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Research Article

THERMOPHORESIS PARTICLE DEPOSITION EFFECT ON MHD FREE CONVECTION FLOW OVER A VERTICAL PLATE WITH SORET AND DUFOUR EFFECTS

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ABSTRACT

The present study is to investigate the effect of heat and mass transfer of an electrically conducting, non-Newtonian power-law fluid in MHD free convection adjacent to a vertical plate within a porous medium in the presence of the thermophoresis particle deposition effect. The equations governing flow are transformed into a set of coupled non-linear ordinary differential equations using similarity transformations and the resulting non-linear differential equation is linearized by Quasi-linearization method and the resulting equations are solved numerically by using implicit finite difference scheme. The parametric study is performed to study the effects of various parameters such as the magnetic parameter M_a, the Dufour number D_f and the Soret number S_r. The results indicate that Increasing the Soret number or decreasing the Dufour number tends to decrease the temperature distribution inside the boundary, but tends to increase the concentration variation. In addition, the thermophoretic deposition velocity decreases as the magnetic parameter or the Dufour number increases, while it increases as the buoyancy ratio or the Soret number increases.

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 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. Thermophoresis causes small particles to deposit on cold surfaces. Thermophoresis principle is utilized to manufacture graded index silicon dioxide and germanium dioxide optical fiber preforms used in the field of communications. In the field of viscous fluids there is a large body of papers dealing with the effect of thermophoresis particle deposition. We limit ourselves to a short description of the status of the art in the laminar regime.

An extensive review and historical development of thermophoresis was provided by Bakanov [1]. A more recent theoretical study on thermophoresis was reported by Brock [2], who derived the expression for the thermal force. Numerical studies on the effect of thermophoresis were reported by a number of investigators using the Eulerian convection diffusion mass transport equation. Rosner and Park [3] developed a boundary layer model for thermophoretically augmented mass, momentum, and heat transfer.

Thermophoresis in the horizontal plate configuration was focused by Goren [4]. The thermophoretic transport of small particles in forced convection flow over inclined plates was studied by Garg and Jayaraj [5].

Due to a broad range of application in geophysics and energy-related problems, convective flows through porous medium have been the subject of considerable study in the past. Cheng and Minkowycz [6] initiated the study of free convective boundary layer flow about a vertical plate embedded in a saturated Darcian porous medium. Some research works have

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been carried out to include various physical aspects of this related subject, such as the free convection flow over a vertical cylinder embedded in porous media [7]. Saritha *et al* [8] studied heat and mass transfer of laminar boundary layer flow of Non-Newtonian power-law fluid past a porous flat plate with Soret and Dufour effects.

Chamkha and Pop [9] presented the similarity solutions for the free convection flow of a Newtonian fluid from a vertical flat plate in porous media taking into account the effect of thermophoresis particle deposition. Rashad [9] further advanced the analysis of [10] to consider the effects of a magnetic field and thermal radiation on thermophoresis particle deposition. As to the non-Newtonian fluids, Chen and Chen [11,12] attacked, using the Runge–Kutta method, the problems of free convection flow of non-Newtonian power-law fluids over a vertical plate, a horizontal circular cylinder, and a sphere within a Darcy porous medium.

J. Venkata Madhu *et al*. [13] have studied Dufour and Soret effect on unsteady mhd free convection flow past a semi-infinite moving vertical plate in a porous medium with viscous dissipation. The Dufour and Soret effects on mixed free-forced convective boundary layer flow with temperature dependent viscosity, by employing the finite difference method. Various other aspects dealing with the Soret and Dufour effects on convective heat and mass transfer along a vertical surface that have been considered include magnetic field [14], to study the Soret and Dufour effects on heat and mass transfer by natural convection from a cone in porous media. Recently, Tai and Char [15] employed the differential quadrature method (DQM) to attack the problem of Soret and Dufour effects on free convection flow of non-Newtonian fluids along a vertical plate in porous media in the presence of thermal radiation. The effects of Soret and Dufour on the couple heat and mass transfer by MHD mixed convection of a power-law fluid over an inclined plate was examined by Pal and Chatterjee [16]. The group theoretic method has been used to perform the problem of the convective heat and mass transfer over a stretching sheet in the presence of heat source/sink [17].

