HALL-CURRENT EFFECTS ON UNSTEADY MAGNETOHYDRODYNAMICS FLOW BETWEEN STRETCHING SHEET AND AN OSCILLATING POROUS UPPER PARALLEL PLATE WITH CONSTANT SUCTION

by

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The unsteady magnetohydrodynamics flow of an incompressible viscous electrically conducting fluid between two horizontal parallel non-conducting plates, where the lower one is stretching sheet and the upper one is oscillating porous plate, is studied in the presence of a transverse magnetic field and the effects of Hall current. Fluid motion is caused by the stretching of the lower sheet and a constant suction is applied at the upper plate which is oscillating in its own plane. The stretching velocity of the sheet is assumed to be a linear function of distance along the channel. The expressions relating to the velocity distribution are obtained and effects of different values of various physical parameters are calculated numerically and shown graphically.

Key words: *magnetohydrodynamics, stretching sheet, hall current, oscillating porous plate, suction parameter*

Introduction

In recent years, the study of flow over a stretching sheet has generated considerable interest because of its numerous industrial applications such as in the manufacture of sheeting material through an extrusion process, the cooling of bath, the boundary layer along material handling conveyers, the aerodynamic extrusion of plastic sheets glass and polymer industries, fiber industry *etc*. Boundary layer behavior over a moving continuous solid surface is an important type of flow occurring in several engineering processes. Anderson [1] analyzed the flow of visco elastic fluid, past a stretching sheet, in the presence of a transverse magnetic field. He obtained an exact solution of the governing non-linear boundary layer equation and showed that an external magnetic field has the same effect on the flow as the visco elasticity. Chiam [2] considered the motion of micro polar fluids over stretching sheet. Borkakoti *et al.* [3] studied the flow and heat transfer problem in a conducting fluid between two horizontal

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parallel surfaces where the lower one is stretching and the upper one is a porous solid plate in the presence of a transverse magnetic field. Rajagopal *et al*. [4] discussed the flow of a visco elastic fluid over a stretching sheet.

Agarwal *et al.* [5] gave the solution of flow and heat transfer of a micro polar fluid over a stretching sheet using finite element technique. Anderson [6] considered the motion of power law fluids over a stretching sheet. Anderson [6] investigated the flow of electrically conducting visco elastic fluid past a flat and a impermeable elastic sheet. This work was extended by Char [7] to study heat as well as mass transfer. Chauhan [8] investigated the coupled stretching flow of a two dimensional viscous incompressible fluid through a channel bounded by naturally permeable bed. Takhar *et al*. [9] have studied the unsteady flow over a stretching surface with a magnetic field in a rotating fluid. Kumari *et al*. [10] gave the analytical solution of the boundary layer equations over a stretching sheet with mass transfer using series method. Nabil *et al*. [11] obtained a solution of the flow problem in compact form for the motion due to linear velocity of stretching sheet. Sharma *et al*. [12] investigated steady magnetohydrodynamics (MHD) flow through horizontal channel. Lower being stretching sheet and upper being permeable plate bounded by porous medium.

Phukan [13] obtained the numerical solutions for power law velocity distribution of stretching plate. Bhardwaj [14] investigated the steady two dimensional of viscous, incompressible fluid through a channel bounded by a plane stretched sheet and naturally permeable bed. An analysis of heat transfer taking dissipation function into account, in boundary layer flow of a hydromagnetic fluid over a stretching sheet in the presence of uniform transverse magnetic field has been given by Lodha *et al.* [15].

