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Radiation and mass transfer effects on unsteady MHD convective flow past an infinite vertical plate with Dufour and Soret effects

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Porous medium;
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Abstract This paper deals with the effects of heat and mass transfer on two-dimensional unsteady MHD free convection flow past a vertical porous plate in a porous medium in the presence of thermal radiation under the influence of Dufour and Soret effects. The governing nonlinear partial differential equations have been reduced to the coupled nonlinear ordinary differential equations by the similarity transformations. The resulting equations are then solved numerically using shooting method along with Runge–Kutta fourth order integration scheme. The numerical results are displayed graphically showing the effects of various parameters entering into the problem. Finally, the local values of the skin-friction coefficient, Nusselt number and Sherwood number are also shown in tabular form.

1. Introduction

Convection flows in porous media have gained significant attention in the recent years because of their importance in engineering applications such as geothermal systems, solid matrix heat exchangers, thermal insulations, oil extraction and store of nuclear waste materials. These can also be applied to underground coal gasification, ground water hydrology, wall cooled catalytic reactors, energy efficient drying processes and natural convection in earth's crust. Detailed reviews of flow through and past porous media can be found in [1]. Hiremath and Patil [2] studied the effect on free convection currents on the oscillatory flow through a porous medium, which is bounded by vertical plane surface of constant temperature. Fluctuating heat and mass transfer on three-dimensional flow through porous medium with variable permeability has been discussed by Sharma et al. [3]. A comprehensive account of the available information in this field is provided in books by Pop and Ingham [4], Ingham and Pop [5], Vafai [6], Vadasz [7], etc.

When technological processes take place at higher temperatures thermal radiation heat transfer has become very important and its effects cannot be neglected [8]. The effect of radiation on MHD flow, heat and mass transfer become more

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important industrially. Many processes in engineering areas occur at high temperature and knowledge of radiation heat transfer becomes a very important for the design of the pertinent equipment. The quality of the final product depends to a great extent on the heat controlling factors, and the knowledge of radiative heat transfer in the system can lead to a desired product with sought qualities. Olanrewaju et al. [9] analyzed that the three dimensional unsteady MHD flow and mass transfer in a porous space in the presence of thermal radiation. Different researches have been forwarded to analyze the effects of thermal radiation on different flows ([10–17], among other researchers.

But in the above mentioned studies, Dufour and Soret terms have been neglected from the energy and concentration equations respectively. It has been found that energy flux can be generated not only by temperature gradient but also by concentration gradient as well. The energy flux caused by concentration gradient is called Dufour effect and the same by temperature gradient is called the Soret effect. These effects are very significant when the temperature and concentration gradient are very high. The importance of these effects in convective transport in clear fluids has been studied by Bergaman and Srinivasan [18] and Zimmerman et al. [19]. Kafoussias and Williams [20] studied thermal-diffusion and diffusion-thermo effects on mixed free-forced convective and mass transfer boundary layer flow with temperature dependent viscosity. Anghel et al. [21] studied the Dufour and Soret effects on free convection boundary layer over a vertical surface embedded in a porous medium. Postelnicu [22] analyzed the influence of magnetic field on heat and mass transfer from vertical surfaces in porous media considering Soret and Dufour effects. Srinivasacharya and Upendar [23] examined the free convection in MHD micropolar fluid under the influence of Dufour and Soret effects.

In spite of all these studies, the Dufour and Soret effects on unsteady MHD free convective heat and mass transfer past an infinite vertical plate embedded in a porous medium in the presence of thermal radiation and heat absorption has received little attention. Hence, the main object of the present investigation is to study the effects thermal radiation, heat sink, Dufour and Soret effects on the unsteady MHD free convection fluid flow past a vertical porous plate. The governing equations are transformed by using similarity transformation and the resultant dimensionless equations are solved numerically using the shooting method along with fourth – order Runge–Kutta integration scheme. The effects of various governing parameters on the velocity, temperature, and concentration profiles as well as the local skin-friction coefficient, local Nusselt number and local Sherwood number are presented graphically and in tabular form.

2. Mathematical formulation

An unsteady two-dimensional flow of an incompressible and electrically conducting viscous fluid, along an infinite vertical permeable plate embedded in a porous is considered. The x-axis is taken on the infinite plate, and parallel to the free-steam velocity which is vertical and the y-axis is taken normal to the plate. A magnetic field B_0 of uniform strength is applied transversely to the direction of the flow. Initially the plate and the fluid are at same temperature T_∞ in a stationary condition with concentration level C_∞ at all points. For $t > 0$, the plate starts moving impulsively in its own plane with a velocity U_0, its temperature is raised to T_w and the concentration level at the plate is raised to C_w. The flow configuration and coordinate system are shown in the following Fig. 1. The fluid is assumed to have constant properties except that the influence of the density variations with temperature and concentration, which are considered only the body force term. Under the above assumption, the physical variables are functions of y and t only. Assuming that the Boussinesq and boundary layer approximation hold and using the Darcy-Forchheimer model, the basic equations, which govern the problem, are given by:

Continuity equation:

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

Momentum equation:

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

Energy equation:

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho c_p}\frac{\partial q_r}{\partial y} + \frac{D_m k_T}{c_s c_p}\frac{\partial^2 C}{\partial y^2} + Q_1^*(C - C_\infty) \tag{3}$$

Mass diffusion equation:

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial y} = D_m\frac{\partial^2 C}{\partial y^2} + \frac{D_m k_T}{T_m}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

where x, y are the dimensional distance along and perpendicular to the plate, respectively. u and v are the velocity components in the x, y directions respectively, t is the time, g is the gravitational acceleration, ρ is the fluid density, β and β^* are the thermal and concentration expansion coefficients respectively, K is the Darcy permeability, b is the empirical constant, B_0 is the magnetic induction, T is the thermal temperature inside the thermal boundary layer and C is the corresponding concentration, σ is the electric conductivity, α is the thermal diffusivity, c_p is the specific heat at constant pressure, c_s is the concentration susceptibility, T_m is the mean fluid temperature, k_T is the thermal diffusion ratio D_m is the diffusion coefficient, q_r is the heat flux, and Q_1^* is the coefficient of proportionality of the radiation.

