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MHD POWER LAW FLUID FLOW PAST A STRETCHING POROUS SHEET

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ABSTRACT

In the present paper magneto hydrodynamic flow of an MHD power law fluid over a porous stretching sheet is studied by applying exact analytical similarity transformation technique. The flow is caused by linear stretching of a sheet from a permeable wall. The momentum equation is simplified by converting the governing momentum boundary layer partial differential equation into ordinary differential equation by using classical similarity transformation technique with appropriate boundary conditions.

The effect of porosity and magnetic field on the flow profile is analyzed analytically and it is found that permeability and magnetic field tend to make the boundary layer thinner and thereby enhancing the skin wall friction.

Key words: *Stretching sheet, boundary layer thickness, power law fluid, displacement thickness, permeability.*

1. INTRODUCTION

The interest of studying momentum boundary layer flow of non – Newtonian fluids has been increased in the last four decades for their important usage in various manufacturing and processing industries and wide range of applications such as hot rolling, extrusion, glass fiber production, paper production, continuous casting and in wire drawing. Apart from these many metallurgical processes including chemical engineering processes involve cooling of continuous strips or filaments by drawing them into a cooling system. The fluid mechanical properties desired for the outcome of such a process would mainly depend on the rate of stretching and cooling.

Hence because of the growing use of these fluids considerable efforts have been directed towards the study of momentum transfer to control the quality of the final product of these processes. [1–4].

In view of many such applications Crane [5] initiated the analytical study of boundary layer flow due to a stretching sheet. The velocity of the sheet was assumed to vary linearly with the distance from the slit. The motion of a plane sheet in its own plane due to boundary layer flow was investigated by Sakiadis [6]. Erickson [7] extended this problem to study the temperature distribution in the boundary layer when the sheet is maintained at a constant temperature with suction/blowing. These investigations have many significant applications in the polymer industry when a polymer sheet is extruded continuously from a die, with an inextensible stretching sheet. However, in real situations one has to encounter the boundary layer flow over a stretching sheet. Following two different approaches of [5] and [6] the uniqueness of the exact analytical solutions was proved simultaneously by Maclead and Rajgopal [8] and Troy et al [9]. Rajgopal et al [10] made a study on boundary layer flow over a stretching sheet for a special class of non – Newtonian fluids, known as second order fluids and obtained similarity solutions.

Anderson and Dandapat [11] extended the Newtonian boundary layer flow problem considered by crane [5] to an important class of non- Newtonian fluids obeying the power – law model.

Motion of visco – elastic fluids in the presence of transverse uniform magnetic field was studied earlier by several authors Sarpakaya [12] and Djukic [13] etc in different situations. Pavlov [14] studied the boundary layer flow of an MHD fluid due to stretching of a plane elastic surface and obtained an exact similarity solution of the problem.

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Schowalter [15] applied boundary layer theory to study the flow of power law pseudo plastic fluids and obtained similarity solutions. Hassanien *et al* [16] made an investigation on the flow and heat transfer in a power law fluid over a non-isothermal stretching sheet. Naikoti and Borra [17] made an analysis of the influence of transverse magnetic field on the flow transfer of an MHD conducting power – law fluid over a stretching sheet with thermal dispersion. Liao [18] made an excellent work on magneto hydrodynamic stretching sheet problem involving power law fluid model using homotopy based analytical method. Fox *et al* [19] made a study on the flow of a power law fluid over a moving surface. Wang [20] analysed the heat transfer charectristics of the steady laminar mixed convection of non-Newtonian fluids over a vertical plate using the boundary layer equations for the power – law viscosity index. Gorla *et al* [21] presented the study of mixed convection in non – Newtonian fluids along a vertical plate in a porous medium.

Guedda [22] made a theoretical analysis to derive a range of exponents and amplitudes for the boundary layer region for which similarity solutions exists. Howell *et al* [23] investigated the flow and heat transfer in a power – law fluid on a continuous moving sheet.

Recently the problem of laminar natural convection heat transfer from a vertical flat plate at constant temperature to a non – Newtonian pseudo – plastic liquid was studied by Dale and Emery [25] with uniform heat flux. Som and Chen [26] analyzed the natural convection heat transfer in power law fluid from a two – dimensional body of which the surface is subject to power – law variations in temperature and heat flux. Caponkov [27] discussed the free convection flow in power – law fluids past two – dimensional bodies for large Prandtl number for arbitrary variations in body temperature. Recently the effects of magnetic field on a power – law fluid past a vertical plate embedded in a porous medium were studied by Et – Amin and Mohammdein [28].

