Radiation Effects on MHD Free Convective Heat and Mass Transfer Flow Past a Vertical Porous Flat Plate with Suction

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Abstract:- The present paper deals with the radiation effects on MHD free convective heat and mass transfer flow past a vertical porous flat plate with suction. The governing equations are transformed by using similarity transformation and the resultant dimensionless equations are solved numerically using the Runge-Kutta fourth order method with shooting technique. The effects of various governing parameters on the velocity, temperature, concentration, skin-friction coefficient, Nusselt number and Sherwood number are computed and discussed in detail.

Key words : MHD, Heat and Mass Transfer, Suction, Porous medium, Radiation.

I. INTRODUCTION

Study of fluid flow in porous medium is based upon the empirically determined Darcy's law. Such flows are considered to be useful in diminishing the free convection, which would otherwise occur intensely on a vertical heated surface. In addition, recent developments in modern technology have intensified more interest of many researchers in studies of heat and mass transfer in fluids due to its wide applications in geothermal and oil reservoir engineering as well as other geophysical and astrophysical studies.

Yamamoto et al [1] investigated the acceleration of convection in a porous permeable medium along an arbitrary but smooth surface. Suction/blowing on convective heat transfer over a vertical permeable surface embedded in a porous medium was analyzed by Cheng [2]. Raptis and Singh [3] studied flow past an impulsively started vertical plate in a porous medium by a finite difference method. Kim and Vafai [4] have analyzed the buoyancy driven flow about a vertical plate for constant wall temperature and heat flux. Sattar [5] obtained analytical solution by the perturbation technique adopted by Singh and Dikshit [6]. Sattar et al [7] studied unsteady free convection flow along a vertical porous plate embedded in a porous medium.

Some important applications of MHD flow with heat and mass transfer are cooling of nuclear reactors, liquid metals fluid, power generation system and aerodynamics. MHD finds applications in electromagnetic pumps, crystals growing, MHD couples and bearing, plasma jets and chemical synthesis. The effects of magnetic field on free convection flow of electrically conducting fluids past a plate has been studied by many authors such as Soundalgekar [8]. Raptis [9] studied mathematically the case of unsteady two-dimensional natural convective heat transfer of an incompressible, electrically conducting viscous fluid via a highly porous medium bound by an infinite vertical porous plate. Kim [10] studied unsteady MHD convection flow of polar fluids past a semi-infinite vertical-moving porous plate in a porous medium. Ahmed [11] looked the effects of unsteady free convective MHD flow through a porous medium bounded by an infinite vertical porous plate. Chaudhary and Arpita Jain [12] have discussed the MHD heat and mass diffusion flow by natural convection past a surface embedded in a porous medium.

All the above investigations are restricted to MHD flow and heat transfer problems only. However, of late, the radiation effects on MHD flow and heat transfer problems have become more important, industrially. At high operating temperature, radiation effects can be quite significant. Radiation effect on mixed convection along a isothermal vertical plate were studied by Hossain and Takhar [13]. The radiation effects on boundary layer flow with and without applying a magnetic field under different situations has been studied by many

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investigators [14-16]. Prasad *et al.* [17] studied the radiation and mass transfer effects on unsteady MHD free convection flow past a vertical porous plate embedded in porous medium. Mohammed Ibrahim et.al. [18] proposed the radiation and chemical reaction effects on MHD free convection flow past a moving vertical plate.

In many engineering and physical problems, it is highly important to study the effect of heat generation and absorption. Possible heat generation effect may alter the temperature distribution; consequently, the particle deposition rate in nuclear reactors, electronic chips and semi conduction wafers. Rahman and Sattar [19] presented magnetohydrodynamic convective flow of a micropolar fluid past a vertical porous plate in the presence of heat generation/absorption. Sharma and Singh [20] have discussed the unsteady MHD free convective flow and heat transfer along a vertical porous plate with variable suction and internal heat generation. Sharma *et al.* [21] have analyzed the heat and mass transfer effects on unsteady MHD free convective flow along a vertical porous plate with internal heat generation and variable suction.

