. A similarity transformation is used to reduce the governing non-linear partial differential equations into ordinary ones. The obtained locally similar equations are then solved numerically by applying Nachtsheim-Swigert shooting iteration technique with sixth-order Runge-Kutta integration scheme. Comparisons with previously published work are performed and the results are found to be in very good agreement. Numerical results for the dimensionless velocity, temperature and concentration profiles as well as for the skin-friction coefficient, wall heat transfer and particle deposition rate are obtained and reported graphically for various values of the parameters entering into the problem.

Keywords: hydromagnetic flow, free convection, inclined plate, heat generation, thermophoresis.

1 Introduction

Thermophoresis is the term describing the fact that small micron sized particles suspended in a non-isothermal gas will acquire a velocity in the direction of decreasing temperature. The gas molecules coming from the hot side of the particles have a greater velocity than those coming from the cold side. The faster moving molecules collide with the particles more forcefully. This difference in momentum leads to the particle developing a velocity in the direction of the cooler temperature. The velocity acquired by the particles is called

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the thermophoretic velocity and the force experienced by the suspended particles due to the temperature gradient is known as the thermophoretic force. The magnitudes of the thermophoretic force and velocity are proportional to the temperature gradient and depend on many factors like thermal conductivity of aerosol particles and carrier gas. They also depend on the thermophoretic coefficient, the heat capacity of the gas and the Knudsen number. Thermophoresis causes small particles to deposit on cold surfaces.

The common example of this phenomenon is the blackening of glass globe of kerosene lanterns, chimneys and industrial furnace walls by carbon particles. Corrosion of heat cxchanger, which reduces heat transfer coefficient, and fouling of gas turbine blades are other examples of this phenomenon. Thermophoresis principle is utilized to manufacture graded index silicon dioxide and germanium dioxide optical fiber preforms used in the field of communications.

Thermophoresis phenomenon has many practical applications in removing small particles from gas streams, in determining exhaust gas particle trajectories from combustion devices, and in studying the particulate material deposition on turbine blades. It has been found that thermophoresis is the dominant mass transfer mechanism in the modified chemical vapor deposition (MCVD) process as currently used in the fabrication of optical fiber preforms. Thermophoretic deposition of radioactive particles is considered to be one of the important factors causing accidents in nuclear reactors.

Maxwell (cf. Kennard [1]) first investigates the physical process responsible for thermophoresis while explaining the radiometric effect. Goren [2] studied thermophoresis in laminar flow over a horizontal flat plate. He found the deposition of particles on cold plate and particles free layer thickness in hot plate case. Thermophoresis of particles in a heated boundary layer was studied by Talbot et al. [3]. Blasius series solution has been sought by Homsy et al. [4].Thermophoresis in natural convection for a cold vertical surface has been studied by Epstein et al. [5]. The thermophoretic deposition of the laminar slot jet on an inclined plate for hot, cold and adiabatic plate conditions with viscous dissipation effect were presented by Garg and Jayaraj [6]. Jia et al. [7] studied the interaction between radiation and thermophoresis in forced convection laminar boundary layer flow. Chiou [8] analyzed the effect of thermophoresis on submicron particle deposition from a forced laminar boundary layer flow on to an isothermal moving plate through similarity solutions. Recently, Selim et al. [9] studied the effect of thermophoresis and surface mass transfer on mixed convection flow past a heated vertical flat permeable plate.

The study of heat generation or absorption effects in moving fluids is important in view of several physical problems such as fluids undergoing exothermic or endothermic chemical reactions. In addition, natural convection with heat generation can be applied to combustion modeling. In light of these applications, Moalem [10] studied the effect of temperature dependent heat sources taking place in electrically heating on the heat transfer within a porous medium. Vajravelu and Nayfeh [11] reported on the hydromagnetic convection at a cone and a wedge in the presence of temperature dependent heat generation or absorption effects. Chamkha [12] studied the effect of heat generation or absorption on hydromagnetic three-dimensional free convection flow over a vertical stretching surface. Very recently, Rahman and Sattar [13] studied the effect of heat generation or absorption on convective flow of a micropolar fluid past a continuously moving vertical porous plate in presence of a magnetic field.

Therefore, the objective of this paper is to consider the effects of heat generation and thermophoresis on steady, laminar, hydromagnetic, two-dimensional flow with heat and mass transfer along a semi-infinite, permeable inclined flat surface.

