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Study of Viscus Incompressible Fluid Past a Hot Vertical Porous Wall in the Presence of Transverse Magnetic Field with Periodic Temperature using the Homotopy Perturbation Method

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Vivek Kumar Sharma [α] & Divya Saxena [σ]

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I. Introduction

The phenomenon of free convection arises in the fluid when temperature varies, this cause density variations leading to buoyancy forces acting on the fluid elements. This process of heat transfer is encountered in aeronautics, chemical engineering and fluid fuel nuclear reactor. But in case of fluid fuel nuclear reactors, the problems of heat transfer become complicated due to variation in wall temperature. Kafoussias. et.al. (1992) investigate the problem of MHD thermal-diffusion effects on free convective and mass transfer flow over an infinite moving plate. Three-dimensional free convective flow and heat transfer through a porous medium was discussed by Ahmed and Sharma (1997). Unsteady free convective MHD flow of a viscous incompressible fluid in porous medium between two long vertical walls discussed by Sarangi and Jose (1998).

Singh and Chand were consider the unsteady free convective MHD flow past a vertical porous plate with variable temperature (2000). Flow of an electrically conducting viscous incompressible fluid past a hot vertical porous wall in the presence of transverse magnetic field with periodic temperature was studied by Sharma (2002). Jain, Khendelwal and Goyal (2002) discussed MHD Three dimensional flow past a Vertical Porous Plate with Periodic Temperature in slip flow Regime. Unsteady free convective MHD flow past an infinite porous vertical plate with variable suction and heat absorbing sink discussed by Sharma (2007).

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Homotopy Perturbation Method was discussed as 'Applications of Homotopy Perturbation Method to Nonlinear wave equations' by J. H. He(2005). A. A. Hemeda (2012) considered the Homotopy Perturbation Method for solving System of Nonlinear Coupled Equations.

II. Homotopy Perturbation Method

Notes

The Homotopy Perturbation Method is a combination of classical Perturbation Technique and Homotopy Theory, which has eliminated the limitations of the traditional perturbation methods. A brief introduction of Homotopy Perturbation Method is given below:

$$L(u) + N(u) - f(r) = 0, r \in \Omega \tag{1}$$

with boundary conditions

$$B\left(u, \frac{\partial u}{\partial n}\right) = 0, r \in \Gamma \tag{2}$$

here L is the linear operator, N is Nonlinear operator, B is boundary operator and $f(r)$ is known analytic function and Γ is the boundary of the domain Ω .

A Homotopy $v(r,p): \Omega \text{ x } [0,1] \rightarrow \text{R}$ for the problem mentioned in equation (1) is

$$H(v,p) = (1-p)[L(v) - L(v_0)] + p[L(v) + N(v) - f(r)] = 0 \tag{3}$$

Or

$$H(v,p) = L(v) - L(v_0) + p[L(v_0) + N(v) - f(r)] = 0 \tag{4}$$

where $p \in [0,1]$ is an embedding parameter and v_0 is an initial approximation of equation (1) which satisfies boundary conditions. It follows from equation (3) and equation (4) that

$$H(v,0) = L(v) - L(v_0) \; and \; H(v,1) = L(v) + N(v) - f(r) \tag{5}$$

The changing process of p from zero to unity is just that of $v(r,p)$ from $v_0(r)$ to $v(r)$. In topology, this is called deformation and $L(v) - L(v_0)$ and $L(v) + N(v) - f(r)$ are called homotopic in topology.

Let

$$v = v_0 + pv_1 + p^2 v_2 + \cdots \tag{6}$$

And setting $p = 1$ result in an approximate solution of equation (1)

$$u = \lim_{p \to 1} v = v_0 + v_1 + v_2 + \cdots \tag{7}$$

The series of equation (7) is convergent for most of the cases. However, the convergent rate is depends upon the nonlinear operator $N(v)$, the following options are already suggested by He (1999):

1. The second derivative of $N(v)$ with respect to v must be small because the parameter may be relatively large i.e. $p \to 1$.
2. The norm of $L^{-1}\left(\frac{\partial N}{\partial u}\right)$ must be smaller than one so that the series is convergent.

III. Formulation of Problem

Let the wall be along the x^*z^* -plane and y^* axis to be taken normal to it. The magnetic field B_0 is applied normal to the wall in the presence of constant suction velocity v_0. Let the span-wise co-sinusoidal temperature be $\theta_w^* = \theta_0\left(1+\epsilon cos\frac{\pi z}{L}\right)$, is taken at the wall.

Where ϵ (<<1) is a small positive value, L is the wave length and θ_0 is a constant and using the Bousinesque approximation, the governing equations of the fluid flow are:

a) *Equation of Momentum*

$$v_0\frac{\partial u^*}{\partial y^*} = \upsilon\left(\frac{\partial^2 u^*}{\partial y^{*2}} + \frac{\partial^2 u^*}{\partial z^{*2}}\right) + g\beta\theta^* - \frac{\sigma B_0^2(u^*-U)}{\rho} \tag{8}$$

b) *Equation of Energy*

$$\rho C_p v_0\frac{\partial \theta^*}{\partial y^*} = \kappa\left(\frac{\partial^2\theta^*}{\partial y^{*2}} + \frac{\partial^2\theta^*}{\partial z^{*2}}\right) + \mu\left[\left(\frac{\partial u^*}{\partial y^*}\right)^2 + \left(\frac{\partial u^*}{\partial y^*}\right)^2 + \sigma B_0^2(u^*-U)^2\right] \tag{9}$$

Where ρ is the density, μ is the coefficient of viscosity, υ is the kinematic viscosity, g is the acceleration due to gravity, β is the coefficient of volumetric expansion, σ is the coefficient of electrical conductivity, B_0 is the coefficient of electromagnetic induction, C_p the coefficient of specific heat, κ is the thermal conductivity, U is the free stream velocity in x^*- direction, θ^* the temperature at any point and v_0 is the suction velocity.

