Steady MHD Free Convection Flow with Thermal Radiation Past a Vertical Porous Plate Immersed in a Porous Medium

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Abstract: The present study is concerned with thermal radiation in a steady two-dimensional MHD free convection flow through a porous vertical flat plate immersed in a porous medium. In the analysis a Darcy-Fourchheimer model is considered while the fluid is taken to be gray, absorbing-emitting radiation. The non-linear governing equations have been transformed by the usual similarity transformation to a system of ordinary differential equations. These dimensionless similar equations are then solved numerically employing the Nachtshheim-Swigert shooting iteration technique along with sixth order Runge-Kutta integration scheme. Finally the effects of the pertinent parameters are examined.

Key words: Boundary layer, darcy number, free convection, magnetic induction, MHD flow, radiation and suction

INTRODUCTION

Considerable interest has recently been shown in radiation interaction with free convection for heat transfer in fluid. This is due to the significant role of thermal radiation in the surface heat transfer when convection heat transfer is small particularly in free convection problems involving absorbing-emitting fluids. One of the initiators of this problem of radiation transfer in a vertical surface is Goody (1956), who considered a neutral fluid. Cess (1966), on the other hand, considered an absorbing-emitting gray fluid with a black vertical plate. His solution was based on perturbation technique and was applicable for small values of the conduction-radiation interaction parameter. Novotny et al. (1974), however, made a non-gray analysis employing the method of local non-similarity and the continuous correlation of Tien and Lowder (1966) to account for the absorption. The effects of radiation on free convection flow of a gas past a semi infinite flat plate was studied by Soundalgekar and Takhar (1981) using the Cogley-Vincentine-Giles equilibrium model. Ali et al. (1984) studied the same effects on natural convection flow but over a vertical surface in a gray gas. Following Ali et al. (1984) and Mansour (1990) studied the interaction of mixed convection with thermal radiation in laminar boundary layer flow over a horizontal, continuous moving sheet with suction and injection. Alabraba et al. (1992) studied the same problem of free convection interaction with thermal radiation in a hydro-magnetic boundary layer taking into account the binary chemical reaction and less attended Soret-Doufour effects. By using the Rosseland diffusion approximation (Sparrow and Cess, 1978), a study of the combined unsteady free convective dynamic boundary layer and thermal radiation boundary layer at a semi-infinite vertical plate was made by Sattar and Kalim (1996). Hossain and Takhar (1996) also analyzed the same effect of radiation using the Rosseland approximation in a mixed convection flow of an optically dense viscous incompressible fluid past a heated vertical plate with a free uniform stream velocity and surface temperature. Since suction is the best control method of boundary layer growth in the presence of radiation El-Areaway (2003) studied the effect of suction/ injection on a micropolar fluid past a continuously moving plate. Ferdows et al. (2004), however, considered a variable suction in a boundary layer flow at a vertical plate with thermal radiation interaction with convection. Very recently Samad and Rahman (2006) investigated the thermal radiation interaction on an absorbing emitting fluid past a vertical porous plate immersed in a porous medium. They considered an unsteady MHD flow and observed that magnetic field can control the heat transfer and radiation shows a significant effect on the velocity as well as temperature distributions.

In analogy with the above works, in the present study, the steady MHD free convection interaction with thermal radiation of an absorbing-emitting fluid along a
porous vertical plate immersed in a porous medium is investigated taking into account the Rosseland diffusion approximation. The investigation is based in known similarity analysis and the local similarity solutions are obtained numerically.

**Mathematical formulation:** Let us consider a steady two-dimensional MHD flow of a viscous incompressible and electrically conducting fluid of temperature $T$ along a vertical porous plate under the influence of a uniform magnetic field with suction. The flow is assumed to be in the $x$-direction, which is chosen along the plate in the upward direction and $y$-axis normal to plate. The flow configuration and coordinate system are shown in Fig. 1.