2 Formulation of the problem

Consider the steady, laminar, hydromagnetic combined heat and mass transfer by natural convection flow along a continuously moving semi-infinite permeable flat plate that is inclined with an acute angle α from the vertical. With x-axis measured along the plate, a magnetic field of uniform strength B_0 is applied in the y direction which is normal to the flow direction. Fluid suction is imposed at the plate surface. A heat source is placed within the flow to allow for possible heat generation effects. The fluid is assumed to be Newtonian, electrically conducting and heat generating. The temperature of the surface is held uniform at 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 effects of thermophoresis are being taken into account to help in the understanding of the mass deposition variation on the surface. We further assume that (i) the mass flux of particles is sufficiently small so that the main stream velocity and temperature fields are not affected by the thermophysical processes experienced by the relatively small number of particles, (ii) due to the boundary layer behaviour the temperature gradient in the y direction is much larger than that in the x direction and hence only the thermophoretic velocity component which is normal to the surface is of importance, (iii) the fluid has constant kinematic viscosity and thermal diffusivity, and that the Boussinesq approximation may be adopted for steady laminar flow, (iv) the particle diffusivity is assumed to be constant, and the concentration of particles is sufficiently dilute to assume that particle coagulation in the boundary layer is negligible and (v) the magnetic Reynolds number is assumed to be small so that the induced magnetic field is negligible in comparison to the applied magnetic field.

Under the above assumptions, the governing equations (see Selim et al. [9] and Chen [14]) for this problem can be written as

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad \text{(continuity)}, \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} + g\beta(T - T_\infty)\cos\alpha - \frac{\sigma B_0^2}{\rho}u \quad \text{(momentum)}, \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\lambda_g}{\rho c_p}\frac{\partial^2 T}{\partial y^2} + \frac{Q_0}{\rho c_p}(T - T_\infty) \quad \text{(energy)}, \tag{3}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2} - \frac{\partial}{\partial y}(V_T C) \quad \text{(diffusion)}, \tag{4}$$

where u, v are the velocity components in the x and y directions respectively, ν is the kinematic viscosity, g is the acceleration due to gravity, ρ is the density of the fluid, β is the volumetric coefficient of thermal expansion, T, T_w and T_∞ are the temperature of the fluid inside the thermal boundary layer, the plate temperature and the fluid temperature in the free stream, respectively, while C, C_w and C_∞ are the corresponding concentrations, σ is the electrical conductivity, B_0 is the magnetic induction, λ_g is the thermal conductivity of fluid, c_p is the specific heat at constant pressure, Q_0 is the heat generation constant, D is the molecular diffusivity of the species concentration and V_T is the thermophoretic velocity.

The appropriate boundary conditions for the above model are as follows:

$$u = U_0, \quad v = \pm\, v_w(x), \quad T = T_w, \quad C = C_w = 0 \quad \text{at } y = 0, \tag{5a}$$

$$u = 0, \qquad T = T_\infty, \quad C = C_\infty \quad \text{as } y \to \infty, \tag{5b}$$

where U_0 is the uniform plate velocity and $v_w(x)$ represents the permeability of the porous surface where its sign indicates suction (< 0) or blowing (> 0). Here we confine our attention to the suction of the fluid through the porous surface and for these we also consider that the transpiration function variable $v_w(x)$ is of the order of $x^{-1/2}$.

The effect of thermophoresis is usually prescribed by means of an average velocity that a particle will acquire when exposed to a temperature gradient. For boundary layer analysis it is found that the temperature gradient along the plate is much lower than the temperature gradient normal to the surface, i.e., $\frac{\partial T}{\partial y} \gg \frac{\partial T}{\partial x}$. So the component of thermophoretic velocity along the plate is negligible compared to the component of its normal to the surface. As a result, the thermophoretic velocity V_T, which appears in equation (4), can be written as:

$$V_T = -k\nu \frac{\nabla T}{T_{ref}} = -\frac{k\nu}{T_{ref}} \frac{\partial T}{\partial y}, \tag{6}$$

where k is the thermophoretic coefficient which ranges in value from 0.2 to 1.2 as indicated by Batchelor and Shen [15] and is defined from the theory of Talbot et al. [3] by:

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

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.