The present paper investigates the radiation effects of an unsteady electrically conducting, viscous, incompressible fluid interaction with heat generation on a free convective flow past a vertical porous flat plate embedded in a porous medium with suction in presence of heat and mass transfer permitted by a transversely applied uniform magnetic field. Skin-friction coefficient, Nusselt number and Sherwood number are also discussed. The similarity solutions are then obtained numerically for various parameters entering into the problem and discussed them from the physical point of view.

II. MATHEMATICAL FORMULATION

Let us consider the problem of an unsteady MHD free convection flow of a viscous, incompressible and electrical conducting fluid along a vertical porous flat plate under the influence of a uniform magnetic field. The flow is assumed to be in the x – direction, which is taken along the plate in the upward direction and y – axis normal to the plate. Initially it is assumed that the plate and the fluid are at a constant temperature T_∞ in a stationary condition with concentration level C_∞ at all points. At time $t > 0$ the plate is assumed to be moving in the upward direction with the velocity U(t) and there is a suction velocity $v_0(t)$ taken to be a function of time, the temperature of the plate raised to T(t) and the concentration level at the plate is raised to C(t) where $T(t) > T_\infty$ and $C(t) > C_\infty$. The plate is considered to be of infinite length, all derivatives with respect to x vanish and so the physical variables are functions of y and t only.

The fluid is assumed to have constant properties except that the influence of the density variations with temperature and concentration, which are considered only in the body force term, and is considered to be gray, absorbing emitting radiation but non-scattering medium and the Rosseland approximation is used to describe the radioactive heat flux in the energy equation. A uniform magnetic field of strength B_0 is applied normal to the plate parallel to y-direction.

Under the usual boundary layer and Boussinesq approximation and using the Darcy-Forchhemier model, the flow and heat transfer in the presence of radiation are governed by the following equations.

Continuity Equation

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

Momentum Equation

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

Energy Equation

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho c_p}\frac{\partial q_r}{\partial y} + \frac{Q_0}{\rho c_p}\left(T - T_\infty\right) \tag{3}$$

Concentration Equation

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

where u and v are the velocity components along x- and y- directions respectively, t is time, υ is the kinematic viscosity, ρ is the density of the fluid, g is the acceleration due to gravity, β is the coefficient of volume expansion, β^* is the volumetric coefficient of expansion with concentration, α is the thermal diffusivity, σ is the electric conductivity, B_0 is the uniform magnetic field induction, T and T_∞ are the temperature of the fluid within the boundary layer and in the free stream respectively, while C and C_∞ are the

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corresponding concentrations, c_p is the specific heat at constant pressure, k is the permeability of the porous medium, Q_0 is the heat generation and D_m is the coefficient of mass diffusivity.

Initially ($t = 0$) the fluid and the plate are at rest. Thus the no slip boundary conditions at the surface of the plate for the above problem for t > 0 are:

$$u = U(t), v = v_0(t), T = T_0(t), C = C_0(t) \ \ at \ y = 0$$

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

By using Rosseland approximation q_r takes the form

$$q_r = -\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial y} \tag{6}$$

where σ^* is the Stefan-Boltzmann constant and k^* is the mean absorption coefficient. It is assumed that the temperature differences within the flow are sufficiently small such that T^4 may be expressed as a linear function of temperature. This is accomplished by expanding T^4 in a Taylor series about T_∞ and neglecting higher-order terms, thus

$$T^4 \approx 4T_\infty^3 T - 3T_\infty^4 \tag{7}$$

Using (6) and (7) in equation (3) we have

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} + \frac{4\sigma^* T_\infty^3}{\rho c_p k^*}\frac{\partial^2 T}{\partial y^2} + \frac{Q_0}{\rho c_p}\left(T - T_\infty\right) \tag{8}$$

In order to obtain a similarity solution in time of the problem, we introduce a similarity parameter δ as

$$\delta = \delta(t) \tag{9}$$

such that δ is a length scale.