In all the above studies the influence of Hall current effects was not concentrated much. If a conductor or a semi conductor has current flowing in it because of an applied electric field and a transverse magnetic field is applied, there develops a component of electric field in the direction orthogonal to both the applied electric field and magnetic field, resulting in a voltage difference between the sides of the conductor. This phenomenon is known as the Hall effect. In an ionized gas, when the strength of the magnetic field is large one can not neglect the effect of Hall current. These Hall currents are particularly important as produce considerable changes in the flow pattern, when the magnetic field is considerably large**.** Gutpa [16] studied the Hall current effects in the steady hydro magnetic flow of an electrically conducting fluid past an infinite porous flat plate. Kumar *et al.* [17, 18] studied the thermal instability of Walters B' viscoelastic fluid permeated with suspended particles in hydromagnetics in porous medium and instability of two rotating viscoelastic (Walters B') superposed fluids with suspended particles in porous medium. Mostafa *et al.* [19] studied laminar fully developed mixed convection with viscous dissipation in a uniformly heated vertical double-passage channel. Bakier *et al*. [20] studied combined of magnetic field and thermophoresis particle deposition in free convection boundary layer from a vertical flat plate embedded in a porous medium. Abdallah [21] investigated analytic solution of heat and mass transfer over a permeable stretching plate affected by chemical reaction, internal heating, Dufour-Soret effect, and Hall effect.

In this paper Hall current effects on unsteady MHD flow of a viscous incompressible electrically conducting fluid between two horizontal parallel non-conducting plane surfaces are considered. The lower surface is a stretching sheet and the upper one is an oscillating porous plate. The fluid motion is caused by stretching of the sheet and suction at the upper porous plate which is oscillating in its own plane. The stretching velocity of the sheet is assumed to be linear function of distance along the channel and the induced magnetic filed is considered negligible in comparisons to the applied magnetic field.

Formation of the problem

Let x-axis be taken along the lower stretching sheet in the flow direction and y-axis is taken normal to the sheet. The lower plate is stretched by introducing two equal and opposite forces along the x-axis, so that the position of the origin remains unchanged. The fluid is sucked through the upper porous plate with constant velocity V_0. A transverse magnetic field B_0 of small magnitude is applied so that induced magnetic field is negligible in comparison to applied magnetic field.

The governing equations are:

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

$$\frac{\partial u}{\partial \bar{t}}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{-1}{\rho}\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\frac{\sigma_e B_0^2}{\rho(1+m^2)}u \tag{2}$$

$$\frac{\partial v}{\partial \bar{t}}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=\frac{-1}{\rho}\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

The boundary conditions are $y = 0$; $u = cx$, $v = 0$

$$y=h,\quad u=U_0(1+\varepsilon \mathrm{e}^{i\omega t}),\quad v=V_0 \tag{4}$$

Introducing the non-dimensional parameters:

$$\eta=\frac{y}{h},\quad \bar{t}=\frac{t}{c},\quad \varpi=\omega c,\quad R_e=\frac{ch^2}{\nu},\quad M=B_0 h\sqrt{\frac{\sigma_e}{\rho\nu}},\quad M_1=\frac{M}{1+m^2} \tag{5}$$

Such that equation of continuity admits the self similar solution:

$$u=cxf^1(\eta,t);\quad v=chf(\eta,t) \tag{6}$$

By substituting the non-dimensional parameters (5) in eqs. (2) and (3), the non-dimensional forms of the governing equations are:

$$\frac{\partial f^1}{\partial t}+f^{1^2}-ff^{11}-\frac{1}{\mathrm{Re}}f^{111}+\frac{1}{\mathrm{Re}}M_1^2 f^1=-\frac{1}{\rho c^2 x}\frac{\partial p}{\partial x} \tag{7}$$

$$\frac{\partial f}{\partial t}-ff^1-\frac{1}{\mathrm{Re}}f^{11}=-\frac{1}{\rho c^2 h^2}\frac{\partial p}{\partial \eta} \tag{8}$$

Differentiating eq. (8) with respect to x, we have:

$$\frac{\partial^2 p}{\partial x\partial \eta}=0 \tag{9}$$

From eqs. (7) and (9) we get:

$$f^{111}+\mathrm{Re}\,f^{11}f-\mathrm{Re}\,f^{1^2}-M_1^2 f^1-\mathrm{Re}\frac{\partial f^1}{\partial t}=c(t) \tag{10}$$

The corresponding boundary conditions in non-dimensional form are:

$$f = 0;\ f^1 = 1 \ \text{ at } \ \eta = 0 \ \text{ and } \ f = -\beta;\ f^1 = \alpha(1 + \varepsilon\, \mathrm{e}^{i\omega t}) \tag{11}$$

where $\alpha = U_0/cx$ and $\beta = V_0/ch$.