The corresponding boundary conditions are

$$y^* = 0: u^* = 0, \theta^* = \theta_0\left(1+\epsilon\cos\left({}^{\pi z}/_{L}\right)\right);$$

$$y^* \to \infty: u^* \to U, \theta^* \to 0 \tag{10}$$

IV. Method of Solution

Introducing the following dimensionless quantities:

$$u = \frac{u^*}{U}, y = \frac{y^*}{L}, z = \frac{z^*}{L}, \theta = \frac{\theta^*}{\theta_0}, Re = -\frac{v_0 L}{\upsilon}, Pr = \frac{UC_p}{\kappa}, Gr = \frac{g\beta\theta_0\upsilon}{Uv_0^2}, Ec = \frac{U^2}{C_p\theta_0}, M^2 = \frac{\sigma B_0^2 L^2}{\mu}$$

Substituting the dimensionless quantities into equations (8) and (9) and corresponding boundary conditions, we get

$$\frac{\partial u}{\partial y} = -\frac{1}{Re}\left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) - GrRe\theta + \frac{M^2(u-1)}{Re}, \tag{11}$$

$$\frac{\partial \theta}{\partial y} = -\frac{1}{PrRe}\left(\frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2}\right) - \frac{Ec}{Re}\left[\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial z}\right)^2\right] - \frac{EcM^2}{Re}(u-1)^2 \tag{12}$$

where Pr is the Prandtl number, M the Hartmann number, Ec the Eckert number and Re the Reynolds number.
The corresponding boundary conditions are

$$y = 0 : u = 0, \theta = 1 + \epsilon\cos(\pi z),$$

$$y \to \infty : u \to 1, \theta \to 0 \tag{13}$$

Assuming that,

$$u(y,z) = u_0(y) + \in u_1(y,z) + O(\in^2)$$

$$\theta(y,z) = \varphi(y) + \in \theta_1(y,z) + O(\in^2) \tag{14}$$

Using these assumptions into equations (11) and (12) and equating the coefficients of like powers of $\in$, we get

a) Zeroth-Order Equations

$$\frac{d^2 u_0}{dy^2} + Re\frac{du_0}{dy} - M^2 u_0 = -GrRe^2\varphi - M^2 \tag{15}$$

$$\frac{d^2\varphi}{dy^2} + PrRe\frac{d\varphi}{dy} = -EcPr\left[\left(\frac{du_0}{dy}\right)^2 + M^2(u_0-1)^2\right] \tag{16}$$

The corresponding boundary conditions are:

$$y = 0 : u_0 = 0, \varphi = 1;$$

and

$$y \to \infty : u_0 \to 1, \varphi \to 0 \tag{17}$$

b) First-Order Equations

$$\frac{\partial^2 u_1}{\partial y^2} + \frac{\partial^2 u_1}{\partial z^2} + Re\frac{\partial u_1}{\partial y} - M^2 u_1 = -GrRe^2\theta_1 \tag{18}$$

$$\frac{\partial^2 \theta_1}{\partial y^2} + \frac{\partial^2 \theta_1}{\partial z^2} + PrRe\frac{\partial \theta_1}{\partial y} = -2EcPr\frac{\partial u_0}{\partial y}\frac{\partial u_1}{\partial y} - 2EcM^2Pru_1(u_0-1) \tag{19}$$

Notes

The corresponding boundary conditions are:

$$y = 0: u_1 = 0, \theta_1 = \cos \pi z \, ;$$

$$y \to \infty: u_1 = 0, \theta_1 = 0 \tag{20}$$

Notes

The Homotopy for zeroth order equations are following:

$$H(u_0, p) = (1-p)\left[\frac{d^2u_0}{dy^2} + Re\frac{du_0}{dy} - M^2u_0 + (1 - Re - M^2)e^{-y} + M^2\right] + p\left[\frac{d^2u_0}{dy^2} + Re\frac{du_0}{dy} - M^2u_0 + GrRe^2\varphi + M^2\right] = 0 \, , \tag{21}$$

and

$$H(\varphi, p) = (1-p)\left[\frac{d^2\varphi}{dy^2} + PrRe\frac{d\varphi}{dy} - (1 - PrRe)e^{-y}\right] + p\left[\frac{d^2\varphi}{dy^2} + PrRe\frac{d\varphi}{dy} + EcPr\left(\left(\frac{du_0}{dy}\right)^2 + M^2(u_0 - 1)^2\right)\right] = 0 \tag{22}$$