With this similarity parameter, a similarity variable is then introduced as

$$\eta = \frac{y}{\delta} \tag{10}$$

In terms of this length scale, a convenient solution of the equation (1) can be taken as

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

where v_0 is the mass transfer parameter, which is positive for suction and negative for injection. Following Samad and Rahman [22], we see that *U(t), T(t) and C(t)* are now considered to have the following form:

$$\begin{aligned} U(t) &= U_0\delta_1^{2n+2} \\ T(t) &= T_\infty + \left(T_0 - T_\infty\right)\delta_1^{2n} \\ C(t) &= C_\infty + \left(C_0 - C_\infty\right)\delta_1^{2n} \end{aligned} \tag{12}$$

where n is a non-negative integer and, U_0, T_0 and C_0 are respectively the free stream velocity, mean temperature and concentration. Here $\delta_1 = \dfrac{\delta}{\delta_0}$, where δ_0 is the value of δ at $t = t_0$.

Now to make the equations (2), (4) and (8) dimensionless, we introduce the following transformations:

$$\begin{aligned} u &= U(t)f(t) = U_0\delta_1^{2n+2}f(\eta) \\ T &= T_\infty + \left(T_0 - T_\infty\right)\delta_1^{2n}\theta(\eta) \\ C &= C_\infty + \left(C_0 - C_\infty\right)\delta_1^{2n}\phi(\eta) \end{aligned} \tag{13}$$

Using equations (9), (10) and (13) the equations (2), (4) and (8) are become (using the analysis of Hashimoto [23], Sattar et al. [24] and Sattar and Maleque [25])

$$f'' + (2\eta + v_0)f' - \left(4n + 4 + M + \frac{1}{M}\right)f + Gr\theta + Gc\phi - \frac{Fs}{Da}f^2 = 0 \tag{14}$$

$$\theta'' + (2\eta + v_0)\left(\frac{3R\Pr}{3R+4}\right)\theta' - \left(\frac{12nR\Pr}{3R+4}\right)\theta + \left(\frac{3R\Pr}{3R+4}\right)Q\theta = 0 \tag{15}$$

$$\phi'' + (2\eta + v_0)Sc\phi' - 4nSc\phi = 0 \tag{16}$$

where $Gr = \dfrac{g\beta(T_0 - T_\infty)\delta_0^2}{\upsilon U_0}$ is the local Grashof number, $Gc = \dfrac{g\beta^*(C_0 - C_\infty)\delta_0^2}{\upsilon U_0}$ is the modified Grashof number, $M = \dfrac{\sigma B_0^2\delta^2}{\rho\upsilon}$ is the local magnetic

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field parameter, $Fs_{*} = \frac{b}{\delta}$ is the Forchhemier number, $Fs = \frac{b}{\delta}\left(\frac{\delta}{\delta_0}\right)^{2n+2} \mathrm{Re}$ is the modified Forchhemier number, $\mathrm{Re} = \frac{v_0 \delta}{\upsilon}$ is the local Reynolds number, $Da = \frac{k}{\delta^2}$ is the Darcy number, $\mathrm{Pr} = \frac{\upsilon}{\alpha}$ is the Prandtl number, $R = \frac{\kappa k^*}{4\sigma^* T_\infty^3}$ is the thermal radiation parameter, (κ is the thermal conductivity), $Q = \frac{Q_0 \delta^2}{\rho c_p \upsilon}$ is the heat generation parameter and $Sc = \frac{\upsilon}{D_m}$ is the Schmidt number.

The corresponding boundary conditions for t > 0 are given by

$$f = 1, \theta = 1, \phi = 1 \quad \text{at } \eta = 0,$$

$$f = 0, \theta = 0, \phi = 0 \text{ as } \eta \to \infty \qquad (17)$$

A. Skin-Friction Coefficient, Nusselt Number And Sherwood Number

The parameters of engineering interest for the present problems are the skin-friction coefficient, local Nusselt number and local Sherwood number which indicate physically wall shear stress, rate of heat transfer and rate of mass transfer respectively.