Method of solution

In view of the boundary conditions, we assume that:

$$f(\eta, t) = f_0(\eta) + \varepsilon \mathrm{e}^{i\omega t} f_1(\eta) \quad \text{and} \quad C(t) = C_0 + \varepsilon \mathrm{e}^{i\omega t} C_1 \tag{12}$$

where $\varepsilon \ll 1$. Substituting eq. (12) in eq. (10) and separating the steady and unsteady parts, we get:

$$f_0^{111} + \mathrm{Re}\, f_0 f_0^{11} - \mathrm{Re}\, f_0^{12} - M_1^2 f_0^1 = C_0 \tag{13}$$

$$f_1^{111} + \mathrm{Re}\, f_1 f_0^{11} + \mathrm{Re}\, f_0 f_1^{11} - 2\,\mathrm{Re}\, f_0^1 f_1^1 - M_1^2 f_1^1 - \mathrm{Re}\, i\omega f_1^1 C_1 \tag{14}$$

The corresponding boundary conditions are:

$$\begin{aligned} &f_0 = 0, \quad f_1 = 0, \quad f_0^{1} = 1, \quad f_1^1 = 0 \quad \text{at} \quad \eta = 0 \quad \text{and} \\ &f_0 = -\beta, \quad f_1 = 0, \quad f_0^{1} = \alpha, \quad f_1^1 = \alpha \quad \text{at} \quad \eta = 1 \end{aligned} \tag{15}$$

Taking Reynolds number as small, a regular perturbation scheme can be developed as:

$$\begin{aligned} &f_i(\eta) = f_{i0}(\eta) + \mathrm{Re}\, f_{i1}(\eta) + o(\mathrm{Re})^2 \quad \text{and} \\ &C_i = C_{i0} + \mathrm{Re}\, C_{i1} + o(\mathrm{Re})^2 \quad \text{for} \quad i = 0 \quad \text{and} \quad 1 \end{aligned} \tag{16}$$

By substituting eq. (16) in eqs. (13) and (14) and equating the like powers of Re, we have the following sets of equations:

– *Zero order equations:*

$$f_{00}^{111} - M_1^2 f_{00}^1 = C_{00} \tag{17}$$

$$f_{01}^{111} - M_1^2 f_{01}^1 + f_{00} f_{00}^{11} - f_{00}^{12} = C_{01} \tag{18}$$

with the corresponding boundary conditions:

$$\begin{aligned} &f_{00} = 0, \quad f_{01} = 0, \quad f_{00}^1 = 1, \quad f_{01}^1 = 0 \ \text{ at } \ \eta = 0 \quad \text{and} \\ &f_{00} = -\beta, \quad f_{01} = 0, \quad f_{00}^1 = \alpha, \quad f_{01}^1 = 0 \ \text{ at } \eta = 1 \end{aligned} \tag{19}$$

– *First order equations:*

$$f_{10}^{111} - M_1^2 f_{10}^1 = C_{10} \tag{20}$$

$$f_{11}^{111} - M_1^2 f_{11}^1 + f_{10} f_{00}^{11} + f_{00} f_{10}^{11} - 2 f_{00}^1 f_{10}^1 - i\omega f_{10}^1 = C_{11} \tag{21}$$

with the corresponding boundary conditions:

$$\begin{aligned} &f_{10} = 0,\ f_{11} = 0,\ f_{10}^1 = 0,\ f_{11}^1 = 0 \ \text{ at } \eta = 0 \\ &f_{10} = 0,\ f_{11} = 0,\ f_{10}^1 = \alpha,\ f_{11}^1 = 0 \ \text{ at } \eta = 1 \end{aligned} \tag{22}$$

