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Application of Adomian Decomposition Method to the Solution of Magnetohydrodynamic Boundary Layer Flow Over A Flat Plate

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Abstract
The Adomian decomposition method (ADM) is one of the powerful methods used to solve nonlinear differential equations which includes application to MHD boundary layer flow over a flat plate. In this study, we have shown the ability of the method to solve the governing equations of the MHD boundary layer flow problem. The effects of physical parameters such as magnetic field and Prandtl number embedded in the flow are presented and discussed. The results obtained are compared with existing work.
Keywords: Adomian decomposition method (ADM), magnetohydrodynamics, boundary layer

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Nomenclature
Pr- Prandtl number
Nu- Nusselt number
Sk- Skin friction (heat transfer coefficient)
M- Magnetic parameter/ Hartmann number
$f^{'}$- Dimensionless velocity of the fluid
$\cup_{\infty}$−Free stream velocity
(u, v)- Dimensional velocity component of the fluid
T- Dimensional temperature
T_{∞} - Temperature of the fluid far away from the plate
$T_{w\_}$ Temperature of the fluid near the plate or wall temperature
B_0 – Applied Magnetic field
α – Permeability parameter (thermal diffusivity)
p −Pressure
Greek Alphabets
η – dimensionless similarity variable
λ – pressure gradient parameter
φ − stream function
μ – Kinematic Viscosity
σ- Stefan Boltzman constant (electrical conductivity)
ρ- Density of the fluid
θ – Dimensionless temperature

I. Introduction

Problems involving nonlinear partial differential equations can be found in a wide variety of scientific applications such as mathematics, physics, biology, chemistry and engineering problems. More so, many important mathematical models can be expressed in terms of nonlinear partial differential equations which are very difficult to solveAli and Al-saif, [1]; Nhawu*et al*, [12]. The governing equations of the MHD boundary layer flow is one of such models.

Over the years, numerical methods have been used to solve such nonlinear equations. The numerical methods when applied on these kind of equations which are usually very large and difficult to compute causes a loss of accuracy due to the round-off error. Hence, the Adomian decomposition method (ADM) which requires less computation was introduced Ali and Al-saif, [1]. The ADM was developed in the 1980s by George Adomian. This method involves separating the equation under investigation into linear and nonlinear parts. The highest order derivative operator contained in the linear part of the equation is inverted and the inverse operator is then applied to the equation. Any given conditions are taken into consideration. The nonlinear part is decomposed into a series of Adomian polynomials. A solution in the form of a series whose terms are determined by a recursive relationship using these Adomian polynomials are generated Shukur, [16]; Agom and Badmus, [2];Oke, [14];Alhaddad, [3].

The ADM has so many advantages. It solves nonlinear problems directly and with less complications without linearizing, perturbing or making any assumptions that may alter the physical properties/behavior of the model. It requires less computational work and at the same time maintain high accuracy of the numerical solution. It has wide applicability to several types of problems and scientific fields and also develops a reliable analytic solution Jaradat, [8]; Holmquist, [7].

Recently, so many researches have used different methods to study MHD boundary layer flow problems. Jhankal, [9] studied MHD boundary layer flow with low pressure gradient over a flat plate utilizing HPM. Desale and Pradham, [6] obtained a numerical solution of MHD boundary layer flow of an incompressible, viscuous fluid over a nonlinear stretching sheet using the implicit finite difference keller box method. Majety and Gangadhar, [11] analyzed MHD boundary layer flow past a wedge through porous medium with the influence of thermal radiation, heat source, viscuous dissipation and chemical reaction using legendary nactsheim-swigert shooting technique and Runge-kutta sixth order iteration scheme. Chuadhary and Kumar, [5] studied an unsteady MHD boundary layer flow towards a shrinking surface in the presence of a uniform transverse magnetic field using perturbation method. Rajput *et al.*, [14] transformed the problem of a steady laminar MHD boundary layer flow over a continuously moving flat plate using similarity variable. The derivation of the governing equation was done using one parameter group of transformation. Reddy *et al*, [15] numerically studied a steady two dimensional laminar MHD boundary layer flow of a power-law fluid passing through a moving flat plate under the influence of transverse magnetic field using implicit finite difference scheme. Quasi-linearization technique was used to linearize the ODE solution and the systems of algebraic equations were solved using Guass-seidal iterative method. Kumar, [10] investigated the effect of linear thermal stratification in a steady MHD boundary layer convective flow over a stretching sheet in the presence of mass transfer and magnetic field using Runge-kutta forth order method along with shooting technique. Bhattacharyya and Layek [4] analyzed the diffusion of chemically reactive solute distribution in MHD boundary layer flow of an electrically conducting incompressible fluid over a porous flat plate using Runge-kutta method and shooting technique.