The boundary conditions for the velocity, temperature and concentration are as follows:

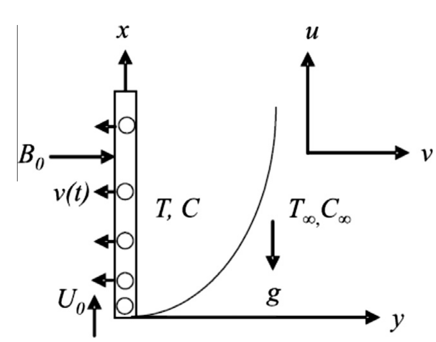

Figure 1 Flow configuration and coordinate system.

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

$$u = 0, \quad T = T_\infty, \quad C = C_\infty \text{ as } y \to \infty. \tag{6}$$

By using the Rosseland diffusion approximation [24] and following [25] among other researchers, the radiative heat flux, q_r is given by

$$q_r = -\frac{4\sigma^*}{3K_s}\frac{\partial T^4}{\partial y} \tag{7}$$

where σ^* and K_s are the Stefan–Boltzman constant and the Roseland mean absorption coefficient, respectively. We assume that the temperature differences within the flow are sufficiently small such that T^4 may be expressed as a linear function of temperature.

$$T^4 \approx 4T_\infty^3 T - 3T_\infty^4 \tag{8}$$

Using (7) and (8) in the last term of Eq. (3) we obtain

$$\frac{\partial q_r}{\partial y} = -\frac{16\sigma^* T_\infty^3}{3K}\frac{\partial^2 T}{\partial y^2} \tag{9}$$

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

$$\delta = \delta(t) \tag{10}$$

A convenient solution of Eq. (1) in terms of this length scale is considered to be in the following form

$$v = v(t) = -\frac{v}{\delta}v_0 \tag{11}$$

where $v_0 > 0$ is the suction parameter.

These non-linear partial differential equations are then transformed by a similarity transformation into a system of ordinary differential equations given as;

$$f'' + (2\eta + v_0)f' + Gr\theta + Gc\phi - Mf - \frac{1}{Da}f - \frac{Re\,Fs}{Da}f^2 = 0 \tag{12}$$

$$\frac{(1+R)}{\Pr}\theta'' + (2\eta + v_0)\theta' + Du\phi'' + Q_1\phi = 0 \tag{13}$$

$$\frac{1}{Sc}\phi'' + (2\eta + v_0)\phi' + Sr\theta'' = 0 \tag{14}$$

where primes denote differentiation with respect to η and $Gr = \frac{g\beta(T_w - T_\infty)\delta^2}{vU_0}$ is the local Grashof number, $Gr = \frac{g\beta^*(C_w - C_\infty)\delta^2}{vU_0}$ is the local modified Grashof number, $M = \frac{\sigma\delta^2 B_0^2}{\rho v}$ is the magnetic field parameter, $Da = \frac{K}{\delta^2}$ is the local Darcy number, $Fs = \frac{b}{\delta}$ is the local Forchheimer number, $Re = \frac{U_0\delta}{v}$ is the local Reynolds number, $\Pr = \frac{v}{\alpha}$ is the Prandtl number, $R = \frac{k_T k^*}{4\sigma^* T_\infty^3}$ is the thermal radiation parameter, $Q_1 = \frac{Q_1^*(C_w - C_\infty)}{(T - T_\infty)}$ is the absorption of radiation parameter, $Sr = \frac{D_m k_T(T_w - T_\infty)}{T_m v(C_w - C_\infty)}$ is the Soret number, $Du = \frac{D_m k_T(C_w - C_\infty)}{c_s c_p v(T_w - T_\infty)}$ is the Dufour number, parameter and $Sc = \frac{v}{D_m}$ is the Schmidt number.

The corresponding boundary conditions for $t > 0$ are transformed to:

$$f = 1, \quad \theta = 1, \quad \phi = 1 \;\; at \;\; \eta = 0 \tag{15}$$

$$f = 0, \quad \theta = 0, \phi = 0 \;\; as \;\; \eta \to \infty. \tag{16}$$

The parameters of engineering interest for the present problem are the skin-friction coefficient, the Nusselt number and the Sherwood number, which are given respectively by the following expressions. Knowing the velocity field the skin-friction at the plate can be obtained, which in non-dimensional form is given by

$$\frac{1}{2}Re^{\frac{1}{2}}C_f = f'(0) \tag{17}$$

Knowing the temperature field, the rate of heat transfer coefficient can be obtained, which in non-dimensional form, in terms of Nusselt number, is given by