Solution of the problem

On solving the eqs. (17), (18), (20), and (21) , under the boundary conditions (19) and (22), we obtain:

$$f_{00} = C_1 \cosh M_1\eta + C_2 \sinh M_1\eta + C_3 - \frac{C_{00}}{M_1^2}\eta \tag{23}$$

$$\begin{aligned} f_{01} &= C_4 \cosh M_1\eta + C_5 \sinh M_1\eta + C_6 - \frac{C_{01}}{M_1^2}\eta - \frac{B_1}{M_1^2}\eta - \frac{B_2}{2M_1^2}\eta\cosh M_1\eta - \\ &- \frac{B_3}{2M_1^2}\eta\sinh M_1\eta + \frac{B_4}{2M_1^2}\left(\frac{\eta^2}{2}\cosh M_1\eta - \frac{3}{2M_1}\eta\sinh M_1\eta + \frac{7}{4M_1^2}\cosh M_1\eta\right) + \\ &+ \frac{B_5}{2M_1^2}\left(\frac{\eta^2}{2}\sinh M_1\eta - \frac{3}{2M_1}\eta\cosh M_1\eta + \frac{7}{4M_1^2}\sinh M_1\eta\right) \end{aligned} \tag{24}$$

$$f_{10} = C_7 \cosh M_1\eta + C_8 \sinh M_1\eta + C_9 - \frac{C_{10}}{M_1^2}\eta \tag{25}$$

$$\begin{aligned} f_{11} &= B_{17}\cosh M_1\eta + B_{19}\sinh M_1\eta - \left(B_{17} + \frac{7B_{11}}{8M_1^4}\right) - \left(B_{19}M_1 - \frac{B_9}{2M_1^2} + \frac{B_{12}}{8M_1^3}\right)\eta - \\ &- \frac{B_9}{2M_1^2}\eta\cosh M_1\eta - \frac{B_{10}}{2M_1^2}\eta\sinh M_1\eta + \frac{B_{11}}{2M_1^2}\left(\begin{array}{l}\dfrac{\eta^2}{2}\cosh M_1\eta - \dfrac{3}{2M_1}\eta\sinh M_1\eta + \\ + \dfrac{7}{4M_1^2}\cosh M_1\eta\end{array}\right) + \\ &+ \frac{B_{12}}{2M_1^2}\left(\frac{\eta^2}{2}\sinh M_1\eta - \frac{3}{2M_1}\eta\cosh M_1\eta + \frac{7}{4M_1^2}\sinh M_1\eta\right) + \\ &+ i\omega\left[\begin{array}{l}\dfrac{C_7}{2M_1^2}\eta\cosh M_1\eta + \dfrac{C_8}{2M_1^2}\eta\sinh M_1\eta - \dfrac{C_9}{M_1^2}\eta + \dfrac{C_{10}}{M_1^4}\left(\dfrac{\eta^2}{2} + \dfrac{1}{M_1^2}\right) - \\ -B_{18}\cosh M_1\eta - B_{20}\sinh M_1\eta + B_{18} - \dfrac{C_{10}}{M_1^6} + B_{20}M_1\eta - \left(\dfrac{C_7}{2M_1^2} - \dfrac{C_9}{M_1^2}\right)\eta\end{array}\right] \end{aligned} \tag{26}$$

where A_1 to A_{12}; B_1 to B_{24}, and C_{00}, C_{01}, C_{10}, C_{11} are constants.