Thus in the current investigation it is considered extension of ref[30] ie the free convection boundary layer steady two – dimensional flow of a non – Newtonian power – law fluid model. [Ref Vujannovic *et al* [29]. It is the simplest and most common type called the Ostwald – de Wale model] i.e., power – law fluid in the presence of uniform transverse magnetic field and porous medium.

2. FLOW ANALYSIS

Consider the two – dimensional steady, laminar flow of an incompressible and electrically conducting power – law fluid in the presence of transverse magnetic field and porous medium past a flat sheet coinciding with the plane Y = 0, the flow being confined to Y > 0. Two equal and opposite forces are applied along X – axis. The basic boundary layer equations for continuity and momentum Anderson *et al.* [30] take the following form.

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = \frac{1}{\rho}\left(\frac{\partial \tau xy}{\partial y}\right) - \frac{\sigma B_0^2}{\rho}u - \frac{v}{k}u \tag{2}$$

Where u and v are the velocity components along x – and y – directions respectively. $\rho,\ \sigma,\ B_0,\ v\ and\ k'$ are the density, electrical conductivity, magnetic field strength, Kinematic viscosity and permeability of the medium respectively. τ_{xy} is the shear stress and the stress tensor is defined rheologically as

$$\tau_{ij} = 2K\,(2D_{ki}\,D_{kj})^{\frac{n-1}{2}}\,D_{ij} \tag{3}$$

Where $D_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$ denotes the stretching tensor, K is called the consistency co – efficient and n is the power – law index. The two parameter rheological equation (3) represents a Newtonian fluid with dynamic co – efficient of viscosity K for n = 1. With $n \neq 1$, the constitutive equation (3) represents shear – thinning i.e., for (n < 1) and shear thickening (n>1) fluids. However, the in elastic power – law model (3) does not exhibit normal – stress differences.

Thus the shear stress in the present study is given by

$$\tau_{xy} = -k\left(-\frac{\partial u}{\partial y}\right)^n \qquad \text{for } \frac{\partial u}{\partial y} < 0 \tag{4}$$

Then equation of motion (2) reduces to the following form.

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{K}{\rho}\frac{\partial}{\partial y}\left(-\frac{\partial u}{\partial y}\right)^n - \frac{\sigma B_0^2 u}{\rho} - \frac{v}{k'}u \tag{5}$$

With the following boundary conditions

$$u = Bx,\ v = 0\ at\ y = o \tag{6}$$

$$u \to 0 \quad as\ y \to \infty \tag{7}$$

Following Shercliff [31], we have neglected the induced magnetic field and porous media under justification for flow at small magnetic Reynolds number and porositic Darcy number.

Further this flow is caused solely by the stretching of the sheet wall and hence there is no free – stream velocity outside the boundary layer.

It can be automatically shown that the system of equations (1) to (5) admits self similarity solutions with respect to the boundary conditions (6) & (7) in terms of the similarity function variable G(η) defined by

$$\Psi = \left(\frac{B^{1-2n}}{\frac{k}{\rho}}\right)^{-\frac{1}{n+1}} x^{\frac{2n}{n+1}} \; G(\eta) \tag{8}$$

and

$$\eta = y\left(\frac{B^{2-n}}{\frac{k}{\rho}}\right)^{\frac{1}{n+1}} x^{\frac{(1-n)}{(1+n)}} \tag{9}$$

Where u and v are the stream functions which are taken as

$$u = -\frac{\partial \Psi}{\partial y} \quad and \quad v = \frac{\partial \Psi}{\partial x} \tag{10}$$

Now using the transformations defined in (8) and (9), equation (5) becomes

$$\mathrm{n}(-\mathrm{G}^{\mathrm{n}})^{(\mathrm{n}-1)}\mathrm{G}_{\eta\eta\eta} - \left(\mathrm{G}_{\eta}\right)^{2} + \left(\frac{2\mathrm{n}}{\mathrm{n}+1}\right)\mathrm{G}\mathrm{G}_{\eta\eta}{}^{-(\mathrm{M}+\mathrm{k}_2)}\;\mathrm{G}_{\eta} = 0 \tag{11}$$