Let

$$u_0 = u_{00} + pu_{01} + p^2u_{02} + \cdots \quad ,$$

$$\varphi = \varphi_0 + p\varphi_1 + p^2\varphi_2 + \cdots \tag{23}$$

Substituting the assumptions from equations (23) into the equations (21) and (22) and comparing the coefficients of like powers of p, we get

$$p^0: \frac{d^2u_{00}}{dy^2} + Re\frac{du_{00}}{dy} - M^2u_{00} + (1 - Re - M^2)e^{-y} + M^2 = 0 \, , \tag{24}$$

$$p^1: \frac{d^2u_{01}}{dy^2} + Re\frac{du_{01}}{dy} - M^2u_{01} - (1 - Re - M^2)e^{-y} + GrRe^2\varphi_0 = 0 \, , \tag{25}$$

$$p^0: \frac{d^2\varphi_0}{dy^2} + PrRe\frac{d\varphi_0}{dy} - (1 - PrRe)e^{-y} = 0 \tag{26}$$

$$p^1: \frac{d^2\varphi_1}{dy^2} + PrRe\frac{d\varphi_1}{dy} + (1 - PrRe)e^{-y} + EcPr\left(\frac{du_{00}}{dy}\right)^2 + EcPrM^2(u_{00} - 1)^2 = 0 \tag{27}$$

Now, the corresponding boundary conditions are:

$$at\ y = 0: u_{00} = 0, u_{01} = 0, \ldots \ and \ \ \varphi_0 = 1, \varphi_1 = 0, \ldots$$

$$at\ y \to \infty: u_{00} = 1, u_{01} = 0, \ldots and \ \ \varphi_0 = 0, \varphi_1 = 0, \ldots \tag{28}$$

The solutions of equation (24) to equation (27) under the corresponding boundary conditions are

$$u_{00} = 1 - e^{-y} \tag{29}$$

$$u_{01} = b_1(e^{-y} - e^{-a_1 y}) \tag{30}$$

$$\varphi_0 = e^{-y} \tag{31}$$

$$\varphi_1 = -e^{-y} + \alpha_1 e^{-2y} + (1-\alpha_1)e^{-PrRey} \tag{32}$$

Notes

When embedding parameter $p \to 0$, we get

$$u_0 = 1 + (b_1 - 1)e^{-y} - b_1 e^{-a_1 y} \tag{33}$$

$$\varphi = (1-\alpha_1)e^{-PrRey} + \alpha_1 e^{-2y} + (1-\alpha_1)e^{-PrRey} \tag{34}$$

Here a_1, b_1 and α_1 are constants and are not mentioned here due to shake of brevity.

To find the solution of first order equations, introducing

$$u_1(y,z) = V(y)\cos\pi z\,,$$

$$\theta_1(y,z) = \psi(y)\cos\pi z \tag{35}$$

Substitute these values in equations (18) & (19), we get

$$\frac{d^2V}{dy^2} + Re\frac{dV}{dy} - (M^2+\pi^2)V = -GrRe^2\psi\,, \tag{36}$$

$$\frac{d^2\psi}{dy^2} + PrRe\frac{d\psi}{dy} - \pi^2\psi = -2EcPr[(1-b_1)e^{-y} + a_1 b_1 e^{-a_1 y}]\frac{dV}{dy} - 2EcPrM^2[(b_1-1)e^{-y} - b_1 e^{-a_1 y}]V \tag{37}$$

Now, the corresponding boundary conditions are:

$$y = 0: V = 0, \psi = 1;$$

$$y \to \infty: V = 0, \psi = 0 \tag{38}$$

Following are the Homotopy for first order equation

$$H(V,p) = (1-p)\left[\frac{d^2v}{dy^2} + Re\frac{dv}{dy} - (M^2+\pi^2)v - (1+Re+M^2+\pi^2)e^{-y} + (4+2Re+M^2+\pi^2)e^{-2y}\right] + p\left[\frac{d^2v}{dy^2} + Re\frac{dv}{dy} - (M^2+\pi^2)v + GrRe^2\psi\right] = 0 \tag{39}$$

$$H(\psi,p) = (1-p)\left[\frac{d^2\psi}{dy^2} + PrRe\frac{d\psi}{dy} - \pi^2\psi - (1-PrRe-\pi^2)e^{-y}\right] + p\left[\frac{d^2\psi}{dy^2} + PrRe\frac{d\psi}{dy} - \pi^2\psi + 2EcPr[(1-b_1)e^{-y} + a_1 b_1 e^{-a_1 y}]\frac{dV}{dy} + 2EcPrM^2[(b_1-1)e^{-y} - b_1 e^{-a_1 y}]V\right] = 0 \tag{40}$$

Notes

Let

$$v = v_0 + pv_1 + p^2 v_2 + \cdots \quad ,$$

$$\psi = \psi_0 + p\psi_1 + p^2\psi_2 + \cdots \tag{41}$$

Substituting the assumptions made in equation (41) into the equations (39) & (40) and comparing the coefficients of like powers of p, we get

$$p^0: \quad \frac{d^2 v_0}{dy^2} + Re\frac{dv_0}{dy} - (M^2+\pi^2)v_0 - (1-Re-M^2-\pi^2)e^{-y} + (4-2Re-M^2-\pi^2)e^{-2y} = 0 \tag{42}$$

$$p^1: \quad \frac{d^2 v_1}{dy^2} + Re\frac{dv_1}{dy} - (M^2+\pi^2)v_1 + (1-Re-M^2-\pi^2)e^{-y} - (4-2Re-M^2-\pi^2)e^{-2y} + GrRe^2\psi_0 = 0 \tag{43}$$

$$p^0: \quad \frac{d^2\psi_0}{dy^2} + PrRe\frac{d\psi_0}{dy} - \pi^2\psi_0 - (1-PrRe-\pi^2)e^{-y} = 0 \tag{44}$$

$$p^1: \quad \frac{d^2\psi_1}{dy^2} + PrRe\frac{d\psi_1}{dy} - \pi^2\psi_1 + (1-PrRe-\pi^2)e^{-y} +$$

$$2EcPr[(1-b_1)e^{-y} + a_1 b_1 e^{-a_1 y}]\frac{dv_0}{dy} + 2EcPrM^2[(b_1-1)e^{-y} - b_1 e^{-a_1 y}]v_0 = 0 \tag{45}$$