From literature, we observe that HPM have been applied on MHD boundary layer flow with low pressure gradient over a flat plate. In this present study, ADM will be used to obtain approximate series solution to MHD boundary layer flow over a flat plate.

II. General Description of the Adomian Decomposition Method (ADM)

In this chapter, we will give a standard description of the ADM. Consider the general equation

$Lu + Nu + Ru = g$,(1)

where $u -$ is the unknown function,

$L -$ is the linear differential operator of higher order which is easily invertible,

$N -$is the nonlinear operator,

$R -$ is the remaining linear part and

$g -$ is the given function.

By defining the inverse operator of L as L^{-1}, we have

$$u = L^{-1}g - L^{-1}Nu - L^{-1}Ru. \qquad (2)$$

By ADM u can be expressed by an infinite series of the form

$u = \sum_{n=0}^{\infty} u_n$,(3)

By ADM also, the nonlinear term can be decomposed by an infinite series of polynomials given by

$N(u) = \sum_{n=0}^{\infty} A_n$,(4)

whereA_n's are the Adomian polynomials defined as $A_n = A_n(u_0, u_1, u_2, \dots\dots, u_n)$.

Substituting equations (3) and (4) into equation (2) and using the fact that R is a linear operator, we obtain

$$\sum_{n=0}^{\infty} u_n = L^{-1}g - L^{-1}\left(\sum_{n=0}^{\infty} R(u_n)\right) - L^{-1}\left(\sum_{n=0}^{\infty} A_n(u_0, u_1, u_2, \dots\dots, u_n)\right), \qquad (5)$$

Hence

$u_0 = L^{-1}g,$

$u_{n+1} = -L^{-1}(R(u_n)) - L^{-1}(A_n(u_0, u_1, u_{2\dots}, u_n))$,(6)

Or equivalently

$$u_0 = L^{-1}g,$$

$$u_1 = -L^{-1}(R(u_0)) - L^{-1}(A_0(u_0)),$$

$u_2 = -L^{-1}(R(u_1)) - L^{-1}(A_1(u_0, u_1))$,(7)

....

To compute A_n, take $N(u) = f(u)$ to be a nonlinear function in u. Then, the infinite series generated by applying the Taylor's series expansion of f about the initial function u_0 is given by

$f(u) = f(u_0) + f'(u_0)(u - u_0) + \frac{1}{2!} f''(u_0)(u - u_0)^2 + \frac{1}{3!} f'''(u_0)(u - u_0)^3 + \ldots$ (8)

where

$$u = u_0 + u_1 + u_2 + u_3 + \cdots,$$

and,

$f(u) = f(u_0) + f'(u_0)(u_1 + u_2 + u_3 + \cdots) + \frac{1}{2!} f''(u_0)(u_1 + u_2 + u_3 + \cdots)^2 + \frac{1}{3!} f'''(u_0)(u_1 + u_2 + u_3 + \ldots)^3 + \ldots$, (9)