Finally the expression for the velocity distribution is obtained in the following form:

$$f(\eta,t) = f_{00}(\eta) + \text{Re}\, f_{01} + \varepsilon(f_{10} + \text{Re}\, f_{11})(\cos\omega t + i\sin\omega t) \tag{27}$$

Results and discussion

The fluid flow along the y-direction at the stretching sheet, characterized by $-f(\eta, t)$ is shown from figs. (1) to (8) for fixed values Re = 0.5, ω = 5 and $wt = \pi/4$, with the variations of α, β, M, and m. In fig. 1, the fluid flow along the y-direction is showed with the variation of α for fixed values of M = 5, m = 5, and β = 2.0. It is noticed that the fluid flow is affected by the back flow whose magnitude is reduced with the increase of α. In fig. 2 variation of –$f(\eta, t)$ is shown for different values of suction parameter β. It is observed that the back flow decreases with the increase of β.

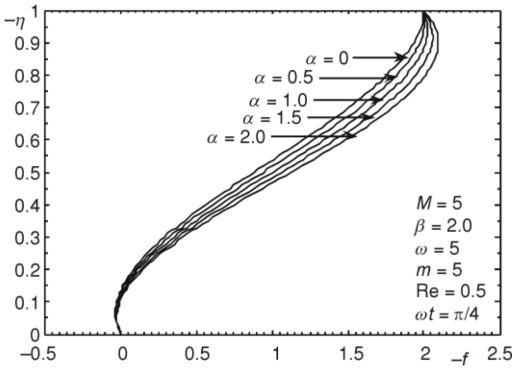

Figure 1. Graph of variation of –$f(\eta, t)$ with α

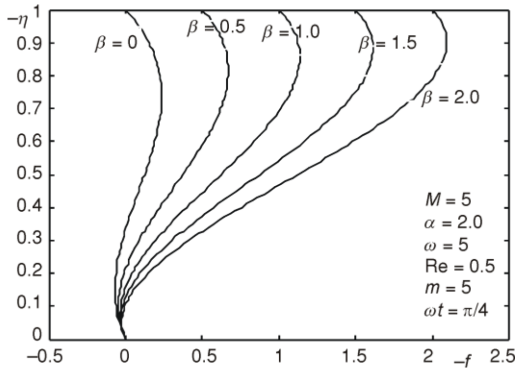

Figure 2. Graph of variation of –$f(\eta, t)$ with β

In fig. 3 variations of –$f(\eta, t)$ is shown for various values of magnetic parameter M, for fixed values of m = 5, α = 0.2, and β = 0.2. It is noticed that the fluid flow is affected by back flow whose magnitude is decreases with the increase of M. In fig. 4 variation of –$f(\eta, t)$ is shown with the variation of M in the absence of Hall parameter m, *i. e.* m = 0. It is noticed that the significance of back flow is much higher with the variation of M. The back flow reduces with the increase of M, but the reverse action is observed near the moving plate (0.75 < η < 1.0). The effect of m is studied through fig. 5, for fixed values of M = 5, α = 0.2, and β = 0.2. It is noticed that the back flow of the fluid increases with the increase of m. In fig. 6 variation of –$f(\eta, t)$ with m is showed for higher value of Hartmann number M, *i. e.* M = 10. It is noticed that the back flow of the fluid increases with the increase of m, but the reverse action if observed near the moving plate. In fig. 7 variation of –$f(\eta, t)$ with m is showed for small value of Hartmann number M, *i. e.* M = 2. It is observed that the back flow of the fluid increases with the increase of m up to m = 5 and then the effect of m is not found. In fig. 8 variation of –$f(\eta, t)$ with variation of m is shown for fixed values of M = 1, α = 2, and β = 2. It is noticed that there is no influence of m on the fluid flow.