Where M = $\frac{\sigma B_0^2 u}{\rho B}$ = the magnetic parameter

k$_2$ = $\frac{v}{k'}$ = the permeability parameter

Boundary conditions (6) and (7) convert to

$$\mathrm{G}_{\eta}\,(0) = 1\,, \qquad \mathrm{G}(0) = 0 \tag{12a}$$

$$\mathrm{G}_{\eta}\,(\infty) = 0\,, \tag{12b}$$

For the value n=1 in equation (11) we obtain the equation of momentum for a Newtonian fluid as follows.

$$G_{\eta\eta\eta} - (G_{\eta})^2 + \mathrm{G}\, G_{\eta\eta} - (\mathrm{M} + \mathrm{k}_2)\, G_{\eta} = 0 \tag{13}$$

With above boundary conditions (12a) and (12b). Equation (13) has an exact analytical solution of the form

$$G_{\eta}(\eta) = e^{-E\eta}, \quad E > 0 \tag{14}$$

and

$$G(\eta) = \frac{1}{E}\left(1 - e^{-E\eta}\right) \tag{15}$$

Satisfying the boundary conditions $G_{\eta}(0) = 1$ and $G_{\eta}(\infty) = 0$ and G(0) = 0.

Where E = $\sqrt{1 + M + k_2}$ (see Pavlov [14]) and Andersson and Dandpat [30] for non – porous medium.

3. ANALYTICAL SOLUTION METHOD

Anderson *et al* [30] solved the present problem by standard fourth order Runge - Kutta integration technique for non – porous case and they solved the same by Keller Box method and also Anderson *et al.* [10] applied the same numerical method recently to the non magnetic case also.

In the present paper the non – linear momentum equation [13] for power – law fluid with magnetic and porositic case is solved by special perturbation method with exact analytical solution with respect to the boundary conditions [12] for the case n = 1 is obtained.

Putting $G_{\eta} = y \quad \Rightarrow \quad G(_{\eta}) = \frac{y^2}{2}$ (16)

Then Equation [13] reduces to

$$Y'' - \frac{Y^2 Y'}{2} - aY = Y^2 \tag{17}$$

Whose solution is assumed in the following form

$$Y = y_0 + \epsilon\, y_1 + \epsilon^2\, y_2 + \ldots\ldots\ldots\ldots \tag{18}$$

Now substituting for Y, Y', Y'' in (17) and equating the like co – efficient of ϵ, we obtain the following set of equations in $y_{0,}\ y_1$ and y_2 as

$$\frac{d^2 y_0}{d\eta^2} - {y_0}^2\,\frac{dy_0}{d\eta} - a y_0 = {y_0}^2 \tag{19}$$

With Boundary conditions y_0 (0) = 1 and y_0 (∞) = 0 (19 a)

$$\frac{d^2y_1}{d\eta^2} - y_0{}^2\frac{dy_1}{d\eta} + 2\,y_0y_1\frac{dy_0}{d\eta} - ay_1 - 2\,y_0y_1 = 0 \quad (20)$$

With y_1 (0) = 1 and y_2 (∞) = 0 (20a)

$$\frac{d^2y_2}{d\eta^2} - y_0{}^2\frac{dy_2}{d\eta} - y_1{}^2\frac{dy_0}{d\eta} - 2\,y_0y_1\frac{dy_1}{d\eta} - 2y_0y_2\frac{dy_0}{d\eta} - ay_1 - 2y_1y_2 - 2y_2y_0 = y_1{}^2 \quad (21)$$

With y_2 (0) =1 and y_2 (∞) = 0 (21a)

Solving equations (19), (20) and (21) subjected to the boundary conditions (19a), (20a) and (21a), the final solution of equation (17) is obtained as

$$Y_{(\eta)} = \frac{1}{a}\left(e^{\alpha\eta} - 1\right) + e^{-\beta\eta} \quad (22)$$

$where\quad \alpha = \frac{-1\sqrt{1+4a}}{2}\quad \beta = \frac{-1-\sqrt{1+4a}}{2}$ where a = $(M + k_2)$

since Y = $G_\eta(\eta) from\ equation\ (16)$

$$\Rightarrow G_\eta(\eta) = \frac{1}{a}\left(e^{\alpha\eta} - 1\right) + e^{-\beta\eta} \quad (23)$$

and the solution for

$$G(\eta) = \frac{1}{M+k_2}\left[\frac{1}{\alpha}\left(e^{\alpha\eta} - 1\right)\right] + \frac{1}{\beta}\left(1 - e^{-\beta\eta}\right) \quad (24)$$

4. SKIN FRICTION

The important boundary layer characteristic is the skin friction co-efficient τ_{xy} at the sheet y = 0 is defined and derived as

$$[\tau_{xy}]_{y=0} = 2\left[-G_{\eta\eta}(0)\right]^{n}(R_e)^{-\frac{1}{n+1}}$$

Where R_e is the local Reynolds no. and $R_e = (c_x)^{2-n}\cdot\frac{x^{\eta}}{\left(\frac{k}{\rho}\right)}$ based on sheet velocity.