Now, the corresponding boundary conditions are:

$$at\ y=0: v_0 = 0, v_1 = 0, \dots\ and\ \ \psi_0 = 1, \psi_1 = 0, \dots ,$$

$$at\ y \to \infty: v_0 = 0, v_1 = 0, \dots\ and\ \ \psi_0 = 0, \psi_1 = 0, \dots \tag{46}$$

Solutions of equation (42) to equation (45) under the corresponding boundary conditions

$$v_0 = e^{-y} - e^{-2y} \tag{47}$$

$$v_1 = \beta_1 e^{-c_1 y} - (1+\beta_1)e^{-y} + e^{-2y} \tag{48}$$

$$\psi_0 = e^{-y} \tag{49}$$

$$\psi_1 = (1-\gamma_1-\gamma_2-\gamma_3-\gamma_4)e^{-c_2 y} - e^{-y} + \gamma_1 e^{-2y} + \gamma_2 e^{-3y} + \gamma_3 e^{-(a_1+1)y} + \gamma_4 e^{-(a_1+2)y} \tag{50}$$

Taking limit on embedding parameter as $p \to 0$, we get

$$v = \beta_1 e^{-c_1 y} - \beta_1 e^{-y}, \tag{51}$$

$$\psi = (1-\gamma_1-\gamma_2-\gamma_3-\gamma_4)e^{-c_2 y} + \gamma_1 e^{-2y} + \gamma_2 e^{-3y} + \gamma_3 e^{-(a_1+1)y} + \gamma_4 e^{-(a_1+2)y} \tag{52}$$

Here $a_1, c_1, c_2, \beta_1, \gamma_1, \gamma_2, \gamma_3$ and γ_4 are constants but are not mentioned due to shake of brevity.
Now, using equation (51) and equation (52) into equation (35), we have

$$u_1(y,z) = (\beta_1 e^{-c_1 y} - \beta_1 e^{-y}) \cos \pi z\,, \tag{53}$$

$$\theta_1(y,z) = \left[(1-\gamma_1-\gamma_2-\gamma_3-\gamma_4)e^{-c_2 y} + \gamma_1 e^{-2y} + \gamma_2 e^{-3y} + \gamma_3 e^{-(a_1+1)y} + \gamma_4 e^{-(a_1+2)y}\right] \cos \pi z \tag{54}$$

Finally, we have

$$u(y,z) = 1 + (b_1 - 1)e^{-y} - b_1 e^{-a_1 y} + \epsilon(\beta_1 e^{-c_1 y} - \beta_1 e^{-y}) \cos \pi z \tag{55}$$

$$\theta(y,z) = (1-\alpha_1)e^{-PrRey} + \alpha_1 e^{-2y} + \epsilon\big[(1-\gamma_1-\gamma_2-\gamma_3-\gamma_4)e^{-c_2 y} + \gamma_1 e^{-2y} + \gamma_2 e^{-3y} + \gamma_3 e^{-(a_1+1)y} + \gamma_4 e^{-(a_1+2)y}\big] \cos \pi z \tag{56}$$

c) Skin Friction Coefficient
The coefficient of skin friction at the wall is given by

$$\tau_w = \left(\frac{\partial u}{\partial y}\right)_{y=0} = -b_1 + 1 + a_1 b_1 + \epsilon \beta_1 (1 - c_1) \cos \pi z \tag{57}$$

d) Heat Transfer Coefficient (Nusselt Number)
The rate of heat transfer in terms of Nusselt Number at the wall is given by

$$N_u = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} = PrRe(1-\alpha_1) + 2\alpha_1 - \epsilon[-c_2(1-\gamma_1-\gamma_2-\gamma_3-\gamma_4) - 2\gamma_1 - 3\gamma_2 - (a_1+1)\gamma_3 - (a_1+2)\gamma_4] \cos \pi z \tag{58}$$

Table 1 : The coefficient of skin-friction and Nusselt number

Re	M	Gr	Ec	Pr	τ_w	τ_w	Nu	Nu
					z=1/4	z=1/3	z=1/4	z=1/3
1	0.1	5	0.001	0.7	6.05688	6.02876	0.88645	0.83201
2	0.1	5	0.001	0.7	22.3344	22.2089	1.67060	1.59138
1	0.2	5	0.001	0.7	5.94895	5.92087	0.93244	0.86454
1	0.1	6	0.001	0.7	7.06627	7.03253	0.87398	0.82320
1	0.1	5	0.002	0.7	6.05688	6.02876	0.82463	0.78848
1	0.1	5	0.001	0.75	6.05688	6.02876	0.93423	0.88044