The present paper analyses the effect of heat and mass transfer of non-Newtonian fluid through an impermeable vertical plate embedded in a fluid saturated porous medium considering the Soret and Dufour effects in the presences of the thermophoresis particle deposition effect.

Mathematical Analysis

Consider the Darcian free convective heat and mass transfer flow of a non-Newtonian and electrically conducting fluid with electric conductivity re through an impermeable vertical plate embedded in a fluid-saturated porous medium. The x-axis is taken along the vertical plate from its leading edge and the y-axis is taken to be normal to the plate. The surface of the plate is maintained at a constant temperature T_w and a constant concentration C_w, whereas those of the ambient medium are T_1 and C_1, respectively, and $T_w > T_1$ and $C_w > C_1$. The gravitational acceleration, g, is acting downward in the negative x-direction. Moreover, a uniform magnetic field of strength B_0 is imposed perpendicular to the streamwise direction.

To formulate of the present problem, the following assumptions are made: the fluid and the porous medium are everywhere in local thermodynamic equilibrium; the flow is laminar and incompressible; the flow of a non-Newtonian fluid through the porous medium is obeyed by the power law; thermophysical properties of the fluid and the porous medium are maintained constant, isotropic and homogeneous; the species concentration far from the wall C_1 is infinitesimally small in comparison with that of the wall C_w; the magnetic Reynolds number is taken to be small so that the induced magnetic field is negligible; no external electric field is applied and the Hall effect is neglected; and the boundary layer and Boussinesq approximations are valid.

Under the above assumptions, the boundary layer equations for the present study, in usual notation, are (Chen and Chen [11], Mahdy and Postelnicu [14])

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad \text{-- (1)}$$

$$u^n + u\frac{K\sigma_e {B_0}^2}{\mu} = -\frac{K\rho_\infty g}{\mu}\left(\beta_T(T - T_\infty) + \beta_C(C - C_\infty)\right) \qquad \text{-- (2)}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_m\frac{\partial^2 T}{\partial y^2} + \frac{D_m}{C_s}\frac{K_T}{C_p}\frac{\partial^2 C}{\partial y^2} \qquad \text{-- (3)}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_m\frac{\partial^2 C}{\partial y^2} - \frac{\partial (CV_t)}{\partial y} + \frac{D_m K_T}{T_m}\frac{\partial^2 T}{\partial y^2} \qquad \text{-- (4)}$$

Here u and v are the velocity components in the *x*- and *y*-directions, respectively; K is the Darcy permeability of the porous medium and n is the flow behavior index; ρ and μ are the density and viscosity of the fluid. β_T and β_C are, respectively, the thermal expansion and the concentration expansion coefficients of the non-Newtonian fluid. Furthermore, T is the temperature, C is the concentration; α_m and D_m are the effective thermal diffusivity and mass diffusivity; C_p and C_s are the specific heat at constant pressure and concentration susceptibility; T_m is the mean fluid temperature; and K_T is the thermal diffusion ratio.

The second term on the right-hand side of the species concentration Eq. (4) represents the thermophoresis effect. It is assumed that the species concentration is dilute and the species velocity due to external body forces can be negligible. Thus the thermophoretic velocity v_t associated with the boundary layer approximation is given by Talbot *et al*. [18] as:

$$v_t = -\frac{kv}{T}\frac{\partial T}{\partial y} \qquad \text{-- (5)}$$

where k is the thermophoretic coefficient and kv denotes the thermophoretic diffusivity.

