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Steady Mixed Convective Hydromagnetic Flow Past a Vertical Porous Plate in Presence of Source and Sink

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Abstract

Purpose: This paper deals with the steady mixed convective hydromagnetic flow past a vertical porous plate embedded in a homogeneous porous medium in presence of source and sink.

Findings: The objective is to obtain the solution by using homotopy analysis method. The zeroth order and m^{th} order deformations equations are obtained by using HAM.

Keywords: Mixed convection; Porous medium; Homotopy analysis method; Convergence; System of nonlinear differential equations

Introduction

In mathematics and physics, nonlinear partial differential equations are partial differential equations with nonlinear terms. A few nonlinear differential equations have known exact solutions, but many which are important in applications do not. Sometimes these equations may be linearized by an expansion process in which nonlinear terms are discarded. When nonlinear terms make vital contributions to the solution this cannot be done, but sometimes it is enough to retain a few small ones. Then a perturbation theory may be used to obtain the solution. The differential equations may sometimes be approximated by an equation with small nonlinearities in more than one way, giving rise to different solutions valid over different range of its parameters. Free convection heat transfar in MHD laminar flow past porous plate embedded porous medium has been the subject of great deal of attention because of any engineering applications suchas in heat exchangers nuclear reactors, the design of coolant plates for power transformers, electronic cooling,thermal insulation, solor collectors and so on. Reviews and the applications related to convective flows in porous media and/or magnetic field are available in Rosa, Bejan, Kaviany, Vafai, Nield and Bejan, Ferraro and Plumpton. Modeling of natural convection flow, in general, leads to the need to solve non-linear equations.

The approximation solutions of these equtions are obtained through analytical approach. Therefore, many efforts have been made by researchers to find ways to solve these non-linear equations or to reduce the error in the solutions. These methods are widely used in engineering problems. especially in thermo-convection regimes and also in nuclear, geophysical and naval energy systems. Among these methods, the homotopy analysis method and the homotopy perturbation method are two powerful methods, which give acceptable analytical results with convergence and stability. Liao developed the homotopy analysis method and used in a series of papers are witness of the usefulness of HAM. The HAM is independent of any small physical parameter, unlike the regular perturbation technique. Besides, different from all previous analytical methods, the homotopy analysis method provides us with a simple way to ensure the convergence of the series solution, so that we can always get accurate enough approximations [1-4].

Recently, singh and coauthor have studied convective flow problems under different physical situations including some models, where in the use of homotopy analysis method and similarity transformation followed by perturbation technique have been made. Now, it is proposed to study two-dimensional mixed convection flow past a semi-infinite vertical porous plate embedded in homogenious porous medium under the influence of transversely applied uniform magnetic field of small intensity. The solution of the model is obtained by HAM as well as by introducing usual similarity transformations following regular perturbation technique. The non-dimensional velocity and temperature field are obtained by both the methods [5,6].

The main goal of this paper is to obtain the solution by using homotopy analysis method. The zeroth order and m^{th} order deformations equations are obtained by using HAM.

Mathematical Formulation

Consider two dimensional, steady, laminar, mixed convective flow of an electrically conducting incompressible, viscous fluid along a semi-infinite vertical porous flat plate. In cartesian coordinate system, x-axis is measured along the plate and y-axis normal to it. The magnetic field of uniform strength B_0 is applyed in y-direction, which is normal to the flow. Large suction is imposed at the surface of the plate. The plate is stationary in its own plane and the free stream velocity of the fluid is U_∞ and the temperature of the plate is held uniform at T_w, which is higher than ambient temperature. The permeability is considered to be variable depending on the distance measured from the leading edge and there exists presence of source and sink. In addition, the present analysis is based on the following assumptions [7,8]:

1. The magnetic field is of small intensity, so that induced magnetic field is negligible compared to the applied magnetic field.

2. In the energy equation, the Joule heating and viscous dissipation terms as well as the term due to electrical dissipation is negligible.

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3. All the fluid properties are constant except the variation of density with temperature as such Boussinesq approximation is invoked.

4. The fluid has constant kinematic viscousity.

5. The porous medium is homogeneous.

By the equations of continuity, momentum and energy for the present model can be written as:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}+g\beta(T-T_\infty)-\frac{\nu(u-U_\infty)}{k^{'}}-\frac{\sigma B_0^2(u-U_\infty)}{\rho} \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{K_T}{\rho C_P}\frac{\partial^2 T}{\partial y^2}+\frac{Q}{\rho C_P}(T-T_\infty) \tag{3}$$

where,

Q=Heat flux,

Q>0(source), Q<0(sink),

B_0=magnetic induction,

g=acceleration due to gravity,

K=local permeability parameter,

T=temperature inside the thermal boundary layer,

T_∞=temperature far away from the porous plate,

U_∞=free stream velocity,

V_T=thermophoretic velocity,

u,v=velocity of components along x and y directions,

β=the volumetric coefficient of thermal expansion,

ν=kinematic viscousity of the fluid,

ρ=density of the fluid,

σ=electrical conductivity of the fluid.