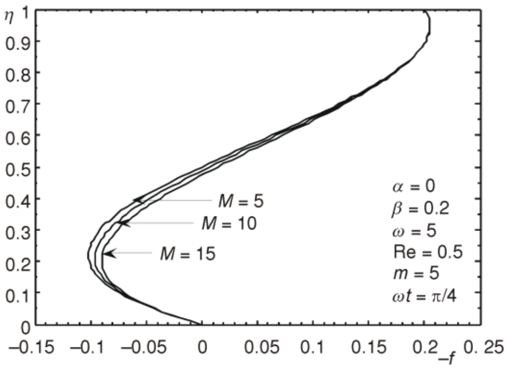

Figure 3. Graph of variation of –$f(\eta,t)$ with magnetic parameter M

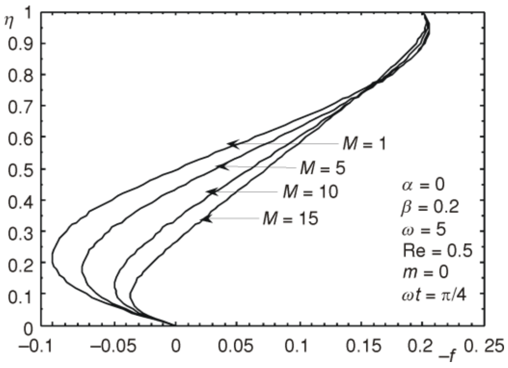

Figure 4. Graph of variation of –$f(\eta,t)$ with magnetic parameter M

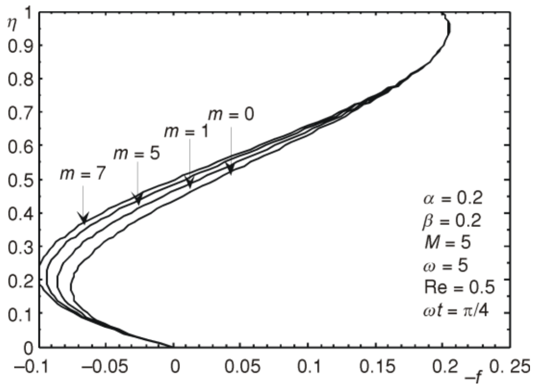

Figure 5. Graph of variation of –*f*(*η*,*t*) with Hall parameter *m*

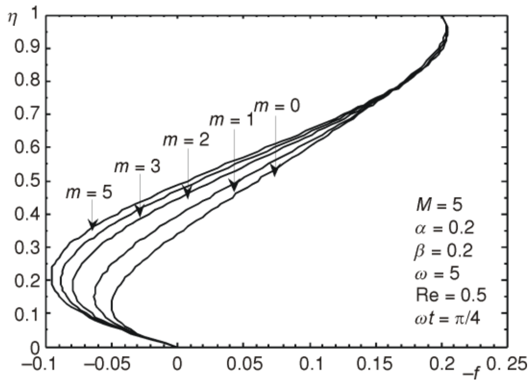

Figure 6. Graph of variation of –*f*(*η*,*t*) with Hall parameter *m*

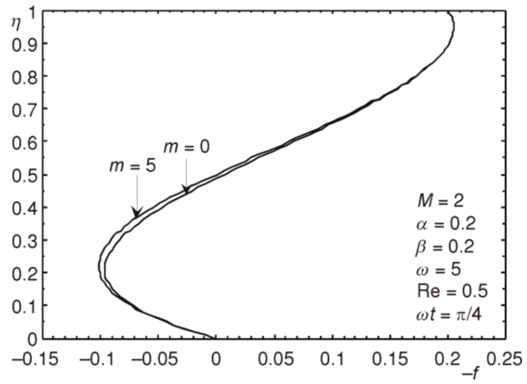

Figure 7. Graph of variation of –*f*(*η*,*t*) with Hall parameter *m*

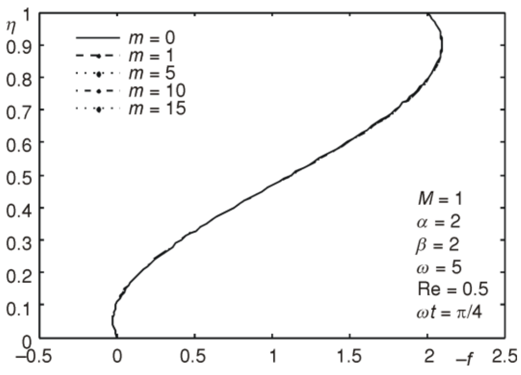

Figure 8.Graph of variation of –*f*(*η*,*t*) with Hall parameter *m*

The stretching effects on the fluid velocity in x-direction characterized by $f^{1}(\eta, t)$ is shown from figs. (9) to (14) for fixed values of Re = 0.5, ω = 5, and $\omega t = \pi/4$. In fig. 9 variation of $f^{1}(\eta, t)$ is shown with the variation of α, for fixed values of M = 2, m = 0, and β = = 0.5. It is observed that along the main stream the velocity is more prominent in the back flow.