5. RESULTS AND DISCUSSION

The present non-Newtonian MHD power – law fluid flow problem with porosity is solved analytically by the special method of perturbation technique for five different values of the magnetic parameter (M≤ 2 .0) and five different values of permeability parameter ($k_2 \leq 10$) and for different values of the power – law index in the range 0.6≤ n ≤ 2.0. computed values of velocity field are presented through the following graphs.

Fig (1a) and (1b) represents the similarity velocity profiles for shear thinning fluid with power law index n=0.6 for different values of magnetic parameter fig (1) and permeability parameter fig (2) respectively. From both the figures it is observed that G_η decreases with increasing values of M_n and k_2. For a given fluid the effect of magnetic field and porous media is therefore to reduce the velocity distribution u = Bx G_η across the boundary layer and parallel to the stretching sheet.

Fig (2a) and (2b) are drawn to represent the velocity profiles G_η vs η for Newtonian fluid (n=1) and for different values of magnetic and permeability parameters m and k_2 respectively. A common feature of both the velocity profiles irrespective of power law index n, is that horizontal velocity distribution G_η lowers with enhancing values of m and k_2 which indicates that the exact analytical solution [14] is accurately reproduced by computations for n = 2 in fig (2a) and (2b).

Similarly Figures (3a) and (3b) depict the flow velocity profiles for shear thickening fluids with power – law index n=2 and it is observed from the figures that velocity distribution is lowered for increasing values of M_n and k_2 which indicates that for shear – thickening fluid, the effect of magnetic field and porous field is to reduce the velocity component u=BxG_η parallel to the stretching surface.

In fig (4) the important aspect of boundary layer characteristic property known as dimensionless. Skin – friction co-efficient τ_{xy} – shear stress at the sheet for y=0 is presented.

Since $G_{\eta\eta}$ (0) values are negative and computed values of -$G_{\eta\eta}$ (0) with m and n are displayed graphically in fig (4a) and (4b). For Different values of M and k_2 respectively. It is observed from the figures that -$G_{\eta\eta}$ (0) increases monotonically with M (fig 4a) and k_2 (fig 4b) for power law fluid. More over fig (4a) and (4b) demonstrate the facts that the magnitude of the wall velocity gradient decreases gradually with increasing values of n and fixed values of M and k_2. This observation is well in agreement with the findings of Anderson *et al.* [11]. However the presence of magnetic and porous media make the difference in $G'_{\eta\eta}$ (0) between shear thickening (n>1) and shear-thinning (n<1) fluids significantly more pronounced.

The graph of boundary layer thickness η_δ for various values of permeability parameter k_2 is presented in fig 5. It is observed from the figure that the thickness of the boundary layer thickness decreases with permeability for the power law fluid considered.

Fig (6) is the representation of dimensionless displacement thickness for various values of permeability parameter and it is found from the figure that the imposition of porous media reduces the sensitiveness of boundary layer thickness.

6. CONCLUSIONS

The magnetic field and porous media tends to make the boundary layer thinner duely increasing the skin wall friction. This combined effect of porosity and magnetism is pronounced more for shear thinning fluids than shear thickening fluids. The imposition of magnetic field and porosity makes the difference between the various fluids more distinct in the near wall-region but less influencial on the global thickness of the boundary layer behaviors.