The appropriate boundary conditions are as follows:

u=0 , $V=v_w(x)$, $T=T_w$, at y=0

$$u\to U_\infty \quad T\to T_\infty \quad as \quad y\to\infty \tag{4}$$

where,

T_w=temperature of the porous plate,

$v_w(x)$=permeability of the porous plate.

In order to obtain similarity equations of the problem, we introduce the following nondimensional variables [9-12]:

$$\xi=y\sqrt{\frac{U_\infty}{2\ell x U_\infty}} \quad \psi=\sqrt{2\ell x u_\infty}F(\xi) \quad G(\xi)=\frac{T-T_\infty}{T_W-T_\infty}$$

where,

ψ is stream function,

$F(\xi)$=non-dimensional velocity,

$G(\xi)$=non-dimensional temperature,

x,y=sparial coordinates along the axes.

Since $u=\frac{\partial\psi}{\partial y}$ and $v=-\frac{\partial\psi}{\partial x}$ we have:

$$u=U_\infty\frac{dF}{d\xi} \quad and \quad v=-\sqrt{\frac{\ell U_\infty}{2x}}(F-\xi\frac{dF}{d\xi}) \tag{5}$$

The equation of continuity (3) is automatically satisfied for u and v.

Substituting (7) in (4) and (5). we obtain the following nonlinear differential equations are similar:

$$\frac{d^3F}{d\xi^3}+\frac{Fd^2F}{d\xi^2}+\gamma G-M_1(\frac{dF}{d\xi}-1)=0 \tag{6}$$

$$\frac{d^2G}{d\xi^2}+PrF\frac{dG}{d\xi}+\frac{Q\lambda_g G}{K}=0 \tag{7}$$

where

$M_1=M+K^{-1}$,

$Re_x=\frac{U_\infty 2x}{\ell}$ (Reynolds number)

$Pr=\frac{\ell\rho C_p}{K_T}$ (Prandtl number)

$M=\frac{\sigma B_0^2 2x}{\rho U_\infty}$ (magnetic field parameter)

$\gamma=\frac{Grx}{Rex^2}$ (buoyancy parameter)

$Gr_x=\frac{g\beta(T_w-T_\infty)(2x)^3}{\ell^2}$ (Groshoff number)

$K=\frac{K^{'}U_\infty}{2x}$ (permeability parameter)

$\lambda_g=\frac{\ell K^{'}}{K_T}$

The case γ>>1 corresponds to pure free convection. γ=1 corresponds to mixed(free and forced) convection and γ<<1 corresponds to pure forced convection. The positive values of S denote heat absorption, whereas negative values denote heat generation.

On introducing (7) the boundary conditions (6) turn into:

F=fw, $\frac{dF}{d\xi}=0$, G=1 at ξ=0

$$\frac{dF}{d\xi}\to 1 \quad G\to 0 \quad as \quad \xi\to\infty \tag{8}$$

Here $f_w=-v_w(x)\sqrt{\frac{2x}{\ell U_\infty}}$ is wall suction velocity at the permeable plate. Here f_w>0 denotes the suction.

Solution of the Problem

To obtain the solution by the use of homotopy analysis method,we choose the initial guesses in the following forms:

$$F_0(\xi)=(f_w-1)+\xi+exp(-\xi),\ G_0(\xi)=exp(-\xi) \tag{9}$$

Also,we choose the linear operators in the following form:

$$L_1(F)=\frac{d^3F}{d\xi^2},\ L_2(F)=\frac{d^2G}{d\xi^2}+\frac{dG}{d\xi} \tag{10}$$

The auxiliary linear operators $L_1(F)$ and $L_2(F)$ expressed in (22) have the following properties:

$$L_1(C_1e^{-\xi}+C_2\xi+C_3)=0,\ L_2(C_4e^{-\xi}+C_5)=0 \tag{11}$$

The constants C_1,C_2,C_3,C_4 and C_5 are to be determined with initial conditions:

Let $q\in[0,1]$ be the embedding parameter h_1 and h_2 be the non-zero

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auxiliary parameters used in (16)-(17). Also, the nonlinear operators N_1 and N_2 in terms of $F(\xi,q)$ and $G(\xi,q)$ are defined as follows:

$$N_1[F(\xi;q)G(\xi;q)] = \frac{d^3F(\xi;q)}{d\xi^3} + \frac{F(\xi;q)d^2F(\xi;q)}{d\xi^2} + \gamma G(\xi;q) - M_1(\frac{dF(\xi;q)}{d\xi} - 1) \quad (12)$$

$$N_2[F(\xi;q)G(\xi;q) = \frac{d^2G(\xi;q)}{d\xi^2} + PrF(\xi;q)\frac{dG(\xi;q)}{d\xi} + \frac{Q\lambda_g G(\xi;q)}{K} \quad (13)$$

Zeroth order deformation equations

The generalization of the homotopy analysis method, the so called zerth order deformation equation are given by,

$$(1-q)L_F[F(\xi;q) - F_0(\xi)] = qh_1N_1[F(\xi;q), G(\xi;q)] \quad (14)$$

$$(1-q)L_G[G(\xi;q) - G_0(\xi)] = qh_2N_2[F(\xi;q), G(\xi;q)] \quad (15)$$

$$F(0;q) = f_w, \quad \frac{dF}{d\xi}(\xi;q) = 0, \quad \frac{dF}{d\xi}(\infty;q) = 1 \quad (16)$$

$$G(0;q) = 1 \quad G(\infty;q) = 0 \quad (17)$$

The auxiliary parameter, h increases the convergence of the results, when q=0 and q=1 have the solutions as,

$$F(\xi;0) = F_0(\xi), F(\xi;1) = F(\xi) \quad (18)$$

$$G(\xi;0) = G_0(\xi), G(\xi;1) = G(\xi) \quad (19)$$

when q increses from 0 to 1 then $F(\xi;0)$ and $G(\xi;0)$ varies from $F_0(\xi)$ and $G_0(\xi)$ to $F(\xi)$ and $G(\xi)$.

Differentiating with respect to q by the use of Taylor's series, we have:

$$F(\xi;q) = F_0(\xi) + \sum_{m=1}^{\infty} F_m(\xi)q^m, F_m(\xi) = \frac{1}{m!}\frac{\partial^m F(\xi;q)}{\partial q^m}|_{q=0} \quad (20)$$

$$G(\xi;q) = G_0(\xi) + \sum_{m=1}^{\infty} G_m(\xi)q^m, G_m(\xi) = \frac{1}{m!}\frac{\partial^m G(\xi;q)}{\partial q^m}|_{q=0} \quad (21)$$

The series (22)-(23) are convergent at (q=1).The solution of (22)-(23) are as follows:

$$F(\xi;q) = F_0(\xi) + \sum_{m=1}^{\infty} F_m(\xi) \quad (22)$$

$$G(\xi;q) = G_0(\xi) + \sum_{m=1}^{\infty} G_m(\xi) \quad (23)$$

mth order deformation equations

To obtain mth-order deformation equations, we define the vector [13,14]:

$$\vec{F}_m = \{F_0, F_1, F_2 ....F_m\} \quad (24)$$

$$\vec{G}_m = \{G_0, G_1, G_2 ....G_m\} \quad (25)$$

$$L_1[F_m(\xi) - X_m F_{m-1}(\xi)] = h_1 R_m^F(\xi) F_1(\xi) \quad (26)$$

$$L_2[G_m(\xi) - X_m G_{m-1}(\xi)] = h_1 R_m^G(\xi) G_2(\xi) \quad (27)$$

subject to the boundary conditions:

$$F_m(0) = \frac{dF_m}{d\xi}(0) = \frac{dF_m}{d\xi}(\infty) = 0 \quad (28)$$

$$G_m(0) = G_m(\infty) = 0 \quad (29)$$

$$R_m^F(\xi) = \frac{d^3F_{m-1}}{d\xi^3} + \sum_{n=0}^{m-1} F_n \frac{Fd^2F}{d\xi^2} + \gamma G - m - 1 - M(\frac{dF_{m-1}}{d\xi} + M_1(1 - X_m)) \quad (30)$$

$$R_m^G(\xi) = \frac{d^2G_{m-1}}{d\xi^2} + Pr\sum_{n=0}^{m-1} F_n \frac{dG_{m-1-n}}{d\xi} + \frac{Q\lambda_g G_{m-1}}{K} \quad (31)$$

$$X_m = \begin{cases} 0 & m \le 1 \\ 1 & m > 1 \end{cases} \quad (32)$$

$$and\ F_1(\xi) = G_2(\xi) = e^{-\xi} \quad (33)$$

Applying the inverse linear operator to both sides of the equations (28) and (29).