A thermophoretic parameter τ can be defined (see Mills et al. [16] and Tsai [17]) as follows:

$$\tau = -\frac{k(T_w - T_\infty)}{T_{ref}}. \tag{8}$$

Typical values of τ are $0.01, 0.1$ and 1.0 corresponding to approximate values of $-k(T_w - T_\infty)$ equal to $3, 30$ and 300 K for a reference temperature of $T_{ref} = 300$ K.

In order to obtain similarity solution of the problem we introduce the following non-dimensional variables:

$$\eta = y\sqrt{\frac{U_0}{2\nu x}}, \quad \psi = \sqrt{2\nu x U_0} f(\eta), \quad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \quad \phi(\eta) = \frac{C}{C_\infty}, \tag{9a}$$

where ψ is the stream function that satisfies the continuity equation (1).

Since $u = \frac{\partial \psi}{\partial y}$ and $v = -\frac{\partial \psi}{\partial x}$ we have from equation (9a)

$$u = U_0 f' \quad \text{and} \quad v = -\sqrt{\frac{\nu U_0}{2x}}(f - \eta f'). \tag{9b}$$

Here prime denotes ordinary differentiation with respect to η.

Now substituting equation (9) in equations (2)–(4) we obtain the following ordinary differential equations which are locally similar:

$$f''' + ff'' + Gr\,\theta\cos\alpha - Mf' = 0, \tag{10}$$

$$\theta'' + Prf\theta' + Pr\,Q\,\theta = 0, \tag{11}$$

$$\phi'' + Sc\,(f - \tau\theta')\phi' - Sc\,\tau\phi\,\theta'' = 0. \tag{12}$$

The boundary conditions (5) then turn into

$$f = f_w, \quad f' = 1, \quad \theta = 1, \quad \phi = 0 \quad \text{at } \eta = 0, \tag{13a}$$

$$f' = 0, \quad \theta = 0, \quad \phi = 1 \quad \text{as } \eta \to \infty, \tag{13b}$$

where $f_w = -v_w(x)\sqrt{\frac{2x}{\nu U_0}}$ is the dimensionless wall mass transfer coefficient such that $f_w > 0$ indicates wall suction and $f_w < 0$ indicates wall injection.

The dimensionless parameters introduced in the above equations are defined as follows: $M = \frac{\sigma B_0^2 2x}{\rho U_0}$ is the local magnetic field parameter, $Gr = \frac{g\beta(T_w - T_\infty)2x}{U_0^2}$ is the local Grashof number, $Pr = \frac{\nu\rho c_p}{\lambda_g}$ is the Prandtl number, $Q = \frac{Q_0 2x}{\rho c_p U_0}$ is the local heat generation parameter, $Sc = \frac{\nu}{D}$ is the Schmidt number and $\tau = -\frac{k(T_w - T_\infty)}{T_{ref}}$ is the thermophoretic parameter.

The skin-friction coefficient, wall heat transfer coefficient (or local Nusselt number) and wall deposition flux (or the local Stanton number) are important physical parameters. These can be obtained from the following expressions:

$$Cf_x Re_x^{1/2} = \frac{\tau_w}{\rho U_0^2} = f''(0), \quad \tau_w = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0}, \tag{14}$$

$$Nu_x Re_x^{-1/2} = \frac{xq_w}{(T_w - T_\infty)\lambda_g} = -\frac{1}{2}\theta'(0), \quad q_w = -\lambda_g\left(\frac{\partial T}{\partial y}\right)_{y=0}, \tag{15}$$

$$St_x Sc Re_x^{1/2} = -\frac{J_s}{U_0 C_\infty} = \phi'(0), \quad J_s = -D\left(\frac{\partial C}{\partial y}\right)_{y=0}, \tag{16}$$

where $Re = \frac{U_0 2x}{\nu}$ is the local Reynolds number.

3 Numerical method

The set of nonlinear ordinary differential equations (10)–(12) with boundary conditions (13) have been solved numerically by applying Nachtsheim-Swigert [18] shooting iteration technique (for detailed discussion of the method see Alam [19], Maleque and Sattar

[20] and Alam et al. [21]) along with 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 to each iteration loop by the statement $\eta_\infty = \eta_\infty + \Delta\eta$. The maximum value of η_∞ to each group of parameters $M, Gr, Pr, Sc, Q, f_w, \tau$ and α determined when the value of the unknown boundary conditions at $\eta = 0$ not change to successful loop with error less than 10^{-6}. A representative set of numerical results is shown graphically in Figs. 1 to 6 to illustrate the influence of the various physical parameters on the solution.