$$Nu\;Re^{-\frac{1}{2}} = -\theta'(0) \tag{18}$$

Knowing the concentration field, the rate of mass transfer coefficient can be obtained, which in non-dimensional form, in terms of Sherwood number, is given by

$$Sh\;Re^{-\frac{1}{2}} = -\phi'(0) \tag{19}$$

3. Mathematical solution

The numerical solutions of the non-linear differential Eqs. (12)–(14) under the boundary conditions (15) and (16) have been performed by applying a shooting method along with the fourth order Runge–Kutta method. First of all higher order non-linear differential Eqs. (12)–(14) are converted into simultaneous linear differential equations of first order and they are further transformed into initial value problem by applying the shooting technique. From this process of numerical computation, the skin-friction coefficient, the Nusselt number and Sherwood number which are respectively proportional to $f'(0)$, $-\theta'(0)$ and $-\phi'(0)$ are also sorted out and their numerical values are presented in a tabular form.

4. Results and discussion

As a result of the numerical calculations, the dimensionless velocity, temperature and concentration distributions for the flow under consideration are obtained and their behavior has been discussed for variations in the governing parameters viz., the thermal Grashof number Gr, modified Grashof number Gc, magnetic field parameter M, Darcy number Da, Forchheimer number Fs, absorption radiation parameter Q_1, the suction parameter v_0, Dufour Du and Soret numbers Sr, radiation parameter R, Prandtl number Pr, and Schmidt number Sc. In the present study, the following default parametric values are adopted. $Gr = 10.0$, $Gc = 5.0$, $M = 1.0$, $Da = 1.0$, $Re = 10.0$, $Fs = 0.09$, $Pr = 0.71$, $R = 1.0$, $Du = 0.03$, $Sr = 2.0$, $Q_1 = 1.0$, $Sc = 0.6$, $v_0 = 1.0$. All graphs therefore correspond to these unless specifically indicated on the appropriate graph.

Fig. 2 shows the influence of thermal buoyancy force parameter Gr on the velocity. As can be seen from this figure, the velocity profile increases with increases in the values of the thermal buoyancy. We actually observe that the velocity overshoot in the boundary layer region. Buoyancy force acts like a favorable pressure gradient which accelerates the fluid within the boundary layer therefore the modified buoyancy force parameter Gc has the same effect on the velocity as Gr shown in Fig. 3. From Fig. 4 we observe that the effect of magnetic

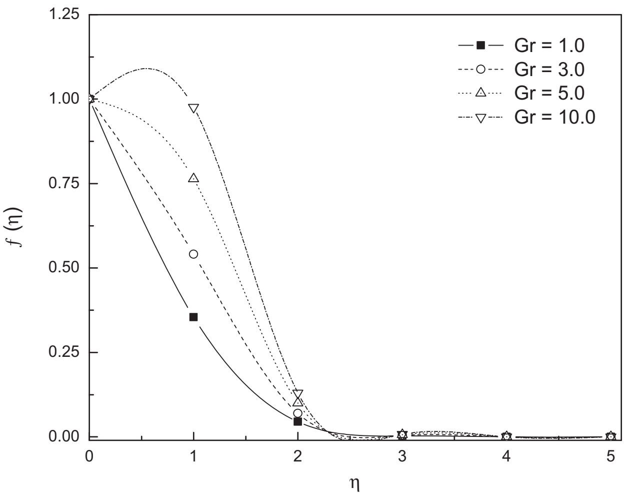

Figure 2 Plot of $f(\eta)$ for varying Gr.

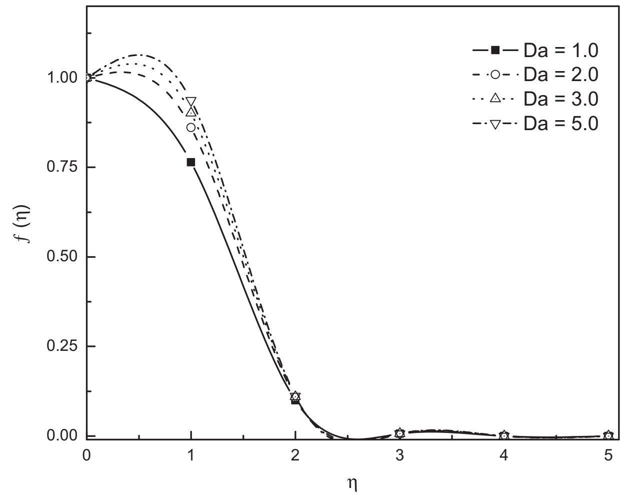

Figure 5 Plot of $f(\eta)$ for varying Da.

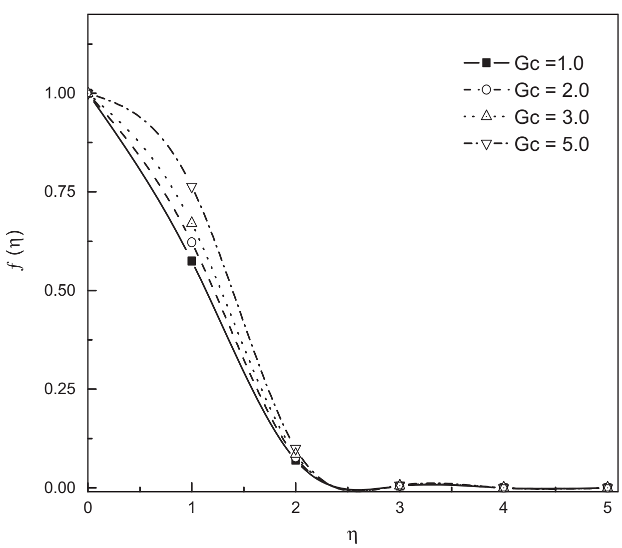

Figure 3 Plot of $f(\eta)$ for varying Gc.