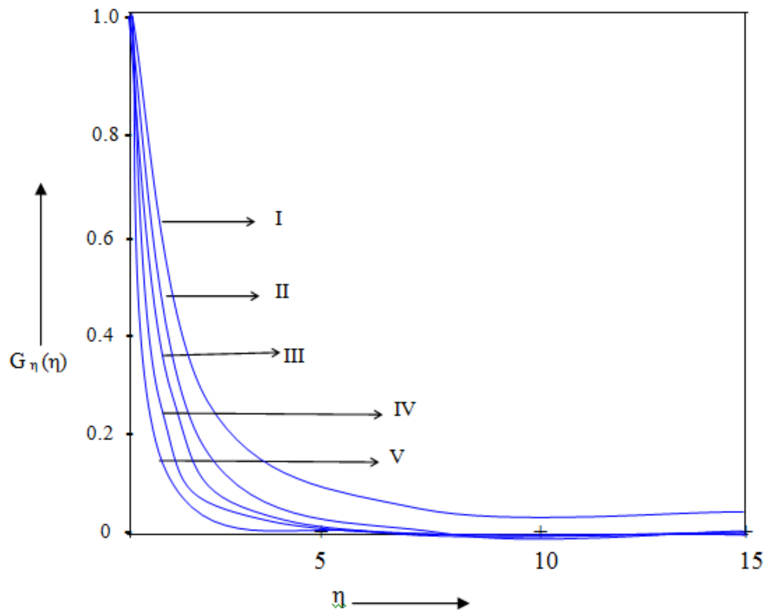

Figure-1a: Similarity velocity profiles for a shear thining fluid (power law index n=0.6) fixed k_2 and for different values of magnetic parameter M = 0.0, 0.5, 1.0, 1.5, 2.0

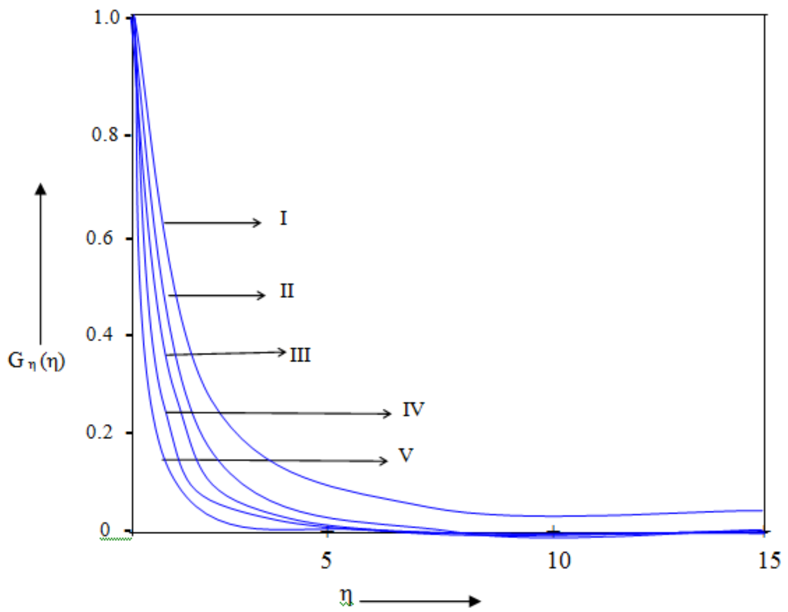

Figure-1b: Similarity velocity profiles for a shear thinning fluid (power law index n=0.6) M = 1 and for different values of permeability parameter k_2 = 2, 4, 6, 8, 10

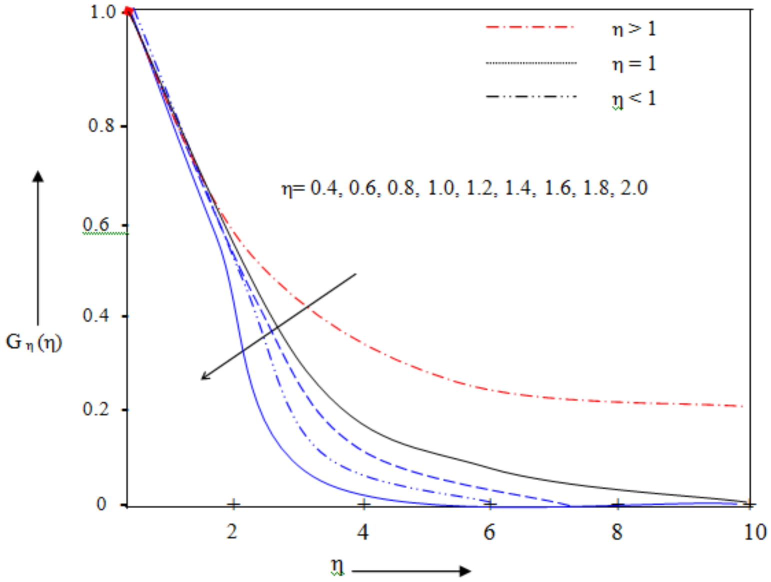

Figure-1c: Similarity horizontal velocity profiles G $_{\eta}$ (η) for power law fluid with n < 1, n = 1 and n > 1for fixed value of M=1, k_2 = 2.