Table 1 presents a comparison of the local Stanton number obtained in the present work and those obtained by Mills et al. [16] and Tsai [17]. It is clearly observed that very good agreement between the results exists. This lends confidence in the present numerical method.

Table 1. Comparison of local Stanton number with those of Mills et al. [16] and Tsai [17] for $Sc = 1000$, $Pr = 0.70$, $\alpha = 90^\circ$ and $Gr = M = Q = 0.0$

τ	f_w	Mills et al. [16]	Tsai [17]	Present work
0.01	1.0	0.7091	0.7100	0.7134
0.01	0.5	0.3559	0.3565	0.3519
0.01	0.0	0.0029	0.0029	0.0030
0.10	1.0	0.7265	0.7346	0.7274
0.10	0.5	0.3767	0.3810	0.3726
0.10	0.0	0.0277	0.0275	0.0278
1.00	1.0	0.8619	0.9134	0.8690
1.00	0.5	0.5346	0.5598	0.5547
1.00	0.0	0.2095	0.2063	0.2075

4 Results and discussion

Numerical calculations have been carried out for different values of M, Q, α, Sc, τ, and f_w and for fixed values of Gr and Pr. The value of Pr is taken to be 0.70 which correspond physically to air. Due to free convection problem positive large value of $Gr = 6$ is taken which correspond to a cooling problem that is generally encountered in nuclear engineering in connection with cooling of reactor. The values of Schmidt number Sc are taken for helium ($Sc{=}0.30$), water-vapour ($Sc{=}0.60$) and ammonia ($Sc{=}0.78$).

Figs. 1(a)–(c) present typical profiles for the velocity, temperature and concentration for various values of the magnetic field parameter M, respectively for a physical situation with heat generation and thermophoretic effect. The presence of a magnetic field normal to the flow in an electrically conducting fluid introduces a Lorentz force which acts against the flow. This resistive force tends to slow down the flow and hence the fluid velocity decreases with the increase of the magnetic field parameter as observed in Fig. 1(a). From Fig. 1(b) we see that the temperature profiles increase with the increase of the magnetic field parameter, which implies that the applied magnetic field tends to heat the fluid, and thus reduces the heat transfer from the wall. In Fig. 1(c), the effect of an applied magnetic field is found to decrease the concentration profiles, and hence increase the concentration boundary layer.

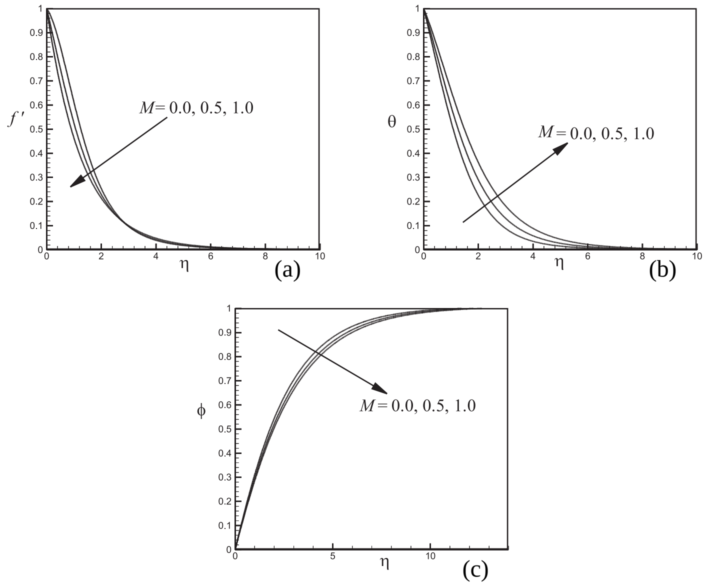

Fig. 1. Variation of dimensionless (a) velocity, (b) temperature and (c) concentration profiles across the boundary layer for different values of M and for $Gr = 6$, $Pr = 0.70$, $Sc = 0.60$, $Q = 0.50$, $f_w = 0.50$, $\tau = 0.1$ and $\alpha = 30°$.