field decreases the value of velocity profile throughout the boundary layer which results in the thinning of the boundary layer thickness. Fig. 5 displays the influence of the Darcy number Da on the velocity profile. Increasing the Darcy number increases the velocity. Fig. 6 depicts the effect of Forchheimer number Fs on the velocity. It is observed that the velocity of the fluid decreases with an increasing of Forchheimer number Fs. Since Forchheimer number Fs represents the inertial drag, thus an increase in the Forchheimer number Fs increases the resistance to the flow and so a decrease in the fluid velocity ensues.

Fig. 7a illustrates the velocity profiles for different values of the Prandtl number Pr. The numerical results show that the effect of increasing values of Prandtl number results in a decreasing velocity. From Fig. 7b, it is observed that an increase in the Prandtl number results in a decrease of the thermal boundary layer thickness and in general lower average temperature within the boundary layer.

Fig. 8a depicts the effect of varying thermal radiation parameter R on the flow velocity. We observe that the thermal radiation enhances convective flow. From Fig. 8b we observe

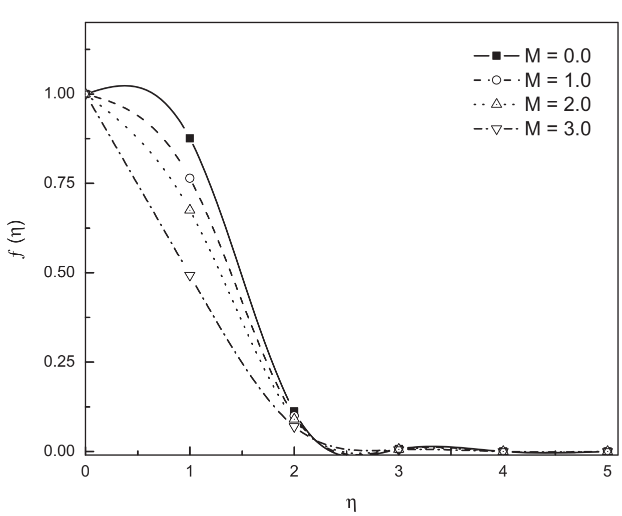

Figure 4 Plot of $f(\eta)$ for varying M.

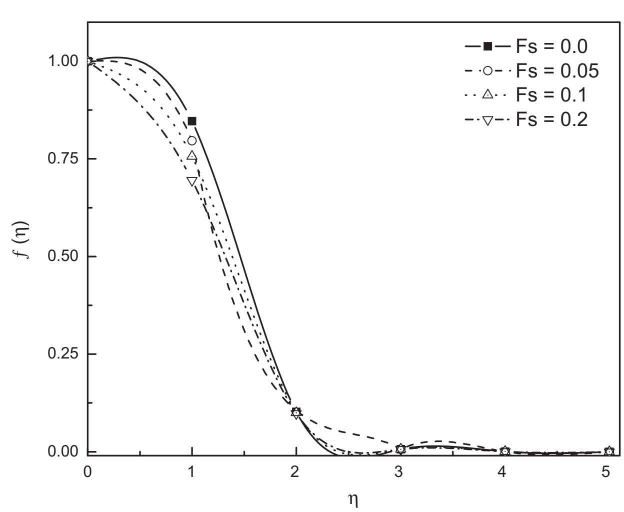

Figure 6 Plot of $f(\eta)$ for varying Fs.

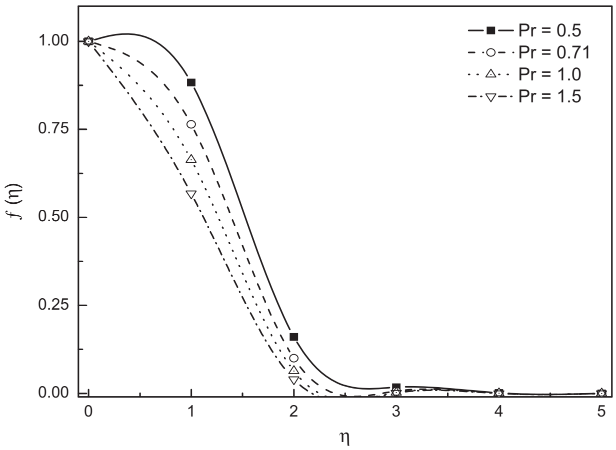

Figure 7a Plot of $f(\eta)$ for varying Pr.

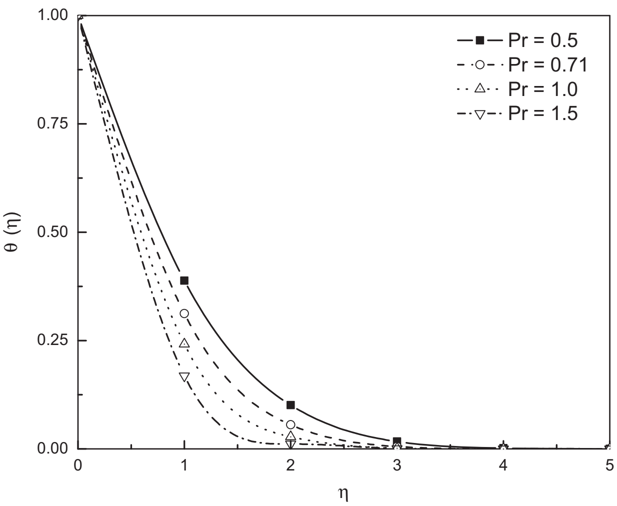

Figure 7b Plot of $\theta(\eta)$ for varying Pr.