By expanding all terms of equation (9), we get

$f(u) =$
$f(u_0) + f'(u_0)(u_1) + f'(u_0)(u_2) + f'(u_0)(u_3) + \cdots + \frac{1}{2!} f''(u_0)(u_1)^2 + \frac{2}{2!} f''(u_0) + \frac{1}{2!} f''(u_0)(u_1 u_2) + \frac{1}{2!} f''(u_0)(u_1 u_3) + \cdots + \frac{1}{3!} f'''(u_0)(u_1)^3 + \frac{3}{3!} f'''(u_0) {u_1}^2 u_2 + \frac{1}{3!} f'''(u_0) {u_1}^2 u_3 + \ldots$, (10)

To obtain the Adomian polynomials, we first reorder and rearrange the terms. The order of each of the terms in (9) depends on both the subscripts and the exponents of the u_n's. For instance,

The order of ${u_m}^n$ is mn. That is, ${u_1}^2$ is of order $1 \times 2 = 2$.

The order of $u_m u_n$ is $m + n$. That is, $u_1 u_2$ is of order 2.

The order of ${u_n}^m {u_l}^k$ is $mn + kl$. That is, ${u_2}^3 {u_1}^3$ is of order $(2 \times 3) + (1 \times 3) = 9$ and so on.

In general, A_n consists of all terms of order n. Therefore, the first three terms of Adomian polynomials are listed as:

$$A_0 = f(u_0),$$

$A_1 = f'(u_0)(u_1)$,
$A_2 = f'(u_0)(u_2) + \frac{1}{2!} f''(u_0)(u_1)^2$,
$A_3 = f'(u_0)(u_3) + \frac{2}{2!} f''(u_0)(u_1 u_2) + \frac{1}{3!} f'''(u_0)(u_1)^3$ …….. (11)

Hence, the general formula for the Adomian polynomials is given as

$A_n = \frac{1}{n!} \frac{d^n}{d\lambda^n} [N(\sum_{i=0}^{n} \lambda^i u_i)]_{\lambda=0}$, $n = 0, 1, 2, 3$ ...(12)

To find the A_n's by Adomian general formula, these polynomials will be computed as follows:

$$A_0 = \frac{1}{0!} \frac{d^0}{d\lambda^0} \left[N\left(\sum_{i=0}^{0} \lambda^i u_i \right) \right]_{\lambda=0} = N(u_0),$$

$$A_1 = \frac{1}{1!} \frac{d}{d\lambda} \left[N\left(\sum_{i=0}^{1} \lambda^i u_i \right) \right]_{\lambda=0} = \frac{d}{d\lambda} N(u_0 + \lambda u_1) = u_1 N'(u_0)$$

$$A_2 = \frac{1}{2!} \frac{d^2}{d\lambda^2} \left[N\left(\sum_{i=0}^{2} \lambda^i u_i \right) \right]_{\lambda=0} = \frac{1}{2!} \frac{d^2}{d\lambda^2} N(u_0 + \lambda u_1 + \lambda^2 u_2) = u_2 N'(u_0) + \frac{1}{2!} N''(u_0)(u_1)^2$$

$A_3 = \frac{1}{3!} \frac{d^3}{d\lambda^3} [N(\sum_{i=0}^{3} \lambda^i u_i)]_{\lambda=0} = \frac{1}{3!} \frac{d^3}{d\lambda^3} N(u_0 + \lambda u_1 + \lambda^2 u_2 + \lambda^3 u_3) = u_3 N'(u_0) + \frac{2}{2!} u_1 u_2 N''(u_0) + \frac{1}{3!} N'''(u_0)(u_1)^3$ (13)

III. APPLICATION

Consider a steady MHD boundary layer flow problem of Jhankal, [9]. The continuity, Momentum and energy equations of this flow are as follows:

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

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{dp}{dx} + \mu \frac{\partial^2 u}{\partial y^2} - \frac{\sigma B_0^2 u}{\rho},$$

$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial^2 y}$, (14)