Solution by Analytic Approximation Method

To obtain the velocity and temperature field, the coupled equations (8)-(9) cannot be solved directly. To solve them, we assume:

$$\zeta = \xi f_w, \quad F(\xi) = f_w\Theta(\zeta), \quad G(\xi) = f_w^2\Phi(\zeta) \quad (34)$$

$$\frac{d^3\Theta}{d\zeta^3} + \Theta(\zeta)\frac{d^2\Theta}{d\zeta^2} = \varepsilon(M_1\frac{d\Theta}{d\zeta} - \gamma\Phi - \varepsilon) \quad (35)$$

$$\frac{d^2\Phi}{d\zeta^2} + Pr\frac{d\Phi}{d\zeta} = -\frac{Q\lambda_g\Phi\varepsilon}{K} \quad (36)$$

Introducing (36), the boundary conditions (10) become:

$$\Theta(\zeta) = 1 \quad \frac{d\Theta}{d\zeta} = 0, \quad \Phi(\zeta) = \varepsilon, \quad at\ \zeta = 0$$

$$\frac{d\Theta}{d\zeta} \to \varepsilon \quad \Phi(\zeta) \to 0 \quad \zeta \to \infty \quad (37)$$

where $\varepsilon = (1/f_w^2)$ is very small. Hence, $\Theta(\zeta)$ and $\Phi(\zeta)$ can be expressed in terms of ε as follows:

$$\Theta(\zeta) = 1 + \varepsilon\Theta_1(\zeta) + \varepsilon^2\Theta_2(\zeta) + \varepsilon^3\Theta_3(\zeta) + ... \quad (38)$$

$$\Phi(\zeta) = 1 + \varepsilon\Phi_1(\zeta) + \varepsilon^2\Phi_2(\zeta) + \varepsilon^3\Phi_3(\zeta) + ... \quad (39)$$

Introducing these expressions (29)-(30) for $\Theta(\zeta)$ and $\Phi(\zeta)$ into equations (37)-(38) and considering the terms upto $o(\varepsilon^3)$, we obtain following three sets of ordinary differential equations and corresponding boundary conditions:

First order $o(\varepsilon)$:

$$\frac{d^3\Theta_1}{d\zeta^3} + \frac{d^2\Theta_1}{d\zeta^2} = 0 \quad (40)$$

$$\frac{d^2\Phi_1}{d\zeta^2} + Pr\frac{d\Phi_1}{d\zeta} = \frac{-2Q\lambda_g\varepsilon}{K} \quad (41)$$

with the following boundary conditions:

$$\Theta_1(\zeta) = 0, \quad \text{——} = 0, \quad \Phi_1(\zeta) = 1\ at\ \zeta = 0$$

$$\frac{d\Theta_1}{d\zeta} \to 1, \quad \Phi_1(\zeta) \to 0\ as\ \zeta \to \infty \quad (42)$$

Second order $o(\varepsilon^2)$:

$$\frac{d^3\Theta_2}{d\zeta^3} + \frac{d^2\Theta_2}{d\zeta^2} + \Theta_1(\zeta)\frac{d^2\Theta_1}{d\zeta^2} = M_1\frac{d\Theta_1}{d\zeta} - \gamma\Phi_1(\zeta) - 1 \quad (43)$$

$$\frac{d^2\Phi_2}{d\zeta^2} + Pr\frac{d\Phi_2}{d\zeta} = \frac{-2Q\lambda_g\Phi_1}{K} - 2Pr\Theta_1\frac{d\Phi_1}{d\zeta} \quad (44)$$

with the following boundary conditions:

$$\Theta_2(\zeta) = 0, \quad \frac{d\Theta_2}{d\zeta} = 0, \quad \Phi_2(\zeta) = 0\ at\ \zeta = 0$$

$$\frac{d\Theta_2}{d\zeta} \to 0, \quad \Phi_2(\zeta) \to 0\ as\ \zeta \to \infty \quad (45)$$