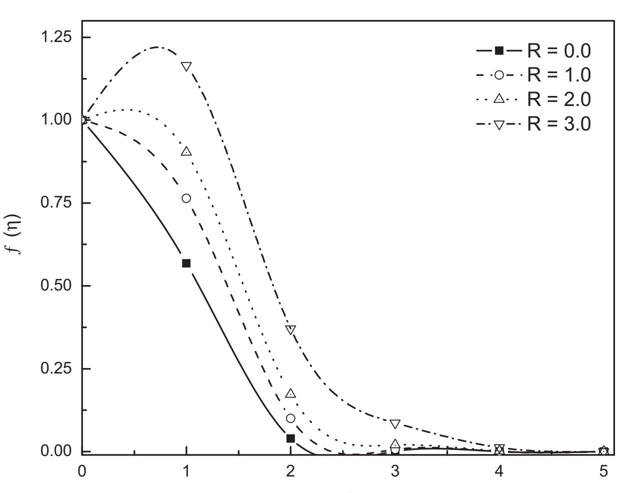

Figure 8a Plot of $f(\eta)$ for varying R.

that the effect of thermal radiation is to enhance heat transfer as thermal boundary layer thickness increases with increase in the thermal radiation. We observe that the effect of R is to

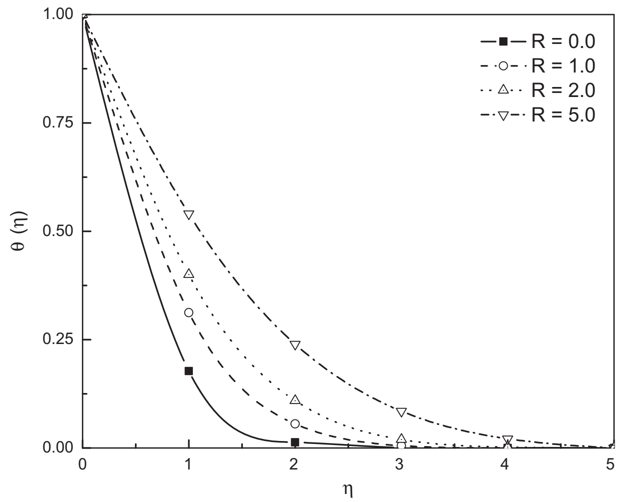

Figure 8b Plot of $\theta(\eta)$ for varying R.

increase the temperature distribution in the thermal boundary layer. This is because the increase of R implies increasing of radiation in the thermal boundary layer, and hence increases the values of the temperature profiles in the thermal boundary layer.

The effect of increasing the value of the absorption of the radiation parameter Q_1 on the velocity is shown in Fig. 9a. We observe in this that increasing the value of the absorption of the radiation parameter due to increase in the buoyancy force accelerates the flow rate. The effect of absorption of radiation parameter on the temperature profiles is shown in Fig. 9b. It is seen from this figure that the effect of absorption of radiation is to increase temperature in the boundary layer as the radiated heat is absorbed by the fluid which in turn increases the temperature of the fluid very close to the porous boundary layer and its effect diminishes far away from the boundary layer.

The influence of Schmidt number Sc on the velocity and concentration profiles is plotted in Figs. 10a and 10b respectively. As the Schmidt number Sc increases the concentration decreases. This causes the concentration buoyancy effects to

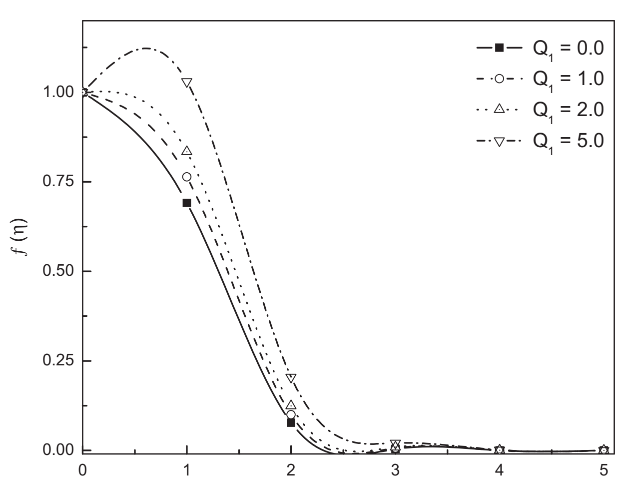

Figure 9a Plot of $f(\eta)$ for varying Q_1.