The associated boundary conditions are as follows:

$$v = 0, T = T_w, C = C_w \; at \; y = 0 \qquad \text{-- (6)}$$

$$u \to 0, T \to T_\infty, C \to C_\infty \; as \; y \to \infty \qquad \text{-- (7)}$$

As a prelude to obtain solutions, the governing Eqs. (1)–(4) are first transform into a dimensionless form. To do this, the following dimensionless variables are introduced.

$$X = \frac{x}{l},\; Y = \frac{y}{l},\; U = \frac{u}{U_c},\; V = \frac{v}{U_c},\; V_t = \frac{lv_t}{\alpha_m},$$
$$\theta = \frac{T - T_\infty}{T_w - T_\infty},\; \emptyset = \frac{C - C_\infty}{C_w - C_\infty} \qquad \text{--(8)}$$

Where $U_c = \left[\rho_\infty g\ \beta_T K\ (T_w - T_\infty)/_{\mu}\right]^{1/n}$ is the characteristic velocity and l is the length of the plate. Substituting Eq. (8) into Eqs. (1)–(5) yields

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \quad \text{-- (9)}$$

$$U^n + M_a U = \theta + N\varphi \quad \text{-- (10)}$$

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{1}{Ra^*}\left(\frac{\partial^2 \theta}{\partial Y^2} + D_f \frac{\partial^2 \varphi}{\partial Y^2}\right) \quad \text{-- (11)}$$

$$U\frac{\partial \varphi}{\partial X} + V\frac{\partial \varphi}{\partial Y} = \frac{1}{Ra^*}\left(\frac{1}{Le}\frac{\partial^2 \varphi}{\partial Y^2} - \frac{\partial(\varphi V_t)}{\partial Y} + S_r \frac{\partial^2 \theta}{\partial y^2}\right) \quad \text{-- (12)}$$

$$V_t = -\frac{KP_r}{N_t+\theta}\frac{\partial \theta}{\partial Y} \quad \text{-- (13)}$$

In the foregoing equation,

$M_a = \left(\frac{K\sigma_e {B_0}^2}{\mu}\right)\left[\frac{\rho_\infty g\ \beta_T K\ (T_w - T_\infty)}{\mu}\right]^{\frac{1-n}{n}}$ is the modified magnetic parameter;

$N = \frac{\beta_C(C_w - C_\infty)}{\beta_T(T_w - T_\infty)}$ is the buoyancy ratio of concentration to temperature;

$Ra^* = \left[\frac{\rho_\infty g\ \beta_T K\ (T_w - T_\infty) l^n}{\mu \alpha_m^n}\right]^{1/n}$ is the modified Rayleigh number;

$Le = \frac{\alpha_m}{D_m}$ is the Lewis number;

$p_r = \frac{\nu}{\alpha_m}$ is the Prandtl number,

and the dimensionless parameters D_f, S_r, N_t are the Dufour number, Soret number and thermophoresis parameter, respectively, which are defined as

$$D_f = \frac{D_m K_T (C_w - C_\infty)}{C_s C_p \alpha_m (T_w - T_\infty)},\ S_r = \frac{D_m K_T (C_w - C_\infty)}{T_m \alpha_m (T_w - T_\infty)},\ N_t = \frac{T_\infty}{(T_w - T_\infty)}$$

By using the following similarity transformations

$$\psi = \sqrt{\frac{X}{Ra^*}} f(\eta)\ ,\ \eta = \sqrt{\frac{Ra^*}{X}} Y, \theta = \theta(\eta), \varphi = \varphi(\eta) \quad \text{--(14)}$$

Where ψ is the stream function defined as $U = \frac{\partial \psi}{\partial Y}, V = -\frac{\partial \psi}{\partial X}$, such that the continuity equation (9) is satisfied automatically. f is the reduced stream function for the flow.