The fluid is considered to be gray, absorbing emitting radiation but non-scattering medium and the Rosseland approximation is used to describe the radiation heat flux in the energy equation. The radiative heat flux in the $x$-direction is negligible to the flux in the $y$-direction. A uniform magnetic field of strength $B_0$ is applied normal to the plate parallel to $y$-direction. The plate temperature is initially raised to $T_w (> T_\infty)$ which is thereafter maintained constant.

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

**Continuity equation:**

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

**Momentum equation:**

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \frac{1}{\rho} \left( \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial y^2} + g_0 (T - T_\infty) \right)$$

$$- \frac{\rho_e u^2}{k_0} - \frac{\partial u}{\partial n} - \frac{b u^2}{k} \tag{2}$$

**Energy equation:**

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2} = \frac{1}{\rho C_p} \frac{\partial q_r}{\partial y} \tag{3}$$

where $u$ and $V$ are the velocity components along $x$- and $y$- directions respectively, $U$ is the kinematic viscosity, $\rho$ is the density of the fluid, $g_0$ is the acceleration due to gravity, $\beta$ is the coefficient of volume expansion, $\sigma$ is the electric conductivity, $B_0$ is the uniform magnetic field strength (magnetic induction), $K$ is the permeability of porous medium, $T$ and $T_\infty$ are the fluid temperature within the boundary layer and in the free-stream respectively, $q_r$ is the radioactive heat flux, $c_p$ is the specific heat at constant pressure, and $\alpha$ is the thermal diffusivity.

The corresponding boundary conditions for the above problem are given by:

$$u = U_0; v = v_0(x); T = T_w at \ y = 0 \tag{4}$$

$$u = 0; \quad \frac{T}{T_\infty} as \ y \to \infty$$

where $U_0$ is the uniform velocity of the plate, $V_0(x)$ is a nonzero velocity component at the wall, $T_w$ is the temperature of the plate and $T_\infty$ is the temperature of the fluid far away from the plate. By using Rosseland approximation, $q_r$ takes the form:

$$q_r = -\frac{4 \sigma_1}{3 k_1} \frac{\partial T^4}{\partial y} \tag{5}$$

where $\sigma_1$ is the Stefan-Boltzmann constant and $K_1$ 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 $T_\infty$ and neglecting higher order terms, thus:

$$T^4 \equiv 4 T_\infty^3 T - 3 T_\infty^4 \tag{6}$$

Using Eq. (5) and (6), Eq. (3) takes the form:

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{k}{\rho c_p} \frac{\partial^2 T}{\partial y^2} + \frac{16 \sigma_1 T_\infty^3}{3 \rho c_p k_1} \frac{\partial^2 T}{\partial y^2} \tag{7}$$

where $K$ is the thermal conductivity.

In order to obtain similarity solution, for the problem under consideration, we may take the following suitable similarity variables:

$$\eta = \eta \frac{U_0}{2 \sqrt{x^*} f(\eta), \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty} \tag{8}$$

where $f(\eta)$ is the dimensionless stream function. Defining now the velocity components as:
Now introducing the similarity variables from Eq (8) and using Eq (9) into Eq (2) and Eq (6) we have

\[ f''' + f'' + 2 \theta f' - 2 \left( \frac{M}{Re_x} + \frac{1}{Da} \right) f'' + 2 \frac{F_s}{Da} f'^2 = 0 \]  

\[ (3N + 4) \theta'' + 3N \Pr f \theta' = 0 \]  

where \( \gamma = x g \beta \Delta T / u_0^2 = Gr / Re^2 \) is the local buoyancy parameter, \( Gr = g \beta \Delta T x^3 / \nu^2 \) is the local Grashof number, \( Re_x = U_0 x / \nu \) is the local Reynolds number, \( M = B^2 \nu x^2 / \rho v \) is the magnetic field parameter, \( Da = k / \chi^2 \) is the local Darcy number, \( FS = b / x \) is the Forchhemier number, \( N = K K_1 / 4 \sigma T^2 \) is the radiation parameter, \( Pr = \rho c_p / k \) is the Prandtl number.