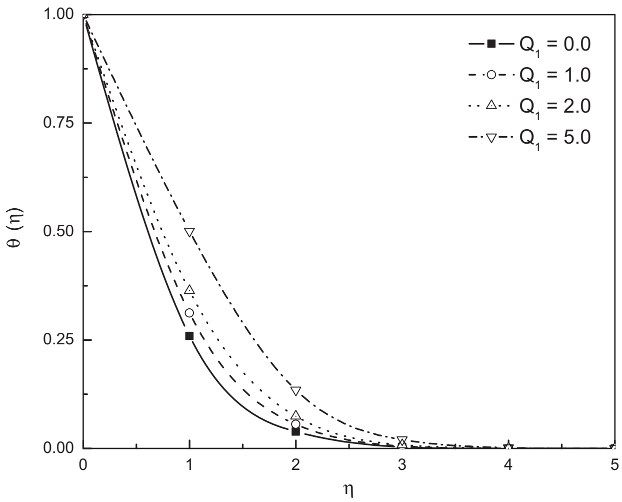

Figure 9b Plot of $\theta(\eta)$ for varying Q_1.

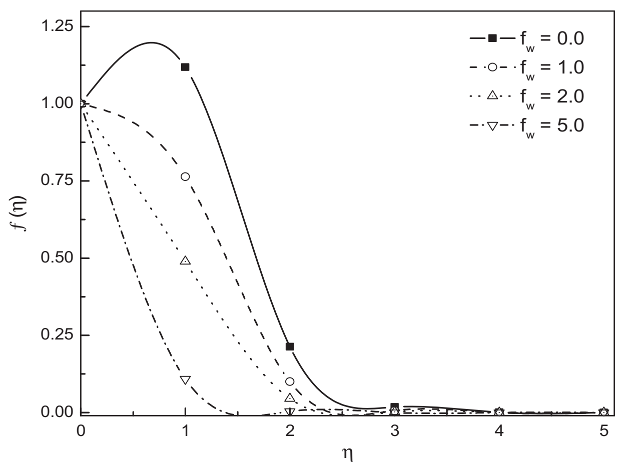

Figure 11a Plot of $f(\eta)$ for varying f_w.

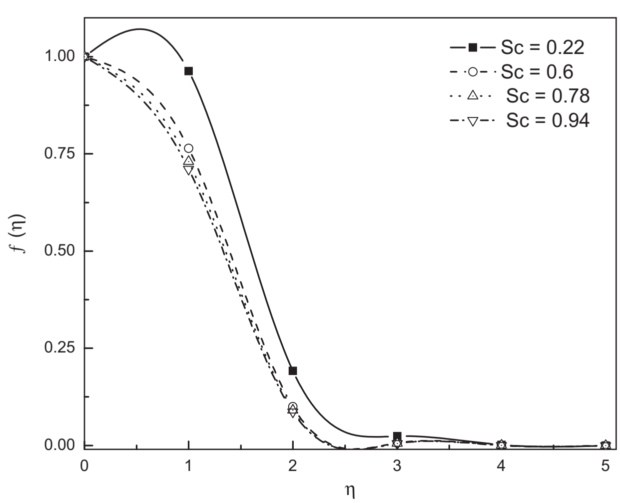

Figure 10a Plot of $f(\eta)$ for varying Sc.

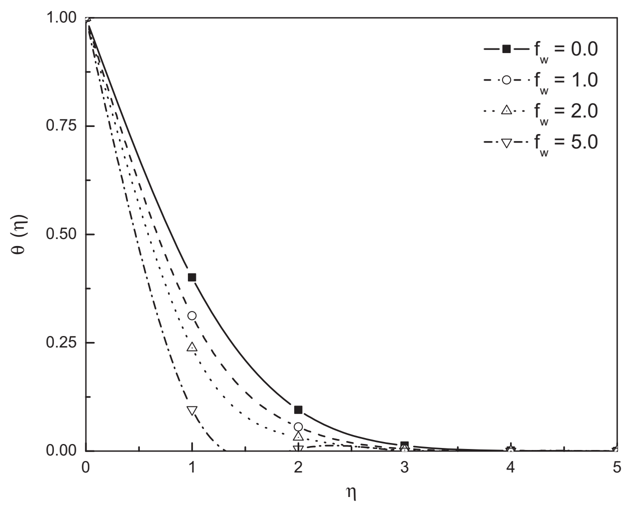

Figure 11b Plot of $\theta(\eta)$ for varying f_w.

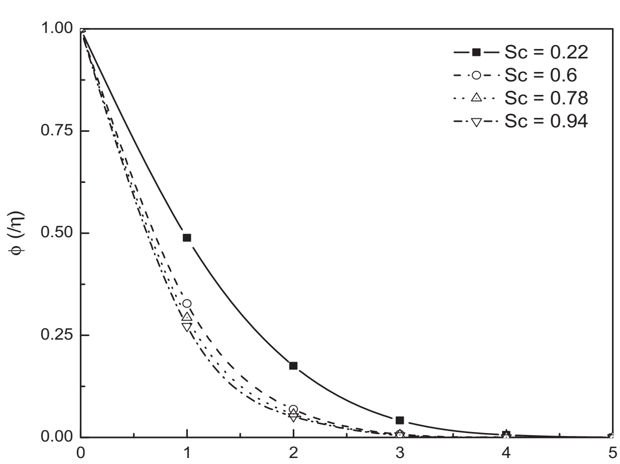

Figure 10b Plot of $\phi(\eta)$ for varying Sc.