Substituting equation (14) into equations (10)-(12), one can arrive at the following ordinary differential equations:

$$(f')^n + M_a f' = \theta + N\varphi \quad \text{--(15)}$$

$$\theta'' + \frac{1}{2} f\theta' + D_f \varphi'' = 0 \quad \text{--(16)}$$

$$\frac{1}{L_e}\varphi'' + \frac{1}{2} f\varphi' + \frac{KP_r}{N_t+\theta}\left(\theta'\varphi' + \theta''\varphi - \frac{\varphi(\theta')^2}{N_t+\theta}\right) + S_r\theta'' = 0 \quad \text{--(17)}$$

The corresponding boundary conditions are obtained as

$f=0, \theta=1, \varphi=1$ at $\eta = 0$ -- (18)

$f'=0, \theta=0, \varphi=0$ as $\eta \to \infty$ -- (19)

It is pertinent to note that n = 1 in Eq. (15) corresponds to Darcian Newtonian fluid flow, while k = 0 in Eq. (17) corresponds to without considering the thermophoresis effect. Finally, the physical quantities of primary interest in this problem are the dimensionless temperature profiles $\theta(\eta)$, the dimensionless concentration profiles $\varphi(\eta)$ and the wall thermophoretic deposition velocity, which is given by

$$V_{tw} = -\frac{KP_r}{N_t+1}\left(\frac{\partial \theta}{\partial \eta}\right)_{\eta=0} \quad \text{-- (20)}$$

NUMERICAL METHOD

The set of governing Eqs. (15)-(17) together with the boundary conditions (18) and (19) is highly nonlinear and coupled. These equations are solved particularly for Newtonian fluids by taking n = 1. Now by using Finite difference Scheme, the governing equations are transformed into a system of linear equations. Now the computation procedure is employed to obtain the numerical solutions in which first the momentum equation is solved to obtain the values of f using which the solution of coupled energy and concentration equations are solved under the given boundary conditions using Thomas algorithm for various parameters entering into the problem and computations were carried out by using The numerical solutions of f are considered as (n+1)th order iterative solutions and F are the nth order iterative solutions. After each cycle of iteration the convergence check is performed, and the process is terminated when $|F - f| < 10^{-4}$

RESULTS AND DISCUSSIONS

The effect of magnetic field parameter on dimensionless velocity profiles with constant Dufour number, Soret number, Lewis number, Prandtl number, Thermophoresis parameter and buoyancy ratio parameter are presented in Fig. 1. It is observed that the velocity of the fluid decreases with the increase in magnetic field parameter.

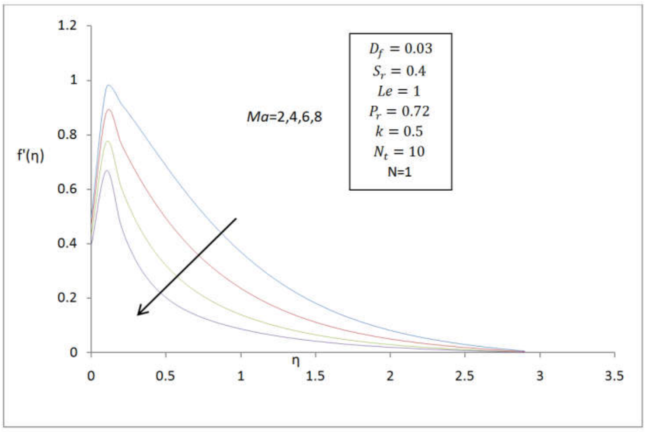

Fig 2 Variation of Temperature profiles with η at different values of *Ma*

The dimensionless temperature profiles for different values of magnetic field with constant Dufour number, Soret number, Lewis number, Prandtl number, Thermophoresis parameter and buoyancy ratio parameter are demonstrated in Fig. 2. It is seen that the temperature of the fluid rises with the increase of magnetic parameter.

The dimensionless concentration profiles for different values of magnetic field with constant Dufour number, Soret number, Lewis number, Prandtl number, Thermophoresis parameter and buoyancy ratio parameter are demonstrated in Fig. 3. It is seen that the concentration of the fluid rises with the increase of magnetic parameter.