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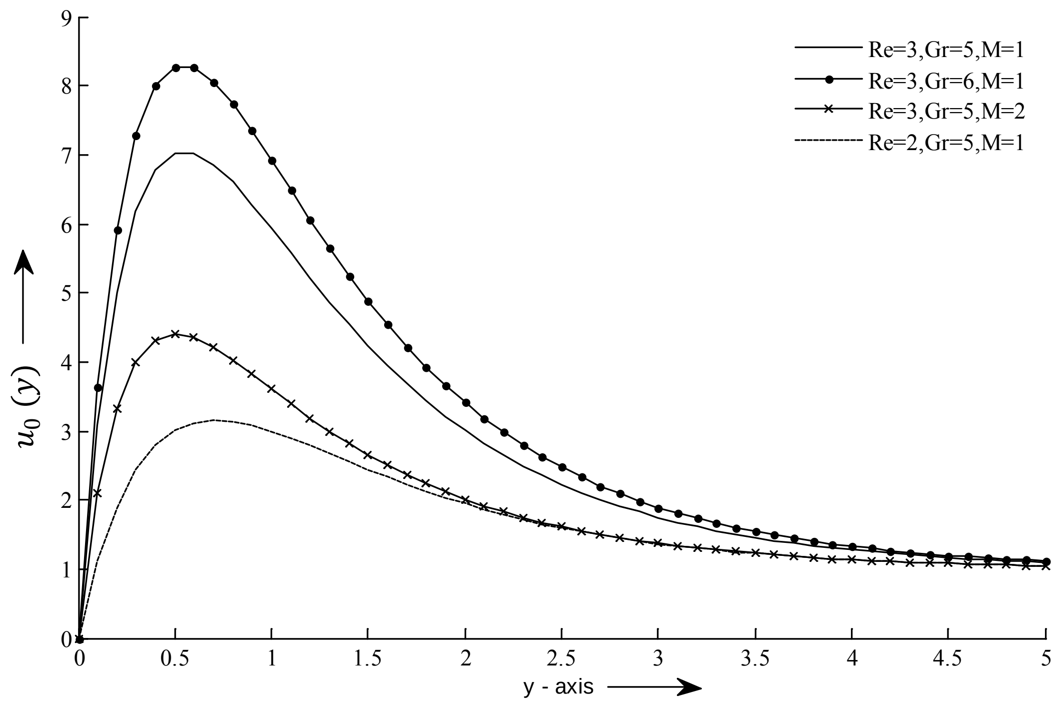