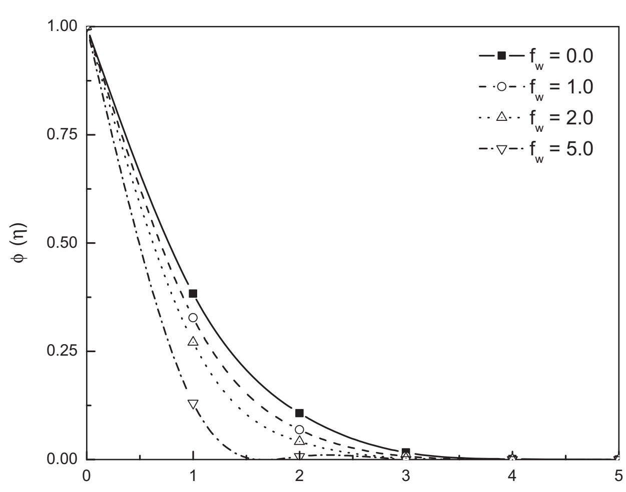

Figure 11c Plot of $\phi(\eta)$ for varying f_w.

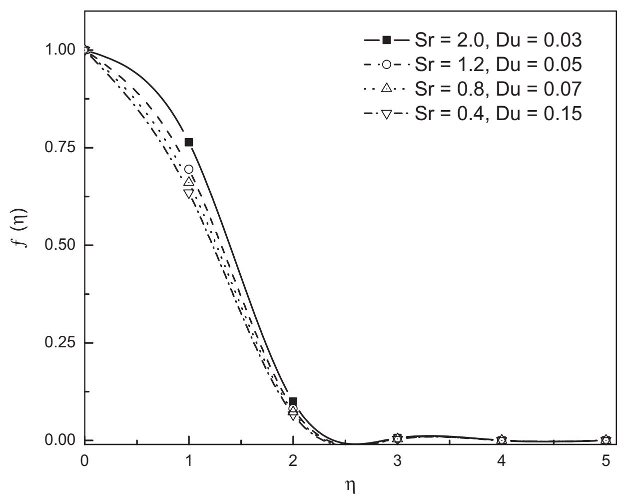

Figure 12a Plot of $f(\eta)$ for varying Sr and Du.

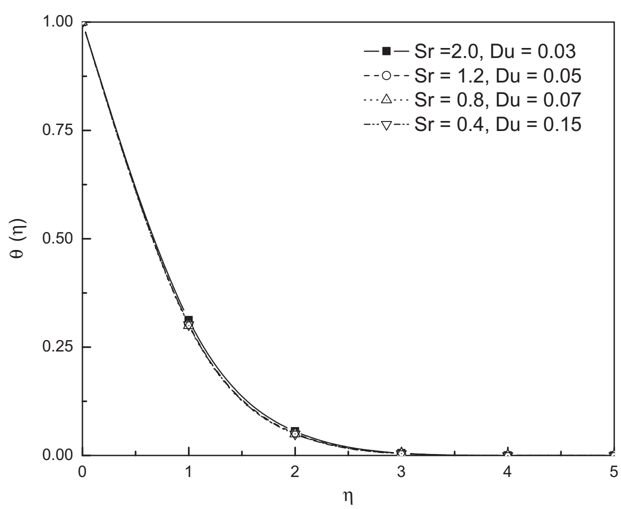

Figure 12b Plot of $\theta(\eta)$ for varying Sr and Du.

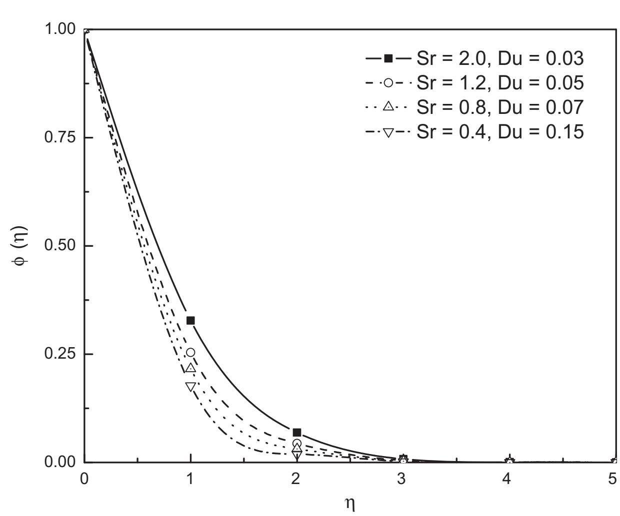

Figure 12c Plot of $\phi(\eta)$ for varying Sr and Du.

Table 1 Numerical values of skin-friction coefficient, Nusselt number and Sherwood number for $Pr = 0.71$, $R = 1.0$, $Q_1 = 1.0$, $Sc = 0.6$, $Du = 0.03$, $Sr = 2.0$, $Re = 10$, $Fs = 0.09$.

Gr	Gc	Da	M	f_w	$f'(0)$	$-\theta'(0)$	$-\phi'(0)$
10	5.0	1.0	1.0	1.0	3.22354	0.907495	0.999473
5.0	5.0	1.0	1.0	1.0	1.38272	0.907495	0.999473
7.0	5.0	1.0	1.0	1.0	2.12685	0.907495	0.999473
10	2.0	1.0	1.0	1.0	2.12228	0.907495	0.999473
10	3.0	1.0	1.0	1.0	2.49203	0.907495	0.999473
10	5.0	2.0	1.0	1.0	3.98701	0.907495	0.999473
10	5.0	3.0	1.0	1.0	4.29471	0.907495	0.999473
10	5.0	1.0	2.0	1.0	2.62288	0.907495	0.999473
10	5.0	1.0	3.0	1.0	2.09948	0.907495	0.999473
10	5.0	1.0	1.0	2.0	2.65463	1.16273	1.11315
10	5.0	1.0	1.0	3.0	1.80371	1.44096	1.22687

Table 2 Numerical values of skin-friction coefficient, Nusselt number and Sherwood number for $Gr = 10$, $Gc = 5.0$, $Da = 1.0$, $M = 1.0$, $f_w = 1.0$, $Du = 0.03$, $Sr = 2.0$, $Re = 10$, $Fs = 0.09$.