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Third order o(ε^3):

$$\frac{d^3\Theta_3}{d\zeta^3}+\frac{d^2\Theta_3}{d\zeta^2}=M_1\frac{d\Theta_2}{d\zeta}-\gamma\Phi_2(\zeta)-\Theta_1(\zeta)\frac{d^2\Theta_2}{d\zeta^2}-\Theta_2(\zeta)\frac{d^2\Theta_1}{d\zeta^2} \quad (46)$$

$$\frac{d^2\Phi_3}{d\zeta^2}+Pr\frac{d\Phi_3}{d\zeta}=-3Pr\Theta_1\frac{d\Phi_2}{d\zeta}-3Pr\Theta_2\frac{d\Phi_1}{d\zeta}-\frac{2Q\lambda_g\Phi_2}{K} \quad (47)$$

with the following boundary conditions:

$$\Theta_3(\zeta)=0,\quad \frac{d\Theta_3}{d\zeta}=0,\quad \Phi_3(\zeta)=0\ at\ \zeta=0$$

$$\frac{d\Theta_3}{d\zeta}\to 0,\quad \Phi_3(\zeta)\to 0\ as\ \zeta\to\infty \quad (48)$$

The solution of these coupled equation, satisfying the corresponding boundary condition as follows:

$$\Theta_1(\zeta)=e^{-\zeta}+\zeta-1 \quad (49)$$

$$\Phi_1(\zeta)=e^{-Pr\zeta}-\frac{2Q\lambda_g\zeta}{PrK}+1 \quad (50)$$

$$\Theta_2(\zeta)=K_2+K_3e^{-\zeta}-(M_1+1)\zeta e^{-\zeta}+K_1e^{-Pr\zeta}-\frac{1}{2}\zeta^2e^{-\zeta}+\frac{1}{4}e^{-2\zeta} \quad (51)$$

$$\Phi_2(\zeta)=K_4e^{-Pr\zeta}+\frac{2Q\lambda_g e^{-Pr\zeta}}{KPr^2}-2\zeta e^{-Pr\zeta}+4e^{-Pr\zeta}-\frac{2e^{-Pr\zeta}}{Pr}-\frac{2Pre^{-(Pr+1)\zeta}}{(Pr+1)} \quad (52)$$

$$\Theta_3(\zeta)=K_{14}+K_{15}e^{-\zeta}+\frac{5}{72}e^{-2\zeta}+K_5e^{-2\zeta}+K_6\zeta e^{-\zeta}+k_7\zeta e^{-\zeta}-\frac{1}{4}\zeta^2e^{-\zeta}+K_8\zeta^2e^{-\zeta}+K_9\zeta^3e^{-\zeta}$$
$$+\frac{1}{8}\zeta^4e^{-\zeta}+k_{10}e^{-Pr\zeta}+K_{11}\zeta e^{-Pr\zeta}+K_{12}\zeta^2e^{-Pr\zeta}+K_{13}e^{-(Pr+1)\zeta} \quad (53)$$

$$\Phi_3(\zeta)=-Pr\zeta e^{-Pr\zeta}-K_{14}Pr^2e^{-pr\zeta}+\frac{2Q\lambda_g\zeta}{Pr}-2Q\lambda_g e^{-Pr\zeta}-$$
$$Pre^{-Pr\zeta}-\frac{2Q\lambda_g\zeta}{Pr^2}-\frac{2Q\lambda_g\zeta}{-(Pr+1)\zeta}KPr(Pr+1)$$
$$+\frac{Q\lambda_g\zeta}{PrK}-\frac{e^{-(Pr+1)\zeta}}{(Pr+1)}-e^{-Pr}\zeta^2+\frac{2e^{-pr\zeta}}{pr}-2e^{-pr\zeta}-$$
$$\frac{3pr(M_1+1)}{(Pr+1)}\zeta e^{-Pr+1\zeta}-\frac{6Pr}{(Pr+1)^2}e^{-(Pr+1)}(M_1+1) \quad (54)$$
$$-\frac{Q\lambda_g e^{-Pr\zeta}}{KPr^2}+\frac{Q^2\lambda_g^2}{K^2Pr}(e^{-Pr\zeta}-\frac{3}{2}Pr\frac{e^{-(Pr+1)\zeta}}{Pr+1}(\zeta^2)+\frac{3}{2}Pr\frac{e^{-(Pr+1)\zeta^2}}{Pr+1}(\zeta)+$$
$$\frac{3Pr}{1}Pr\frac{e^{-2(Pr+1)\zeta^4}}{Pr+1}(\zeta^2)-\frac{3}{2}Pr\frac{e^{-(Pr+1)\zeta}}{Pr+1}+\frac{3}{1}Pr\frac{e^{-(Pr+1)\zeta^2}}{Pr+1}(\zeta)$$

Conclusion

A set of similarity equations governing the fluid velocity and temperature was obtained by use of similarity transformations. The resulting nonlinear and locally similar ordinary differential equations have been solved by applying homotopy analysis method. Zeroth order and mth order deformation are obtained. By using these equations the effects of magnetic field and magnetic parameter can be investigated by using math software tools like MAT LAB, Maple, Mathematica and so on.

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