Figure 1.1 : Zeroth Order Velocity distribution versus y

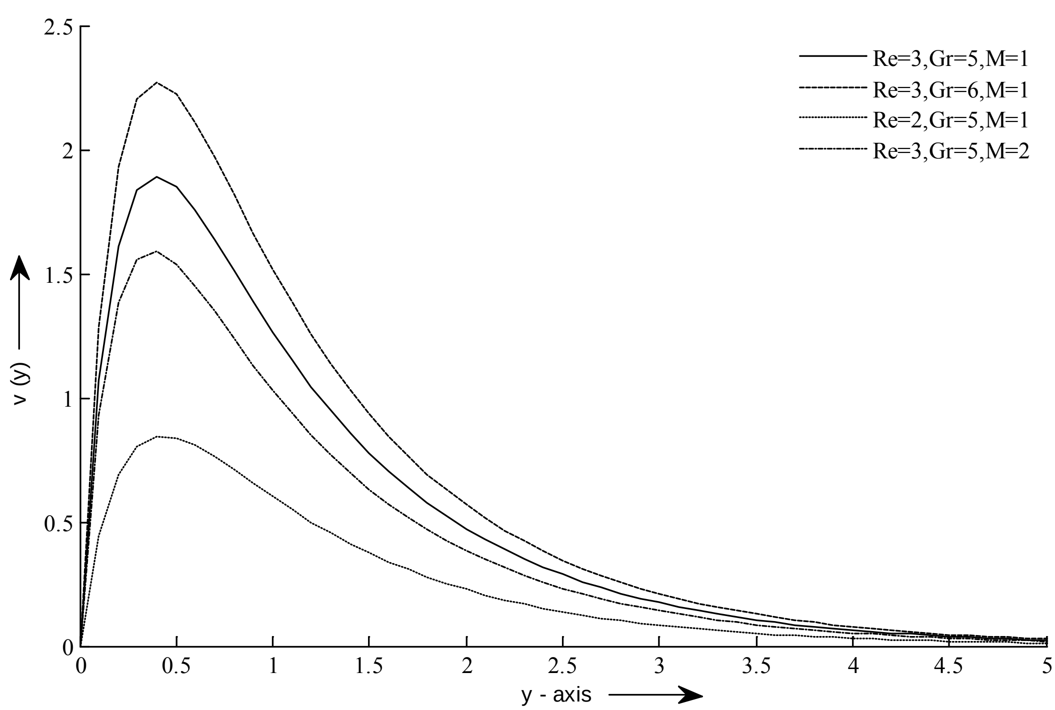

Figure 1.2 : First Order Velocity distribution versus y

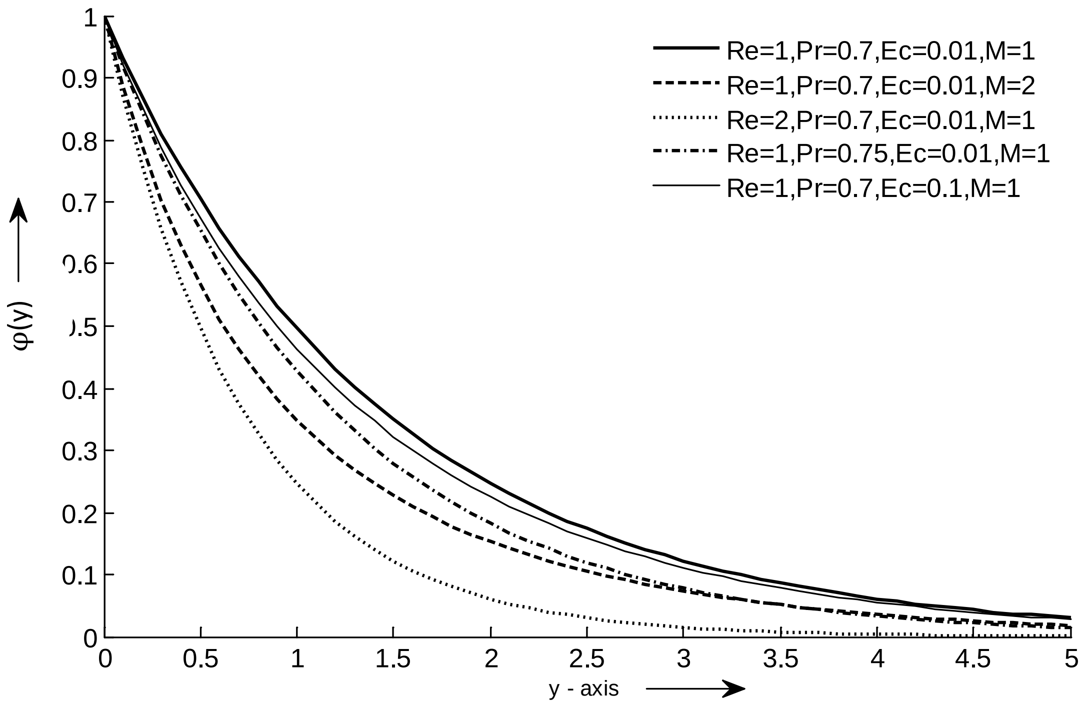

Figure: 1.3 : Zeroth Order Temperature distribution versus y

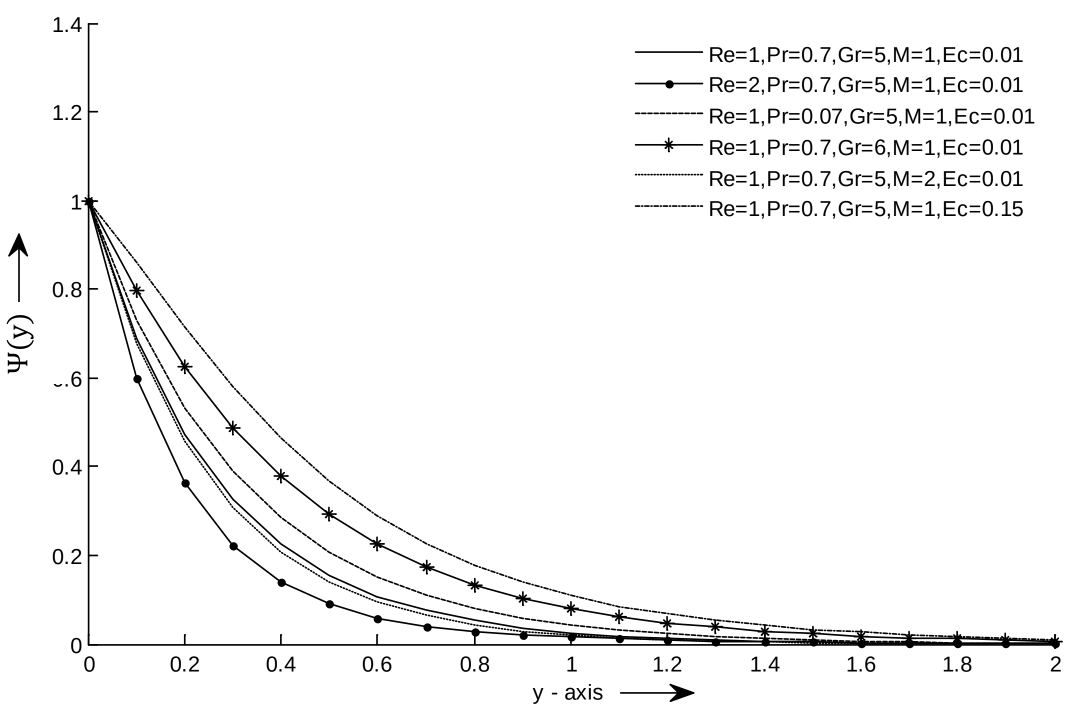

Figure 1.4 : First Order Temperature distribution versus y

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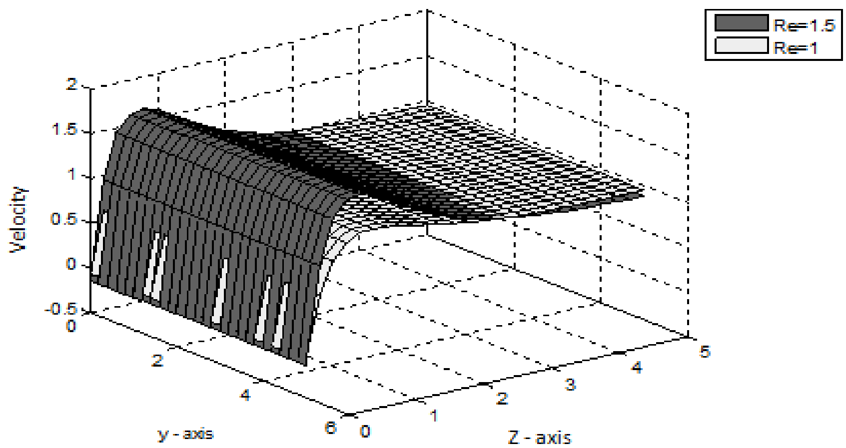