As a result the corresponding boundary conditions take the form

\[ f = f_w, f' = 1, \ \theta = 1 \text{ at } \eta = 0 \]  

\[ f' = 0, \ \theta = 0 \text{ as } \eta \to \infty \]  

where

\[ f_w = -v_0(x) \sqrt{\frac{2x}{\nu U_0}} \]

is the porosity parameter or suction parameter.

The parameters of engineering interest for the present problem are the skin friction coefficient and local Nusselt number which indicate physically wall shear stress and rate of heat transfer respectively. The skin-friction coefficient is given by:

\[ C_f \left( \frac{Re_x}{2} \right)^{1/2} = f''(0) \]  

And the local Nusselt number may be written as:

\[ Nu \left( \frac{Re_x}{2} \right)^{-1/2} = -\theta'(0) \]  

Thus the values proportional to the skin-friction coefficient and Nusselt number are \( f(0) \) and \( -\theta'(0) \) respectively. In Eq (13) and (14), the gradient values of \( f \) and \( \theta \) of the surface are evaluated when the corresponding differential equations are solved satisfying the convergence criteria.

**Numerical computation:** The numerical solutions of the nonlinear differential Eq. (10) and (11) under the boundary conditions (12) have been performed by applying a shooting method namely Nachtsheim and Swigert (1965) iteration technique (guessing the missing value) along with sixth order Runge-Kutta integration scheme. We have chosen a step size of \( \Delta \eta = 0.01 \) to satisfy the convergence criterion of \( 10^{-6} \) in all cases. The value of \( \eta_\infty \) was found to each iteration loop by \( \eta_\infty = \eta_\infty + \Delta \eta \). The maximum value of \( \eta_\infty \) to each group of parameters \( \gamma, f_w, M, N, Pr, Gr, Da \) and \( Fs \) was determined when the value of the unknown boundary conditions at \( \eta = 0 \) not change to successful loop with error less than \( 10^{-6} \). In order to verify the effects of the step size (\( \Delta \eta \)) we ran the code for our model with three different step sizes as \( \Delta \eta = 0.01, \Delta \eta = 0.005, \Delta \eta = 0.001 \) and in each case we found excellent agreement among them. Figure 2 & 3 show the velocity and temperature profiles for different step sizes respectively.

**RESULTS AND DISCUSSION**

For the purpose of discussing the results, the numerical calculations are presented in the form of non-dimensional velocity and temperature profiles. Numerical computations have been carried out for different values of the buoyancy parameter (\( \gamma \)), suction parameter (\( f_w \)), Magnetic field parameter (\( M \)), radiation parameter (\( N \)), Prandtl number (\( Pr \)), Darcy number (\( Da \)) and Forchhemier number (\( Fs \)).

![Fig. 2: Velocity profiles for different step sizes](image)

![Fig. 3: Temperature profiles for different step sizes](image)
Figure 4 and 5 express the effects of buoyancy parameter $\gamma$ on velocity and temperature profiles. From Fig. 4 we see that velocity increases with the increase of $\gamma$. The temperature profiles decreases with the increase of $\gamma$ as seen in Fig. 5.
Figure 6 and 7 show the effects of magnetic field parameter $M$ on the velocity and temperature profiles. From these figures we see that velocity decreases with the increase of the magnetic parameter $M$. The magnetic field lines act like a string and tend to retard the motion of the fluid. The consequence of which is to increase the rate of heat transfer temperature variation is very negligible as seen in Fig. 7.

Figure 8 and 9 show the velocity and temperature profiles for different values of radiation parameter ($N$). From Fig. 8 it is seen that radiation $N$ has decreasing effect on the velocity field with the increase of $N$. On the other hand the effect of $N$ on the temperature profiles (Fig. 9) are very much prominent showing that temperature decreases with the increase of $N$. For large $N$, the decrease of the temperature is found to be more rapid. From these two figures it is apparent that radiation can control the flow characteristics particularly the temperature distribution.