Along with boundary conditions

$v(x, 0) = u(x, 0) = 0$; $T(x, o) = T_w$ at $\eta = 0$,
$u(x, \infty) \to u_\infty$; $T(x, \infty) \to T_\infty$ as $\eta \to \infty$. (15)

The stream function φ satisfies the equation of continuity such that

$u = \frac{\partial \varphi}{\partial y}$; $v = -\frac{\partial \varphi}{\partial x}$,

with $\varphi = \sqrt{\mu x \, \mathrm{U}_\infty} \; f(\eta)$, $\eta = y\sqrt{\frac{\mathrm{U}_\infty}{\mu x}}$

$$\theta(\eta) = \frac{T - T_\infty}{T_{w-}T_\infty}; T = \theta(\eta)(T_{w-}T_\infty) + T_\infty$$

On transforming the governing equations in terms of f and θ we have:

$f''' = -\frac{ff''}{2} + M^2 f'$. (16)

$\theta'' = -\frac{Prf\theta'}{2}$(17)

Along with the boundary conditions

$\theta(0) = 1;\quad \theta(\infty) = 0; \theta'(0) = B,$

$f(0) = 0;\quad f'(0) = 0;\quad f''(0) = A;\ f'(\infty) = 1.$ (18)

where A and B are $assumed$ $values$.

IV. Method Of Solution

By Adomian decomposition method,

$L_f^{-1} f = M^2 L_f^{-1} f' - \frac{1}{2} L_f^{-1} ff''$, (19)

where

$$L_f^{-1} = \iiint_{000}^{\eta\eta\eta} d\eta d\eta d\eta \quad : L_\theta^{-1} = \iint_{00}^{\eta\eta} d\eta d\eta,$$

hence,

$f = f(0) + \eta f'(0) + \frac{\eta^2}{2} f''(0) + M^2 L_f^{-1} f' - \frac{1}{2} L_f^{-1} ff''$. (20)

Also,

$L_\theta^{-1}\theta = -\frac{Pr}{2} L_\theta^{-1} f\theta'$,(21)

hence,

$\theta = \theta(0) + \eta\theta'(0) - \frac{Pr}{2} L_\theta^{-1} f\theta'$.(22)

f and θ can be decomposed into

$f(\eta) = \sum_{n=0}^{\infty} f_n$;$\theta(\eta) = \sum_{n=0}^{\infty} \theta_n$. (23)

$\therefore\ f_0 = \frac{\eta^2}{2} A;\ \theta_0 = 1 + \eta B$, (24)

$f_{n+1} = M^2 L_f^{-1} \sum_{n=0}^{\infty} f_n' - \frac{1}{2} L_f^{-1} \sum_{n=0}^{\infty} C_n;\ \ \theta_{n+1} = -\frac{Pr}{2} L_\theta^{-1} \sum_{n=0}^{\infty} D_n,$ (25)

Where C_n and D_n are the Adomian polynomials and can be computed using the Adomian general formula

$A_n = \frac{1}{n!}\frac{d^n}{d\lambda^n}[N(\sum_{i=0}^{n} \lambda^i u_i)]_{\lambda=0},\ n = 0, 1, 2, 3 \ldots$(26)

On computing the first three terms of the C_n's andD_n's by using the Adomian general formula, we obtain in general:

$C_0 = f_0 f_0''$; $D_0 = f_0\theta_0'$,

$C_1 = f_0 f_1'' + f_1 f_0''$; $D_1 = f_0\theta_1' + f_1\theta_0'$,

$C_2 = f_0 f_2'' + f_1 f_1'' + f_2 f_0''$; $D_2 = f_0\theta_2' + f_1\theta_1' + f_2\theta_0'$.