Figure 1.5 : Velocity Distribution for various values of Reynold's Number

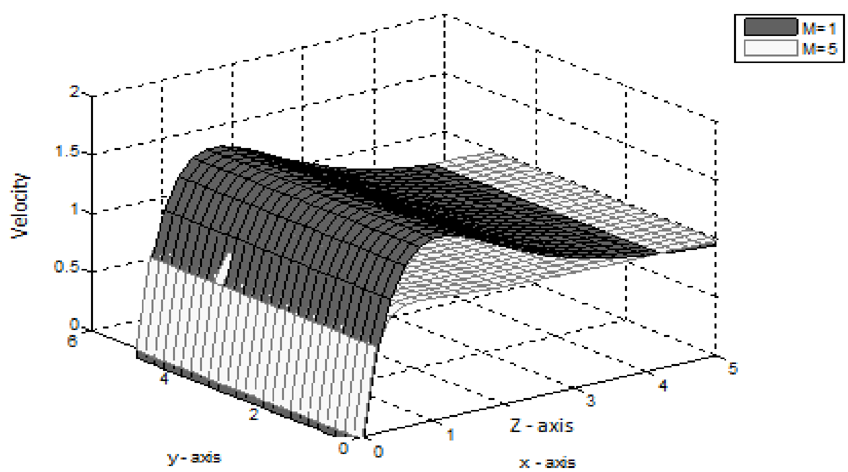

Figure 1.6 : Velocity Distribution for various values of Hartman number

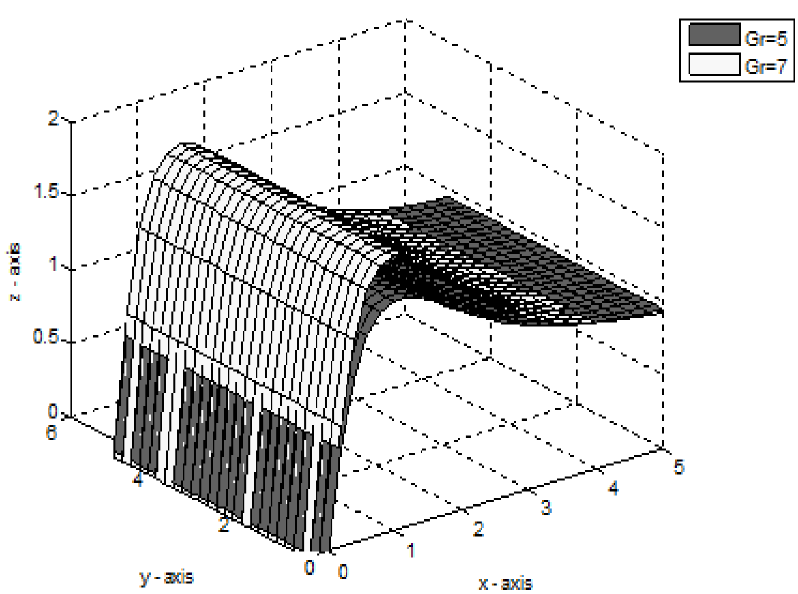

Figure 1.7 : Velocity Distribution for various values of Grasoff Number

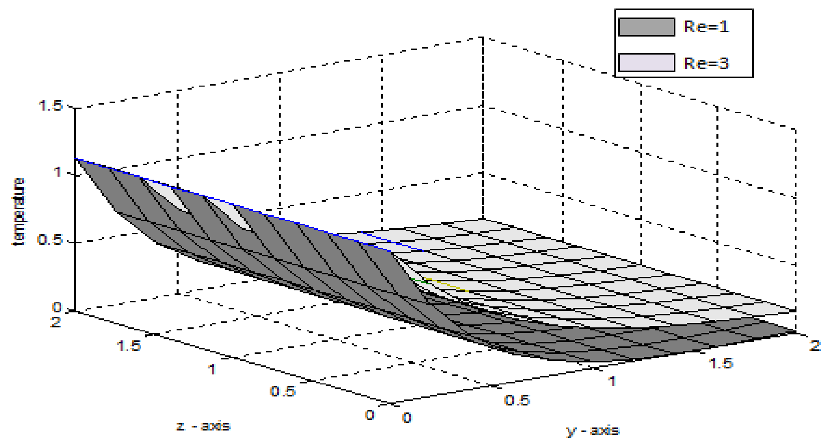

Figure 1.8 : Temperature Distribution for various values of Reynold number

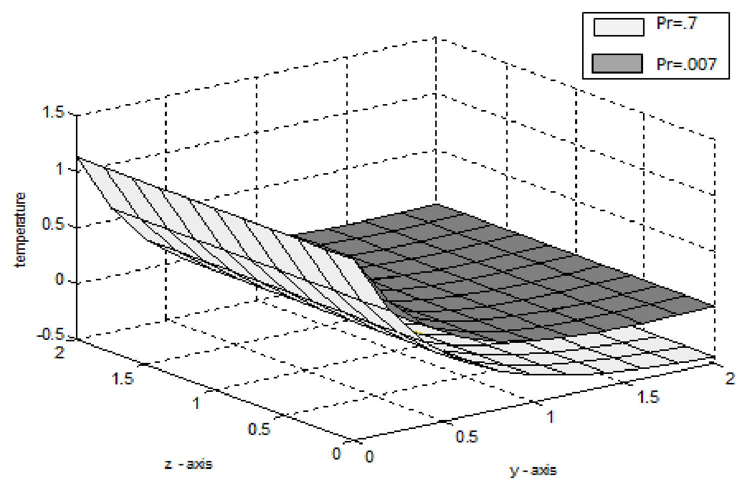

Figure 1.9 : Temperature Distribution for various values of Prandtl number

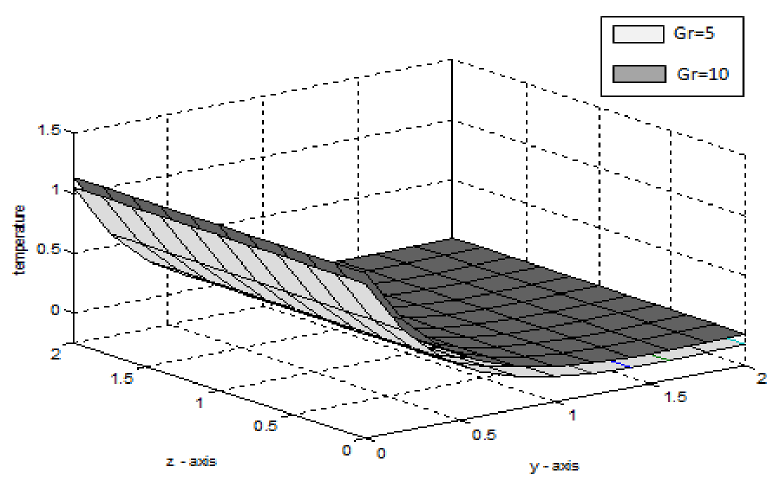

Figure 1.10 : Temperature Distribution for various values of Grasoff Number

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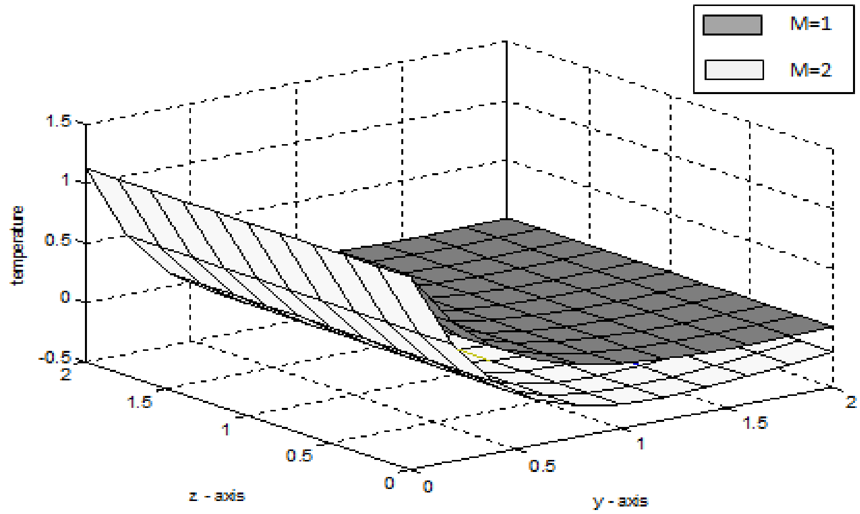

Figure 1.11 : Temperature Distribution for various values of Hartman Number

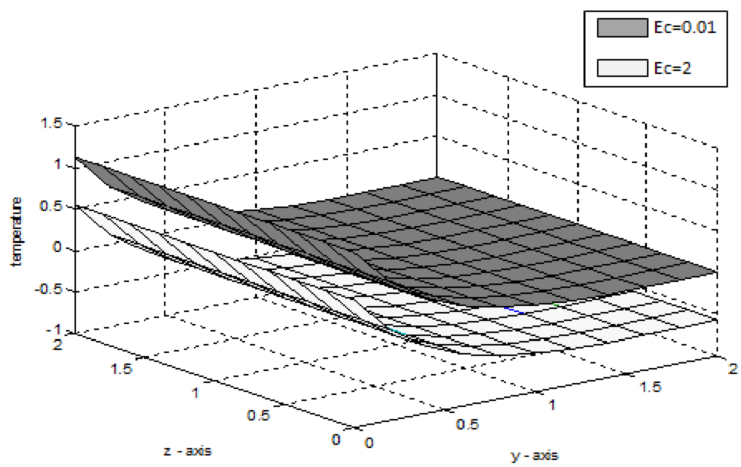

Figure 1.12 : Temperature Distribution for various values of Eckert Number

V. Results and Discussions

It has been observed from the **Table 1** that the coefficient of skin-friction increases due to increase in Reynold Number and Grasoff Number and decreases due to increase in Hartman number.

Again, it is observed that Nusselt number increases due to increase in Reynold Number, Hartman number and Prandtl Number and decreases due to increase in Eckert Number and Grasoff Number.

It has been observed from figure (1.1) and figure (1.2) that Zeroth Order Velocity and First Order Velocity both increases due to increase in Reynold Number and Grasoff Number and decreases due to increase in Hartman number. It has been observed from figure (1.3) that Zeroth Order Temperature decreases due to increase in Reynold Number, Eckert Number, Hartman number and Prandtl Number. Again, it is observed from figure (1.4) that First Order Temperature increase due to increase in Grasoff Number and Eckert Number and it decreases due to increase in Reynold Number, Hartman number and Prandtl Number.

It has been observed from figure (1.5), (1.6) and (1.7) that the velocity increases due to increase in Reynold Number and Grasoff Number and decreases due to increase in Hartman number. It has been observed from figure (1.8), (1.9), (1.10), (1.11) and (1.12) that the temperature increases due to increase in Reynold Number and Grasoff Number and it decreases due to increase in Hartman number, Prandtl Number and Eckert Number.

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