Figs. 2(a)–(c) depict the influence of the dimensionless heat generation parameter Q on the fluid velocity, temperature and concentration profiles respectively. It is seen from Fig. 2(a) that when the heat is generated the buoyancy force increases, which induces the flow rate to increase giving, rise to the increase in the velocity profiles. From Fig. 2(b), we observe that when the value of the heat generation parameter Q increases, the temperature distribution also increases significantly which implies that owing to the presence of a heat source, the thermal state of the fluid increases causing the thermal boundary layer to increase. On the other hand, from Fig. 2(c) we see that the concentration profiles increase while the concentration boundary layer decreases as the heat generation parameter Q increases.

Representative velocity profiles for three typical angles of inclination ($\alpha = 0°, 20°$ and $30°$) are presented in Fig. 3(a). It is revealed from Fig. 3(a) that the velocity is decreased by increasing the angle of inclination. The fact is that as the angle of inclination increases the effect of the buoyancy force due to thermal diffusion decreases by a factor of $\cos\alpha$. Consequently the driving force to the fluid decreases as a result velocity profiles decrease. From Figs. 3(b), (c) we observe that both the thermal and concentration boundary layer thickness increase as the angle of inclination increases.

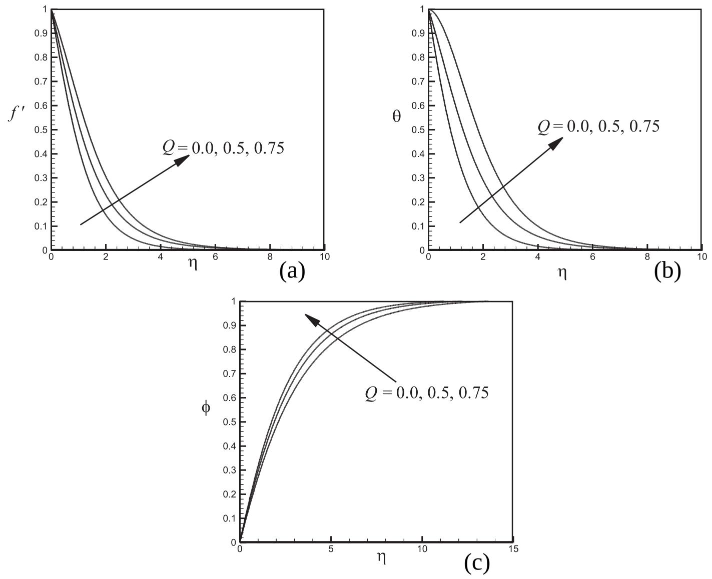

Fig. 2. Variation of dimensionless (a) velocity, (b) temperature and (c) concentration profiles across the boundary layer for different values of Q and for $Gr = 6$, $Pr = 0.70$, $Sc = 0.60$, $M = 0.50$, $f_w = 0.50$, $\tau = 0.1$ and $\alpha = 30°$.

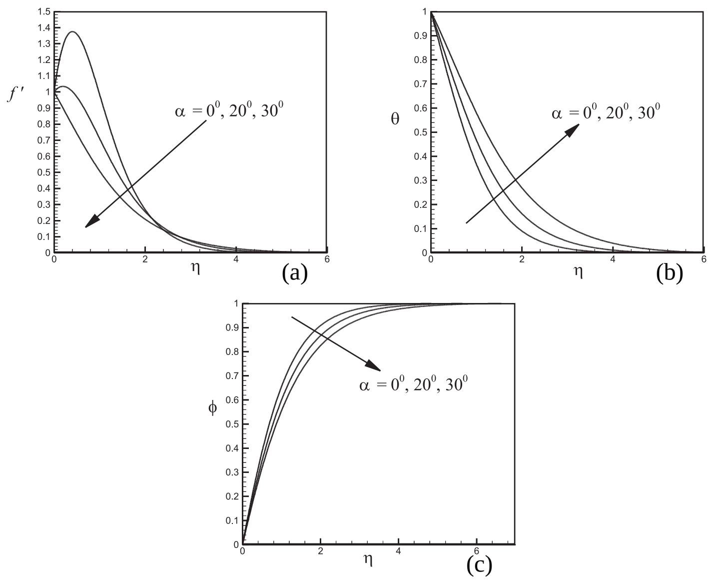

Fig. 3. Variation of dimensionless (a) velocity, (b) temperature and (c) concentration profiles across the boundary layer for different values of α and for $Gr = 6$, $Pr = 0.70$, $Sc = 0.60$, $Q = 0.50$, $f_w = 0.50$, $\tau = 0.1$ and $M = 0.5$.