The skin-friction coefficient is given by

$$C_f \left(\frac{\mathrm{Re}_x}{2}\right)^{\frac{1}{2}} = f''(0), \qquad (18)$$

the local Nusselt number may be written as

$$Nu_x \left(\frac{\mathrm{Re}_x}{2}\right)^{-\frac{1}{2}} = -\theta'(0) \qquad (19)$$

and the local Sherwood number may be written as

$$Sh_x \left(\frac{\mathrm{Re}_x}{2}\right)^{-\frac{1}{2}} = -\phi'(0) \qquad (20)$$

Thus the values proportional to the skin-friction coefficient, Nusselt number and Sherwood number are $f''(0), -\theta'(0)$ and $-\phi'(0)$ respectively.

III. NUMERICAL COMPUTATION

The numerical solutions of the nonlinear differential equations (14) – (16) under the boundary conditions (17) have been performed by applying fourth order Runge-Kutta iteration technique along with shooting method. We have chosen a step size of $\Delta\eta = 0.01$ to satisfy the convergence crite- rion of 10^{-6} in all cases. The value of η_∞ was found to each iteration loop by $\eta_\infty = \eta_\infty + \Delta\eta$. The maximum value of η_∞ to each group of parameters v_0, *Gr*, *Gc*, *M*, *Da*, *Fs*, *n*, *Pr*, *R*, *Q*, and *Sc* determined when the value of the unknown boundary conditions at $\eta = 0$ not change to successful loop with error less than 10^{-6}. Figures 1-11 show the velocity, temperature and concentration profiles for different step sizes respectively considering $Gr = 10.0, Gc = 6.0, M = 0.5, Da = 0.25, Fs = 1.0, \mathrm{Pr} = 0.71, R = 0.5, Q = 0.5, Sc = 0.6, n = 1.0$ and v_0 = *0.5*.

IV. RESULTS AND DISCUSSION

For the purpose of discussing the results, the numerical calculations are presented in the form of non-dimensional velocity temperature and concentration profiles. Numerical computations have been carried out for different values of the magnetic field parameter (*M*), radiation parameter *(R),* suction parameter (v_0), modified Forchhemier number (*Fs*), and Schmidt number (*Sc*).

The effect of radiation parameter *R* on the velocity profiles is shown in Figure 1. This figure shows that velocity decreases with the increase of the radiation parameter *R*. Figure 2. show the effect of radiation parameter *R* on the temperature profiles. For large *R,* it is clear that temperature decreases more rapidly with the increase of radiation parameter *R*. therefore using radiation we can control the flow characteristic and temperature distribution.

The effect of magnetic field parameter on the velocity profiles are shown in Figure. 3. It is observed from this figure that the magnetic field has decreasing effect on the velocity field increases. There is no outcome on the temperature and concentration profiles due the distinction of the values of magnetic field parameter *M.*

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Figures 4 & 5 display the effects of the suction parameter v_0 on the velocity, temperature and concentration profiles respectively. It is observed that, when suction v_0 increases, all the profiles *i.e.* velocity, temperature and concentration are decrease.

The effect of the modified Forchhemier number *Fs* on the velocity field is shown on Figure. 6. It is observed from this figure that modified Forchhemier number has slightly decreasing effect on the velocity field.

The influence of the Schmidt number *Sc* on the dimensionless velocity (f) and concentration (ϕ) profiles are plotted in Figs. 7 and 8 respectively. As the Schmidt number *Sc* increases the concentration decreases. This causes the concentration buoyancy effects to 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. 7 and 8.

Finally, the effects of various parameters on the skin-friction coefficient C_f, local Nusselt number *Nu* and local Sherwood number *Sh* are shown in Tables 1 – 7.

Tabel. 1. Skin-friction coefficient, local Nusselt number and local Sherwood number for different values of M.