Next, we substituteC_0, C_1, C_2, D_0, D_1 and D_2 into equation(25) to obtain

$$f_1 = \frac{M^2 A}{24}\eta^4 - \frac{A^2}{240}\eta^5,$$

$$f_2 = -\frac{M^3 A}{1440}\eta^6 - \frac{M^2 A^2}{1440}\eta^7 + \left(\frac{13\ A^3}{161280} + \frac{M^2 A^2}{26880}\right)\eta^8,$$

$$f_3 = -\frac{M^4 A^2}{1680}\eta^7 + \left(\frac{M^2 A^3}{17472} + \frac{M^3 A}{161280}\right)\eta^8 + \left(\frac{M^3 A^2}{96768} + \frac{M^3 A^2}{1451520} + \frac{M^4 A^2}{207360}\right)\eta^9$$
$$+ \left(\frac{M^2 A^3}{86400} + \frac{M^2 A^3}{2073600} + \frac{13\ M^2 A^3}{2930400} + \frac{M^4 A^2}{4838400}\right)\eta^{10}$$
$$- \left(\frac{13\ A^4}{11404800} + \frac{13\ A^4}{319334400} + \frac{A^4}{4752000} + \frac{M^2 A^3}{950400} + \frac{M^2 A^3}{53222400}\right)\eta^{11},$$

$$\theta_1 = -\frac{Pr\ A\ B}{48}\eta^4,$$

$$\theta_2 = -\frac{Pr\ M^2 A\ B}{1440}\eta^6 + \left(\frac{Pr^2 A^2 B}{2016} + \frac{Pr^2 A^2 B}{20160}\right)\eta^7,$$

$\theta_3 = \frac{\mathrm{Pr}\ A\ BM^3}{161280}\eta^8 + \left(\frac{Pr^2 M^2 A^2 B}{69120} - \frac{Pr^2 M^2 A^2 B}{41472} + \frac{Pr^2 M^2 A^2 B}{207360}\right)\eta^9 - \left(\frac{13\ \mathrm{Pr}\ B\ A^2}{29030400} + \frac{\mathrm{Pr}\ B\ M^2 A^2}{4838400} - \frac{Pr^3 A^3 B}{103680} + \frac{Pr^2 A^3 B}{1036800} - \right.$
$Pr2A3B518400\eta10.$

In general,we have the approximate series solution as,

$$f=\frac{A}{2}\eta^2+\frac{M^2A}{24}\eta^4-\frac{A^2}{240}\eta^5+\frac{M^2A}{720}\eta^6-\left(\frac{M^2A^2}{1680}+\frac{M^2A^2}{10080}+\frac{M^2A^2}{10080}\right)\eta^7+\left(\frac{A^3}{16128}+\frac{A^3}{161280}\right)\eta^8+\frac{M^4A}{40320}\eta^8-\left(\frac{M^2A^2}{48384}+\frac{M^4A^2}{48384}+\frac{M^2A^2}{725760}+\frac{M^4A^2}{120960}+\frac{M^4A^2}{725760}+\frac{M^4A^2}{725760}\right)\eta^9+\left(\frac{M^2A^3}{115200}+\frac{M^2A^3}{691200}+\frac{M^2A^3}{691200}+\frac{M^2A^3}{691200}+\frac{M^2A^3}{414720}+\frac{M^2A^3}{691200}+\right.$$

M2A32419200+M2A314515200+M2A31451520+M2A314515200η10−A41140480+A41140480+A4570240+A431933440+A4319334400η11. (27)

$$\theta=1+\eta B-\frac{Pr\ A\ B}{48}\eta^4-\frac{Pr\ M^2A\ B}{1440}\eta^6+\left(\frac{Pr^2A^2B}{2016}+\frac{Pr\ A^2B}{20160}\right)\eta^7-\frac{\mathrm{Pr}\ A\ BM^2}{10080}\eta^8+\left(\frac{Pr^2M^2A^2B}{69120}+\frac{Pr^2M^2A\ B}{41472}+\frac{Pr\ M^2A^2B}{241920}+\right.$$

Pr M2A2B1451520+Pr M2A2B1451520η9−Pr*B A32903040*+Pr*B A329030400+Pr3A3B103680+Pr2A3B1036800+Pr2A3B518400η10*

(28)

V. Results And Discussion

Numerical results obtained from the variation of the magnetic field parameter (M) and the Prandtl number (Pr) at different values of the pressure gradient $(\boldsymbol{\lambda})$ are presented graphically to illustrate their effects on the velocity and temperature of the flow respectively. Results for Nusselt number$(Nu)$and skin friction coefficient $(Sk)$are also shown.