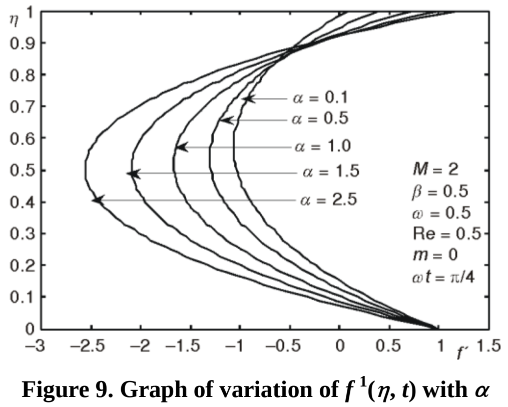

Figure 9. Graph of variation of $f^{1}(\eta, t)$ with α

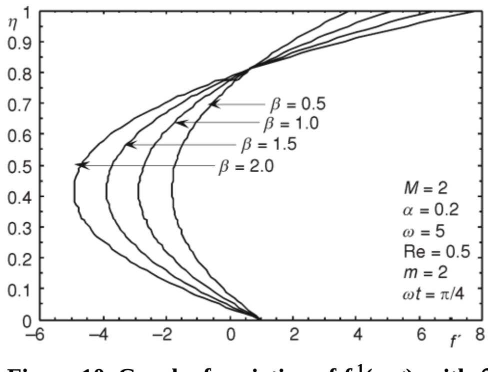

Figure 10. Graph of variation of $f^{1}(\eta, t)$ with β

The magnitude of the back flow increases with the increase of α throughout the width of the channel from the stretching sheet and the reserve action is observed near the moving plate. In fig. 10 variation of $f^{1}(\eta, t)$ is shown with the variation of suction parameter β, for fixed values of $M = 2$, $m = 2$, and $\alpha = 0.5$. It is noticed that the back flow increases with the increase of β and the reverse action is observed near the moving plate. In fig. 11 variation of $f^{1}(\eta, t)$ is shown with the variation of M for fixed values of $m = 2$, $\alpha = 0.5$, and $\beta = 0.5$. It is noticed that the velocity decreases with the increase of magnetic parameter M near the centre, but reverse action is observed neat the stretching sheet ($0 < \eta < 0.35$) and the moving plate ($0.8 < \eta < 1.0$). In fig. 12 variation of $f^{1}(\eta, t)$ is shown with the variation of Hall parameter m for fixed values of $M = 10$, $\alpha = 0.5$, and $\beta = 0.5$. It is observed that the velocity is affected by the back flow. The magnitude of the back flow increases with the increase of m near the centre ($0.3 < \eta < 0.8$) and the reverse action is observed near the plates. In fig. 13 variation of $f^{1}(\eta, t)$ is shown with the variation of m for fixed $M = 2$, $\alpha = 0.5$, and $\beta = 0.5$. It is noticed that the back flow increases with the increase of m at the centre but reverse action takes place near the plates. It is also observed that for $m > 5$ there is no significance of the back flow on velocity. In fig. 14 variation of $f^{1}(\eta, t)$ is shown for $m = 0$, 1, 5, 10, and 15 in the case of low values of M. It is noticed that there is a small increment in the magnitude of the back flow with the increase of m up to m =1, there after no effect of m is observed on velocity.