M	C_f	*Nu*	*Sh*
0.0	0.561469	1.03696	1.91963
0.5	1.10936	1.03696	1.91963
1.0	1.65625	1.03696	1.91963
2.0	2.74726	1.03696	1.91963

Tabel. 2. Skin-friction coefficient, local Nusselt number and local Sherwood number for different values of Da

Da	C_f	*Nu*	*Sh*
0.25	1.10936	1.03696	1.91963
0.5	-3.26919	1.03696	1.91963
1.0	-5.49642	1.03696	1.91963
2.0	-6.62387	1.03696	1.91963

Tabel. 3. Skin-friction coefficient, local Nusselt number and local Sherwood number for different values of *n*

N	C_f	*Nu*	*Sh*
0.0	-3.49026	0.627435	1.09265
1.0	1.10936	1.03696	1.91963
2.0	5.54943	1.35282	2.49383
5.0	18.4671	2.045	3.70835

Tabel. 4. Skin-friction coefficient, local Nusselt number and local Sherwood number for different values of *R*

R	C_f	*Nu*	*Sh*
0.0	0.985658	0.5	1.91963
0.5	1.10936	1.03696	1.91963
1.0	1.1611	1.28546	1.91963
2.0	1.2079	1.52792	1.91963

Tabel. 5. Skin-friction coefficient, local Nuselt number and local Sherwood number for different values of *Q*

Q	C_f	*Nu*	*Sh*
0.0	1.11769	1.08041	1.91963
0.5	1.10936	1.03696	1.91963
1.0	1.10066	0.992098	1.91963
2.0	1.08207	0.897723	1.91963

Tabel. 6. Skin-friction coefficient, local Nuselt number and local Sherwood number for different values of Sc

Sc	C_f	*Nu*	*Sh*
0.22	1.02603	1.03696	1.14646
0.6	1.10936	1.03696	1.91963
0.78	1.13579	1.03696	2.21562
0.94	1.15539	1.03696	2.45676

Tabel. 7. Skin-friction coefficient, local Nuselt number and local Sherwood number for different values of v_0

v_0	C_f	*Nu*	*Sh*
0.0	0.5	0.984044	1.75003
0.5	1.10936	1.03696	1.91963
1.0	1.90771	1.09196	2.10084
2.0	4.20587	1.20806	2.49523

V. CONCLUSIONS

In this paper we have investigated the thermal radiation interaction with unsteady MHD free convective heat and mass transfer flow past a vertical porous flat plate embedded in porous medium under the influence of heat source. From the present study we can make the following conclusions:

- Radiation has significant effects on the velocity as well as temperature distributions. *i.e.* velocity and temperature profiles reduce with the increase of thermal radiation.
- Magnetic field has significant effect on velocity field and retards the motion of the fluid.
- Using suction boundary layer growth can be controlled. Suction stabilizes the hydrodynamic, thermal as well as concentration boundary layers growth.
- The skin-friction coefficient, local Nusselt number and local Sherwood number increase with an increase of suction parameter or constant parameter.

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- As radiation increases, the skin-friction coefficient and local Nusselt number are also increase.
- The skin-friction coefficient and local Nusselt number are reduces with an increase of heat generation parameter.

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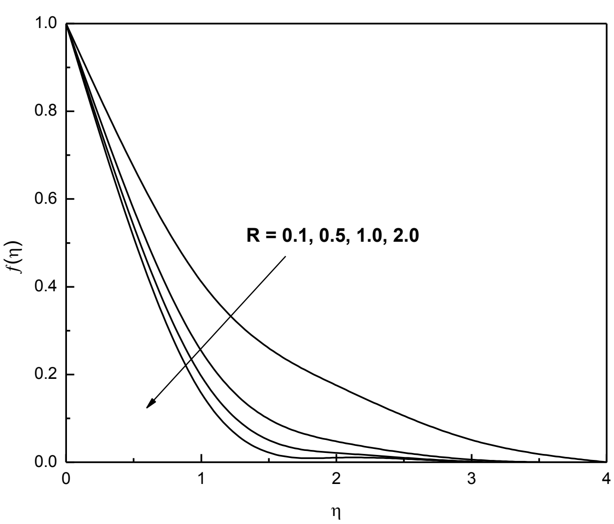