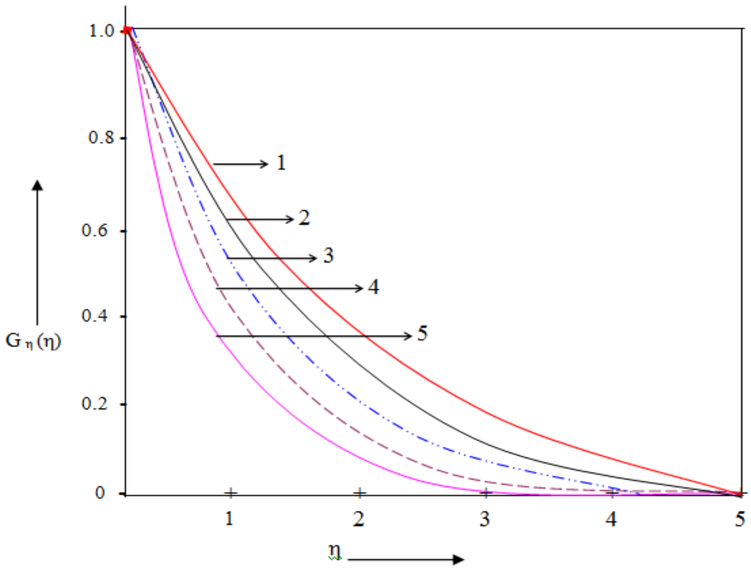

Figure-2a: Similarity velocity profiles for power law fluid with (n = 1-Newtonian)for different values magnetic parameter M= 0.0, 0.5, 1.0, 1.5, 2.01, k_2 = 2.

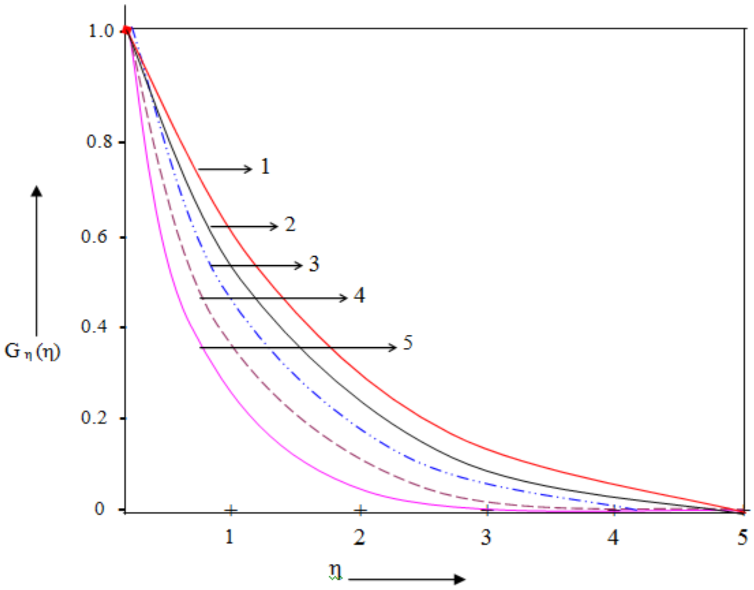

Figure-2b: Similarity velocity profiles for power law fluid with (n = 1-Newtonian) and M=1 for different values of permeability parameter k_2= 2, 4, 6, 8, 10.

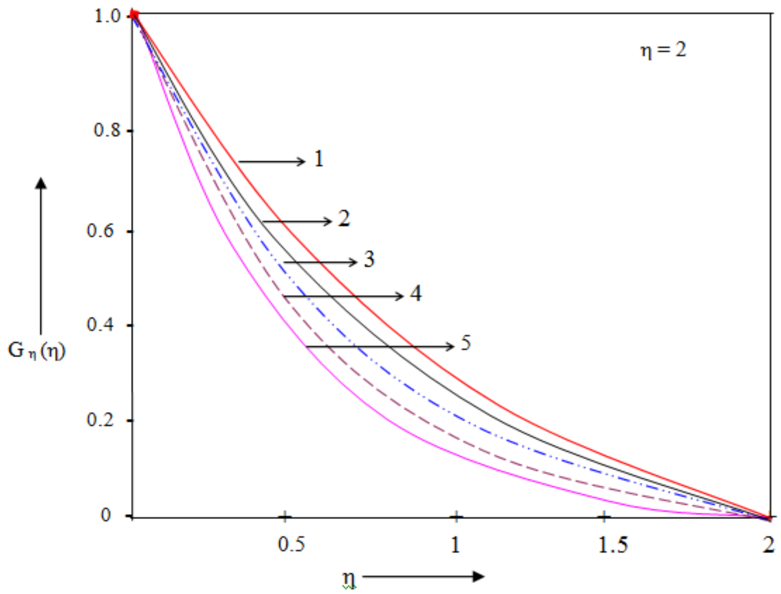

Figure-3a: Similarity velocity profiles for a shear thickening (n = 2) and k_2 = 2 for different values M = 0.0, 0.5, 1.0, 1.5, 2.0