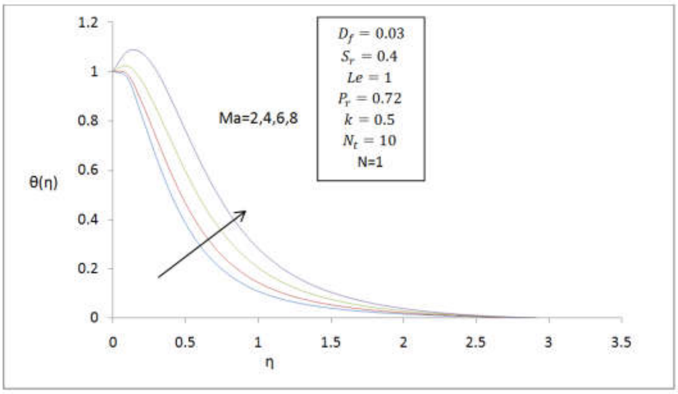

Fig 2 Variation of Temperature profiles with η at different values of *Ma*

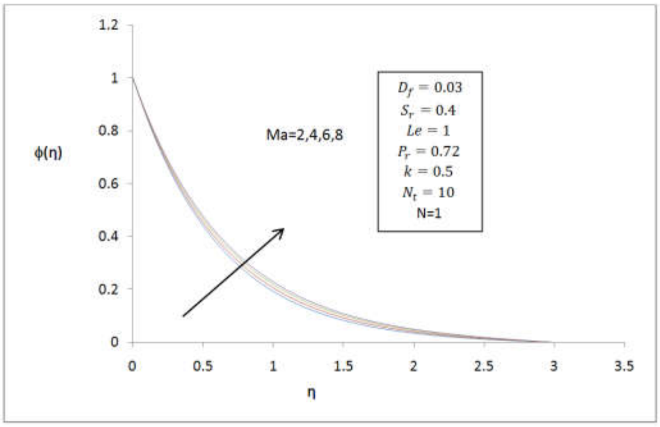

Fig 3 Variation of Concentration profiles with η at different values of *Ma*

The effects of Soret and Dufour numbers on velocity profiles and temperature profiles are shown in Fig. 4. As there is a decrease in the Soret number or an increase in the Dufour number, the temperature decreases. Here the variation in the profiles is very low. The variation in concentration profiles with the change in Soret and Dufour number is displayed in Fig. 5. The concentration increases as there is an increase in Dufour number or decrease in Soret number.

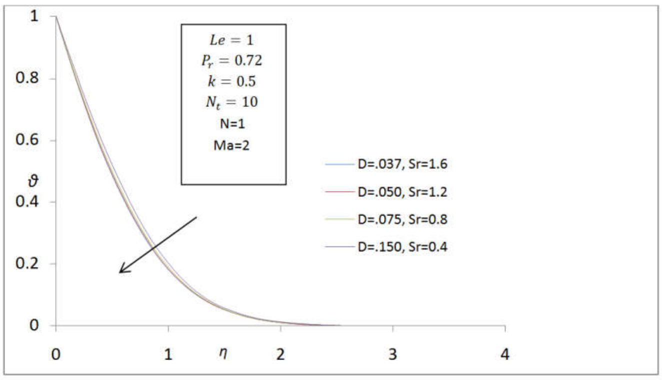

Fig 4 Variation of Temperature profiles with η at different values of D, Sr

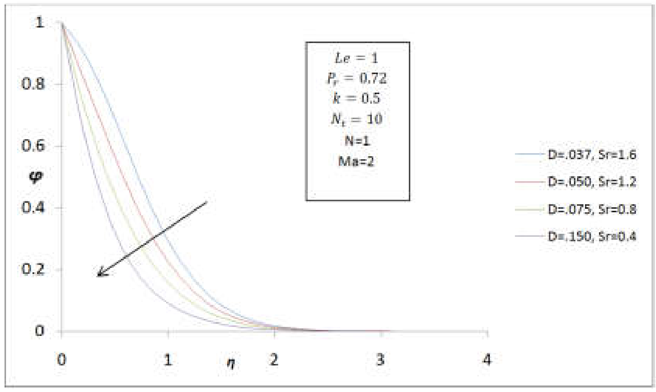

Fig 5 Variation of Concentration profiles with η at different values of D, Sr

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