Figure1. Velocity profiles for different values of radiation parameter *(R)*

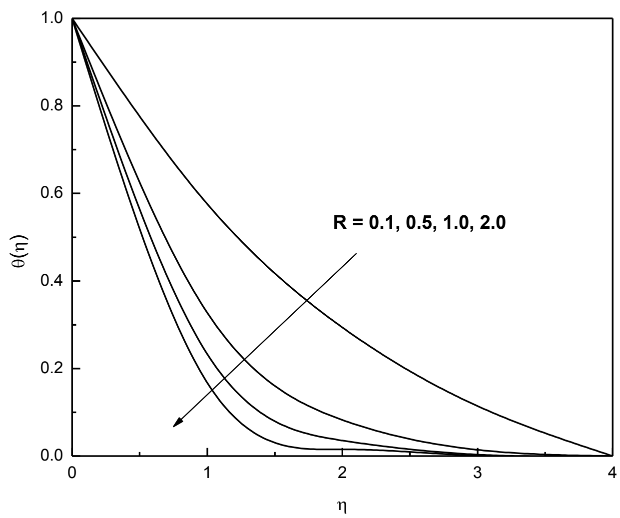

Figure 2. Temperature profiles for different values of radiation parameter *(R)*

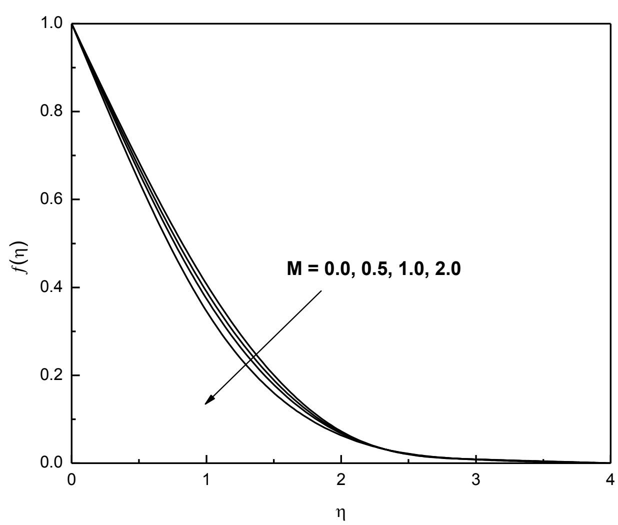

Figure 3. Velocity profiles for different values of Magnetic field parameter (*M)*

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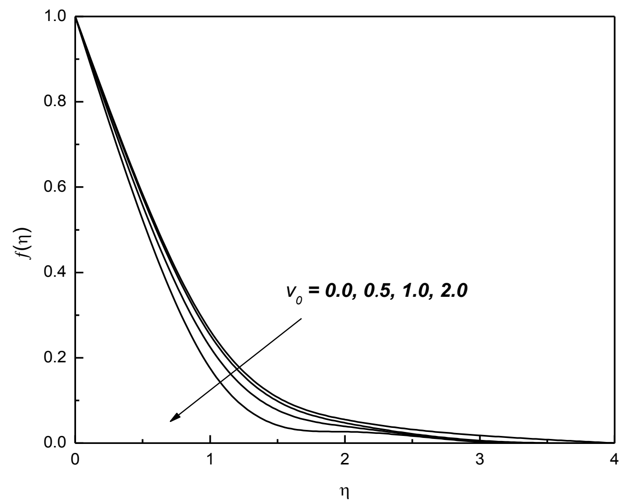

Figure 4. Velocity profiles for different values of suction parameter (v_0)

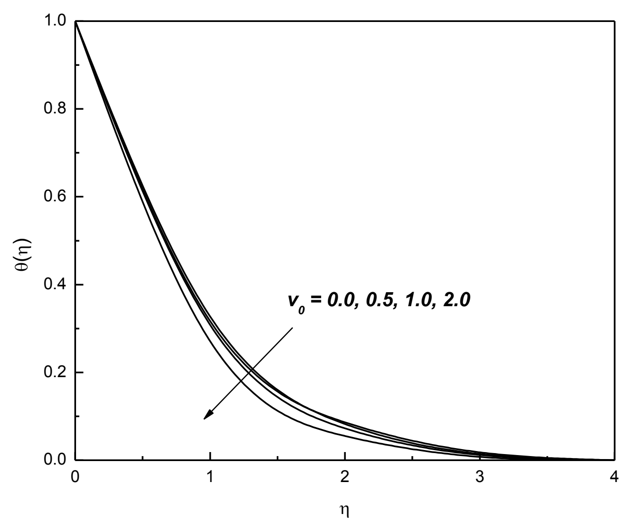

Figure 5. Temperature profiles for different values of suction parameter (v_0)