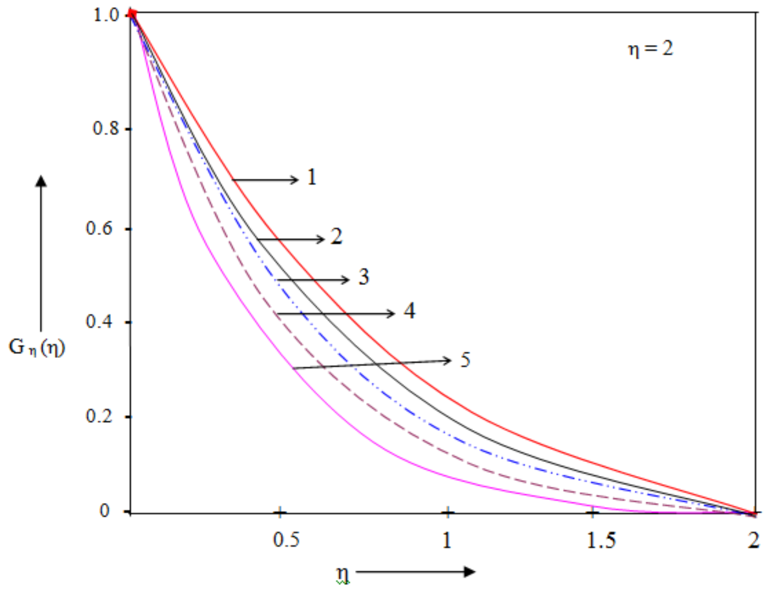

Figure-3b: Similarity velocity profiles for a shear thickening (n = 2) and M = 1 and for different values k_2 = 2, 4, 6, 8, 10

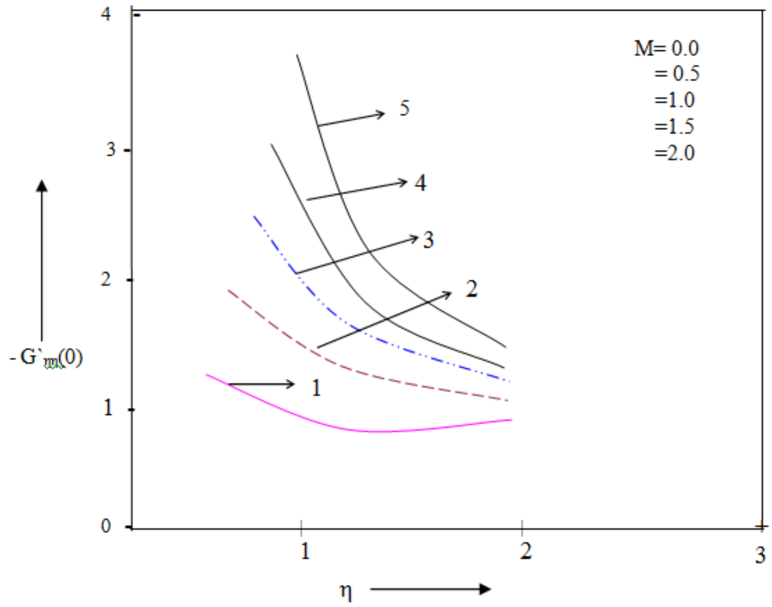

Figure-4a: Shearing skin friction co-efficient with verification of n different values of M at the wall with fixed k_2 = 2