The effects of the suction parameter ($f_w$) on the velocity and temperature profiles are shown in Fig. 10 & Fig. 11. From Fig. 10 we see that the velocity decreases uniformly with the increase of suction. Figure 11 reveals that temperature profiles decreases rapidly with the increase of the suction velocity or mass transfer parameter.

Figure 12 and 13 show the effect of Prandtl number ($Pr$) on the velocity as well as temperature profiles. Since Prandtl number does not arise directly in the momentum Eq (9), its effects on the velocity profiles are negligible very close to the wall. Temperature decreases with the increase of Pr as seen in Fig. 13.

Figure 14 and 15 show the effects of Darcy number ($Da$) on the velocity and temperature profiles. We have
found that velocity increases with the increase of $Da$. Darcy number is the measurement of the porosity of the medium. As the porosity of the medium increases, the value of $Da$ increases. Figure 15 reveals that temperature profiles decreases with the increase of $Da$.

The effects of Forchhemier ($Fs$) number on the velocity and temperature fields are shown in Fig. 16 and 17. It is observed from those figures that $Fs$ has decreasing effect on the velocity field but far away from the plate these profiles overlap while temperature increases with the increases of $Fs$ as seen in Fig. 17.

The effects of the above mentioned parameters on the skin-friction coefficient and Nusselt number are shown in Table 1-4. These effects as observed from the Tables are found to agree with the effects on the velocity and temperature profiles hence any further discussions about them seem to be redundant.

**NOMENCLATURE**

- $B_0$: Uniform magnetic field strength
- $Pr$: Prandtl number
- $qr$: Rosseland approximation
- $C_f$: Skin friction coefficient
- $C_p$: Specific heat at constant pressure
- $q_w$: Local heat flux
- $Da$: Darcy number
- $T$: Temperature within the boundary layer
- $Fs$: Frochhemier number
- $T_w$: Temperature of the fluid at the plate
- $f$: Dimensionless stream
- $T_{far}$: Temperature of the fluid far away from the plate
- $f_w$: Suction parameter
- $U_0$: Uniform velocity
- $Gr_x$: Local Grashof number
- $u$: Component of velocity in the x-direction
- $v$: Component of velocity in the y-direction
- $k$: permeability constant
- $v_0(x)$: Suction velocity
- $M$: Magnetic field parameter
- $x$: Coordinate along the plate
- $N$: Radiation parameter
- $y$: Coordinate normal to the plate
- $Nu_x$: Local Nusselt number

**Greek symbols:**

- $\eta$: Similarity parameter
- $\Psi$: Stream function
- $\Delta \eta$: Step size
- $\gamma$: Buoyancy parameter
- $\psi$: Stream function
- $\theta$: Dimensionless temperature
- $\gamma$: Buoyancy parameter
- $\rho$: Density of the fluid
- $\sigma$: Electric conductivity
- $\mu$: Coefficient of dynamic viscosity
- $\beta$: Coefficient of volume expansion
- $\nu$: Coefficient of kinematic viscosity
- $\eta$: Similarity parameter
- $k$: Thermal conductivity
- $\Delta \eta$: Step size

**CONCLUSION**

In this study we have studied the thermal radiation interaction with steady MHD boundary layer flow past a continuously moving vertical porous plate immersed in a porous medium. From the present study we can make the following conclusions:

- The suction stabilizes the boundary layer growth.
- The velocity profiles increase whereas temperature profiles decrease with the increase of the free convection current.
- Using magnetic field we can control the flow and heat transfer characteristics.
- Radiation has significant effects on the velocity as well as temperature distribution.
- Large Darcy number leads to the increase of the velocity profiles.
REFERENCES