Fig. 4(a) shows typical concentration profiles for various values of the Schmidt number Sc. It is clear from this figure that the concentration boundary layer thickness decreases as the Schmidt number Sc increases and this is the analogous to the effect of increasing the Prandtl number on the thickness of a thermal boundary layer.

The effect of thermophoretic parameter τ on the concentration field is shown in Fig. 4(b). For the parametric conditions used in Fig. 4(b), the effect of increasing the thermophoretic parameter τ is limited to increasing slightly the wall slope of the concentration profiles for $\eta < 0.5$ but decreasing the concentration for values of $\eta > 0.5$. This is true only for small values of Sc for which the Brownian diffusion effect is large compared to the convection effect. However, for large values of Sc ($Sc > 1000$) the diffusion effect is minimal compared to the convection effect and, therefore, the thermophoretic parameter τ is expected to alter the concentration boundary layer significantly. This is consistent with the work of Goren [2] on thermophoresis of aerosol particles in flat plate boundary layer.

In Fig. 4(c) we have shown the combined effect of thermophoretic parameter τ and Grashof number Gr on the wall deposition flux $St_x Sc Re_x^{1/2}$. From this figure we observe that for all values of Gr, the surface mass flux increases as the thermophoretic parameter τ increases. Free convection effect (i.e., the effect of Gr) is much clear from this figure.

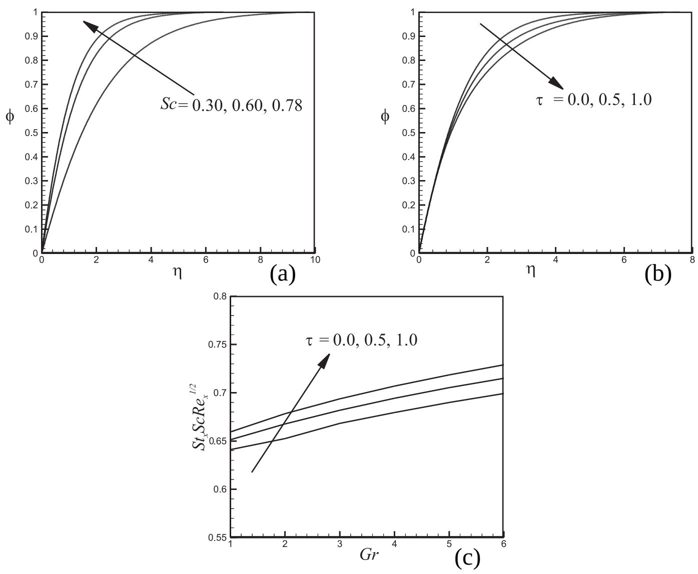

Fig. 4. Variation of dimensionless concentration profiles and wall deposition flux across the boundary layer for different values of (a) Sc ($Gr = 6$, $\tau = 0.1$); (b) τ ($Gr = 6$, $Sc = 0.60$); (c) τ and Gr ($Sc = 0.60$). $Pr = 0.70$, $Q = 0.50$, $f_w = 0.50$, $M = 0.5$ and $\alpha = 30°$.

In Figs. 5(a)–(c), the effects of Q and Pr on the skin-friction coefficient $Cf_x Re_x^{1/2}$, the wall heat transfer $Nu_x Re_x^{-1/2}$ and the wall deposition flux are respectively presented.