Pr	R	Q_1	Sc	$f'(0)$	$-\theta'(0)$	$-\phi'(0)$
0.71	1.0	1.0	0.6	3.22354	0.907495	0.999473
0.5	1.0	1.0	0.6	3.42444	0.76283	1.13561
1.0	1.0	1.0	0.6	3.01622	1.08568	0.826511
0.71	2.0	1.0	0.6	3.45393	0.74325	1.1538
0.71	3.0	1.0	0.6	3.5977	0.652467	1.2376
0.71	1.0	1.0	0.6	3.08348	1.08246	0.81895
0.71	1.0	1.0	0.6	2.96861	1.2372	0.657472
0.71	1.0	1.0	0.5	3.29409	0.900332	0.913251
0.71	1.0	1.0	1.0	3.03908	0.924641	1.30551

Table 3 Numerical values of skin-friction coefficient, Nusselt number and Sherwood number for $Gr = 10$, $Gc = 5.0$, $Da = 1.0$, $M = 1.0$, $f_w = 1.0$, $Du = 0.03$, $Sr = 2.0$, $Re = 10$, $Fs = 0.09$. $Pr = 0.71$, $R = 1.0$, $Q_1 = 1.0$, $Sc = 0.6$, $Re = 10$, $Fs = 0.09$.

Sr	Du	$f'(0)$	$-\theta'(0)$	$-\phi'(0)$
2.0	0.03	3.22354	0.907495	0.999473
0.5	0.03	2.85976	0.94436	1.39099
1.0	0.03	2.9857	0.931751	1.25502
2.0	0.05	3.22774	0.903518	1.00343
2.0	0.1	3.2383	0.893346	1.01358

decrease yielding a reduction in the fluid velocity. The reductions in the velocity and concentration profiles are accompanied by simultaneous reductions in the velocity and concentration boundary layers. These behaviors are clear from Figs. 10a and 10b.

The effects of suction parameter f_w on the velocity field are shown in Fig. 11a. It is clearly seen from this figure that the velocity profiles decrease monotonically with the increase of suction parameter indicating the usual fact that suction stabilizes the boundary layer growth.

The effect of suction parameter f_w on the temperature field is displayed in Fig. 11b. We see that the temperature profiles decrease with increasing values of suction parameter f_w. Fig. 11c depict the influence of suction parameter f_w on concentration profiles. In Fig. 11c we see that the concentration profiles decrease with increasing values of the suction parameter.

The effects of Soret and Dufour numbers on the velocity field are shown in Fig. 12a. It is observed that decrease in Soret number Sr and an increase in Dufour number Du, the velocity profile is decreasing. The effects of Soret and Dufour numbers on the temperature field are shown in Fig. 12b. It is noted that negligible effect of Soret and Dufour numbers on temperature profile. The effects of Soret and Dufour numbers on the concentration field are shown in Fig. 12c. It is also observed that with decrease in Soret number and with increase in Dufour number the concentration profile is decreasing.

Tables 1 and 2 shows the effects of Grashof number Gr, modified Grashof number Gc, Darcy number Da, magnetic field parameter M, suction parameter f_w, Prandtl number Pr, radiation parameter R, the absorption of radiation parameter Q_1 and Schmidt number Sc on the physical parameters skin-friction coefficient $f^{'}(0)$, Nusselt number $-\theta^{'}(0)$ and Sherwood number $-\phi^{'}(0)$ respectively. It can be seen that skin-friction coefficient $f^{'}(0)$ increases as Grashof number Gr, modified Grashof number Gc, Darcy number Da increases, while skin-friction coefficient $f^{'}(0)$ decreases as magnetic field parameter M, suction parameter f_w increase. It can be clearly observed that the rate of heat transfer between the wall and the fluid increases for increasing values of Prandtl number Pr. The Nusselt number is observed to be reduced by increasing values of thermal radiation R, the absorption of radiation parameter Q_1. $-\phi^{'}(0)$ increase as Schmidt number Sc increases.

Finally, the effects of Soret number Sr and Dufour number Du on skin-friction coefficient, Nusselt number and Sherwood number are shown in Table 3. The behavior of these parameters is self-evident from the Table 3 and hence they will not discuss any further due to brevity.

5. Conclusions

In this paper we have studied Dufour and Soret effects on unsteady MHD convective heat and mass transfer flow past an infinite vertical plate embedded in a porous medium in the presence of thermal radiation. From the present numerical study the following conclusions can be drawn:

- An increase in thermal radiation parameter, the velocity and temperature profiles increase.
- Suction stabilizes the hydrodynamic, thermal as well as concentration boundary layers growth.
- Magnetic field retards the motion of the fluid.
- The velocity and concentration profiles decrease as an increase in Schmidt number.
- An increasing of the absorption of radiation parameter, both velocity and temperature profiles increases.
- It is noted that negligible effect of Soret and Dufour numbers on temperature profile.
- The heat transfer rate is reduced by increasing thermal radiation parameter, the absorption of radiation parameter
- The mass transfer rate increases as an increase of Schmidt number.

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