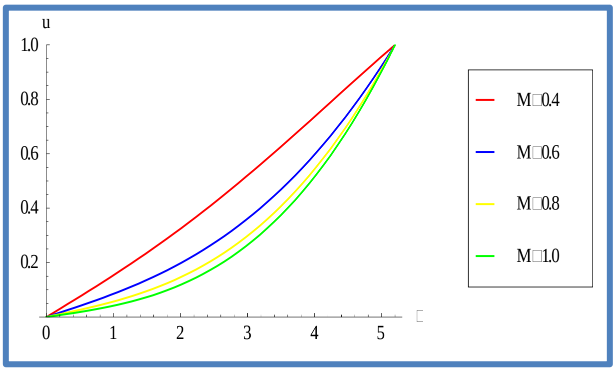

Figure 1: Effect of M on Velocity at $\lambda=0, Pr=0.71$

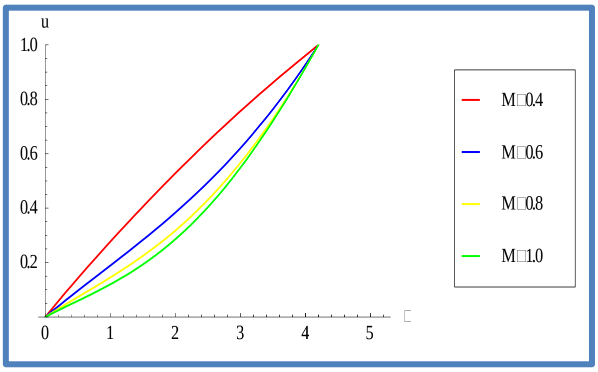

Figure 2: Effect of$M$ on velocity at $\lambda=0.05, Pr=0.71$

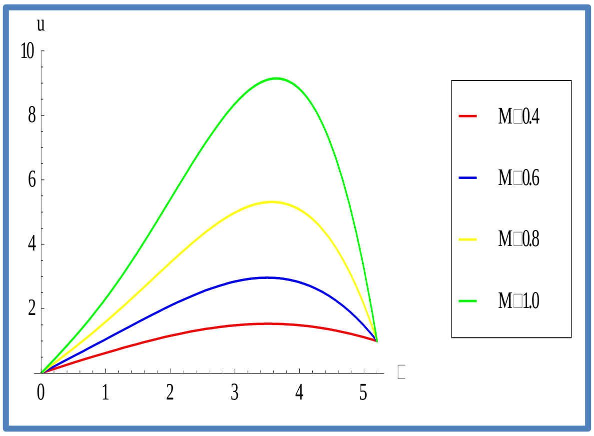

Figure 3: Effect of M on Velocity at $\lambda = 0.1, Pr = 0.71$

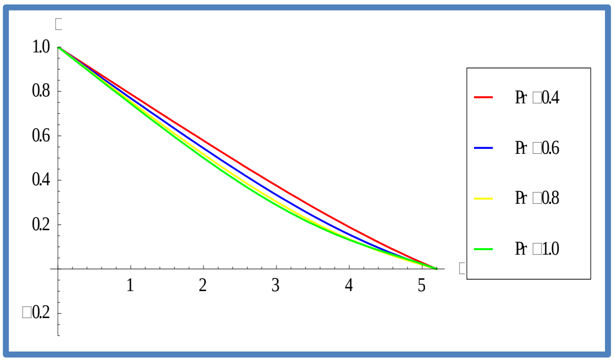

Figure 6: Effect of Pr on Temperature at $\lambda = 0.1, M = 0.8$

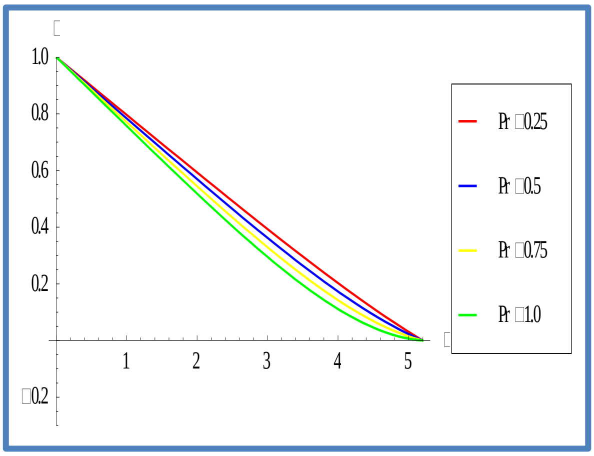

Figure 4: Effect of Pr on Temperature at $\lambda = 0, M = 0.8$

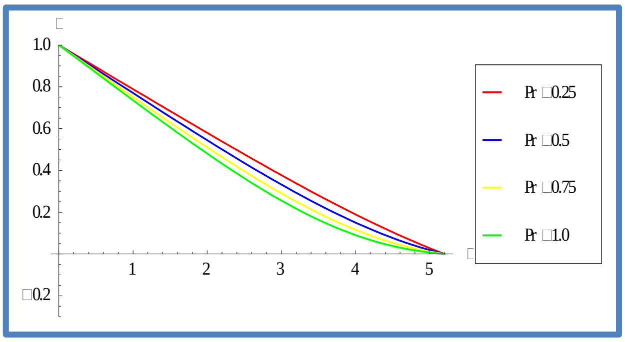

Figure 5: Effect of$M$ on velocity at $\lambda = 0.05, M = 0.8$

Table 1: The effect of Magnetic field parameter (M) variation on Skin Friction(Sk) coefficient

M	λ	Pr	Sk
0.4	0.05	0.71	0.24553
0.6	0.05	0.71	0.165303
0.8	0.05	0.71	0.13041
1.0	0.05	0.71	0.110792

Table 2: The effect of Magnetic field parameter (M) variation on Nusselt number (Nu)

M	λ	Pr	Nu
0.4	0.05	0.71	-0.321858
0.6	0.05	0.71	-0.251597
0.8	0.05	0.71	-0.22978
1.0	0.05	0.71	-0.219099

Figures 1, 2 and 3represent the effects of the magnetic field parameter on the velocity profiles. We notice that at increasing values of the magnetic field parameter,that is, $(M = 0.4, 0.6, 0.8, 1.0)$at$Pr = 0.71\ and\ \lambda = 0.0\ and\ 0.05$, the velocity of the flow decreased. But at $\lambda \geq 0.05$, from figure 4, the flow velocity increased. From figures 4, 5 and 6, wealso observed that as the Prandtl number increases, that is, $(Pr = 0.25,\ 0.5,\ 0.75,\ 1.0)$ and $(Pr = 0.4,\ 0.6,\ 0.8,\ 1.0)$at $M = 0.8\ and\ \lambda = 0.0$, $0.05\ and\ 0.1$ respectively,the flow temperature decreased.

From tables 1 and 2, it is seen that for increasing value of the magnetic field at $Pr = 0.71$ and pressure gradient$\lambda = 0.05$,the skin friction increases while the Nusselt number decreases.

VI. Conclusion

The Adomian decomposition method have successfully been applied on the nonlinear governing equations of MHDboundary layer flow over a flat plate. The results obtained showed excellent agreementwith that of Jhankal [9].

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