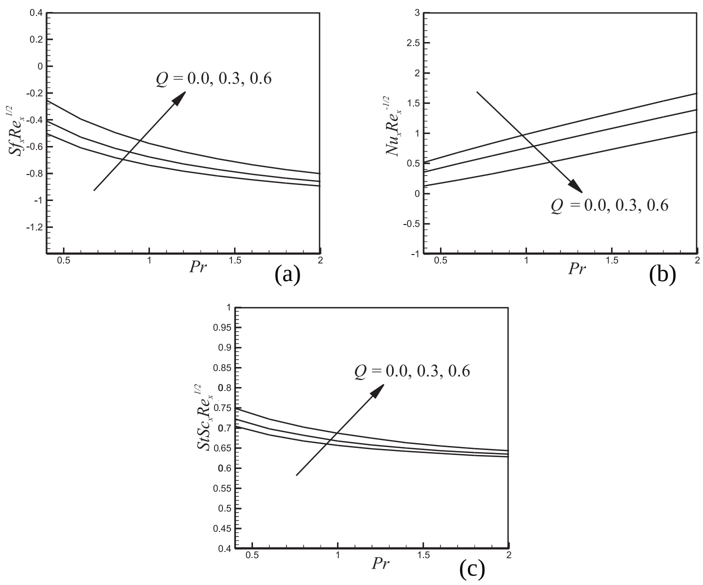

Fig. 5. Effects of Q and Pr on (a) skin-friction coefficient, (b) wall heat transfer and (c) wall deposition flux for $Gr = 6$, $\tau = 0.1$, $f_w = 0.50$, $Sc = 0.60$, $M = 0.5$ and $\alpha = 30°$.

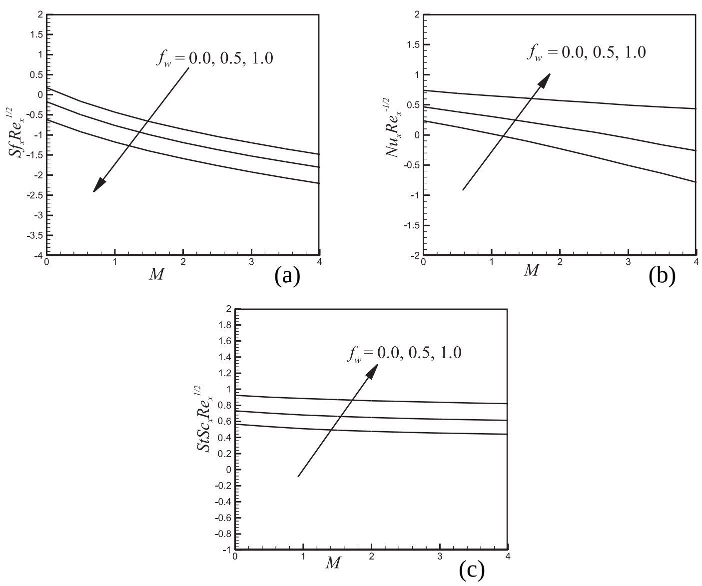

Fig. 6. Effects of M and f_w on (a) skin-friction coefficient, (b) wall heat transfer, (c) wall deposition flux for $Gr = 6$, $\tau = 0.1$, $Q = 0.50$, $Pr = 0.70$, $Sc = 0.60$ and $\alpha = 30°$.

From these figures we see that for fixed value of Pr, both the skin-friction coefficient and Stanton number increases whereas the Nusselt number decreases with the increase of the heat generation parameter Q.

Finally, the combined effects of magnetic field parameter M and suction parameter f_w on the skin-friction coefficient $Cf_xRe_x^{1/2}$, the wall heat transfer $Nu_xRe_x^{-1/2}$, and the wall deposition flux $St_xScRe_x^{1/2}$ are displayed in Figs. 6(a)–(c) respectively. From these figure we observe that for fixed value of the magnetic field parameter M, the skin-friction coefficient decreases whereas both the Nusselt number and the Stanton number increases as the suction parameter f_w increases.

5 Conclusions

In this paper we have studied numerically the effects of thermophoresis and heat generation on hydromagnetic free convection heat and mass transfer flow past a continuously moving semi-infinite inclined permeable plate. The particular conclusions drawn from this study can be listed as follows:

1. In the presence of a magnetic field, the fluid velocity is found to be decreased, associated with a reduction in the velocity gradient at the wall, and thus the local skin-friction coefficient decreases. Also, the applied magnetic field tends to decrease the wall temperature gradient and concentration gradient, which yield a decrease the local Nusselt number and the local Stanton number.

2. Increasing the angle of inclination has the effect to decrease the velocity boundary layer, but to increase the thermal and concentration boundary layers.

3. For a fixed magnetic field parameter, the local skin-friction was found to decrease whereas the local Nusselt and Stanton number was found to increase when the value of wall suction increases.

4. As the heat generation parameter increases, both the velocity and thermal boundary layer increases whereas concentration boundary layer decreases.

5. As the thermophoretic parameter τ increases, the surface mass flux also increases.

Finally it is hoped that the present work can be used as a vehicle for understanding the thermophoresis particle deposition on heat and mass transfer produced in steady, laminar boundary-layer flow past an inclined permeable surface in the presence of a magnetic field and heat generation.

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