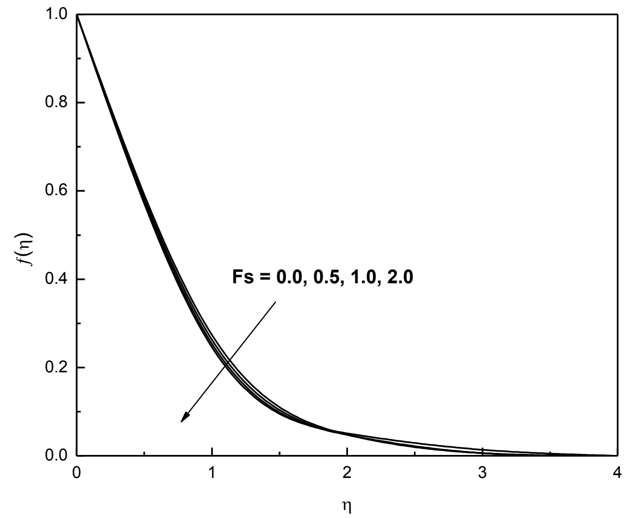

Figure 6. Velocity profiles for different values of modified Forchhemier number *(Fs)*

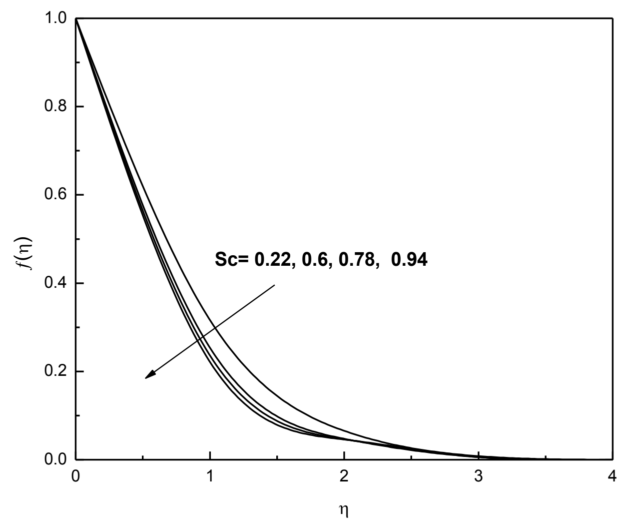

Figure 7. Velocity profiles for different values of Schmidt number *(Sc)*

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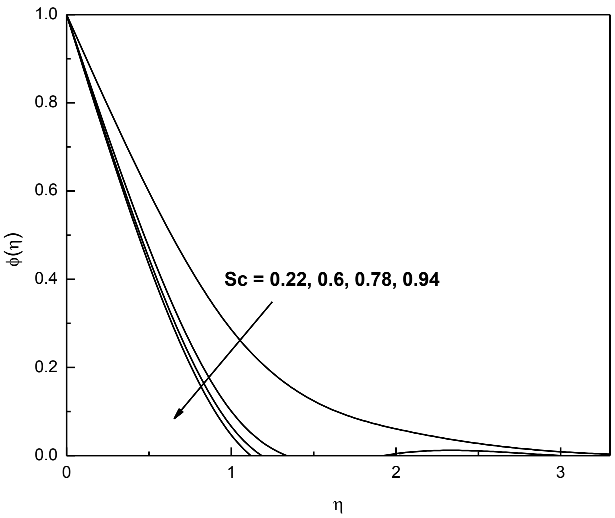

Figure 8. Temperature profiles for different values of Schmidt number *(Sc)*

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