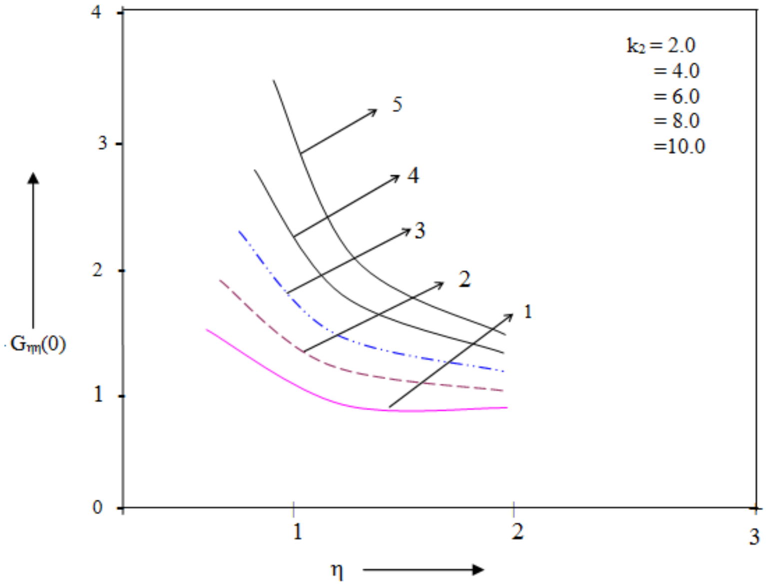

Figure-4b: Graph of Dimensionless velocity gradient at the wall with power law index n for different values of k_2 with M = 1

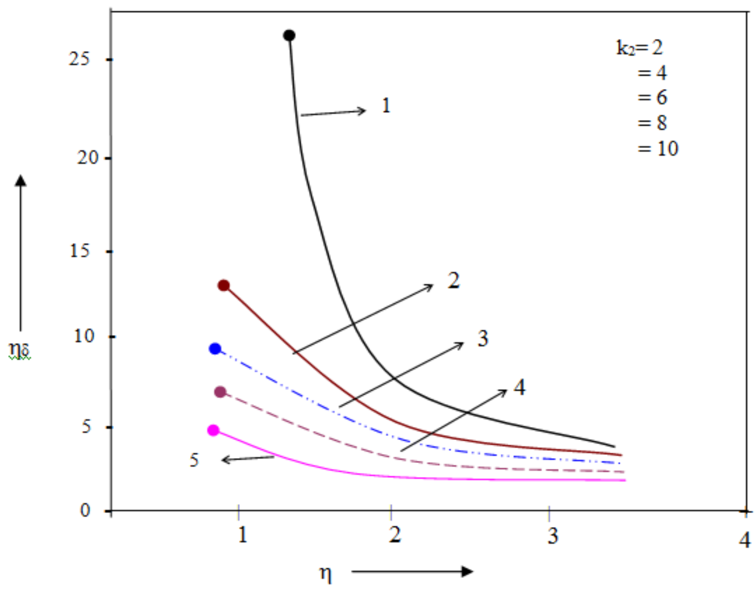

Figure-5: Graph of Dimensionless boundary layer thickness η_δ Vs. power law index n with different values of k_2 and fixed value of M = 1

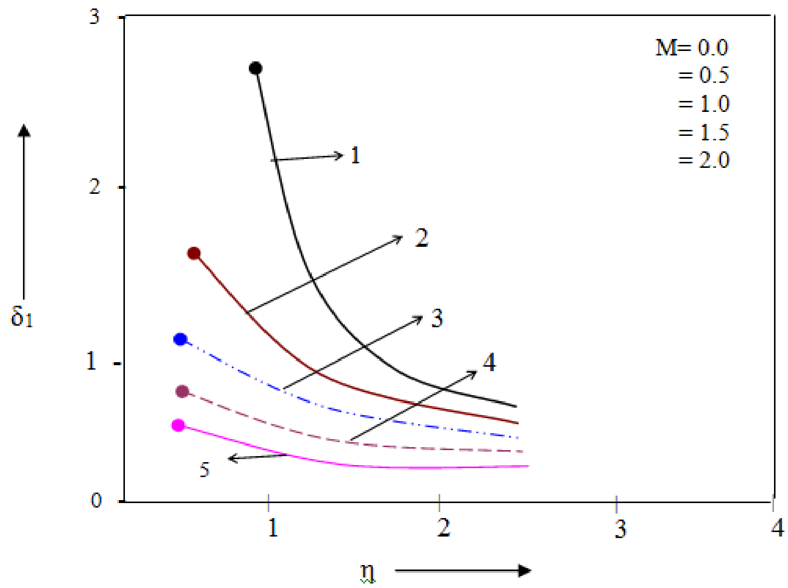

Figure-6: Graph of displacement thickness δ_1 Vs. power law index number n with different values of magnetic parameter M

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