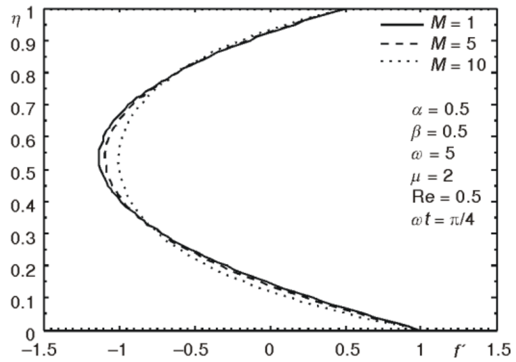

Figure 11. Graph of variation of $f^{1}(\eta, t)$ with M

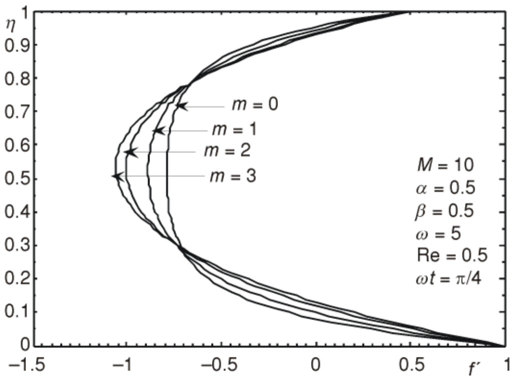

Figure 12. Graph of variation of $f^{1}(\eta, t)$ with m

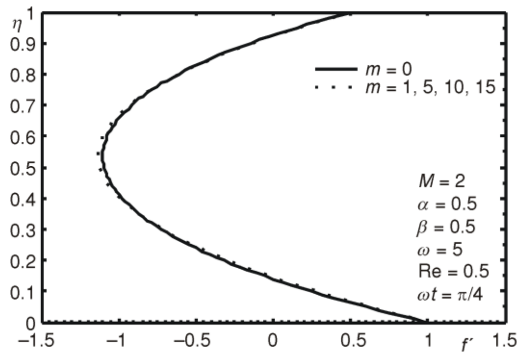

Figure 13. Graph of variation of $f^{1}(\eta, t)$ with m

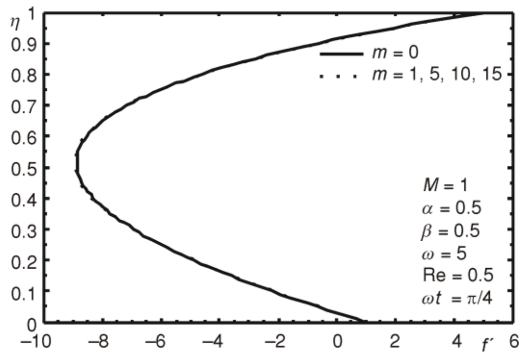

Figure 14. Graph of variation of $f^{1}(\eta, t)$ with m

Conclusions

In this paper Hall current effect on unsteady MHD flow of a viscous in compressible electrically conducting fluid between two horizontal parallel non conducting plane surfaces is considered. The lower surface is a stretching sheet and the upper one is an oscillating porous plate. The fluid motion is caused by stretching of the sheet and suction at the upper porous plate which is oscillating in its own plane. The stretching velocity of the sheet is assumed to be linear function of distance along the channel and the induced magnetic filed is considered negligible in comparisons to the applied magnetic filed.

In the analysis of the problem the following conclusions are made.

- The fluid flow at the stretching sheet along y-direction is characterized by $-f(\eta,t)$ is affected by the back flow, the magnitude of the back flow is reduced with the increase of suction parameter β, Hartmann number M and the value of α.
- The magnitude of back flow is increased with the increase of Hall parameter m. However for small values of M, Hall parameter influences the flow at lower level.
- The stretching effects on the fluid velocity in x-direction is characterized by $f^{1}(\eta, t)$. Along the main stream the fluid velocity is more prominent in the back flow which increases throughout the width of the channel with the increase of suction parameter β and with the value of α, but the back flow digresses near the moving plate.
- The back flow of the fluid velocity increase with the increase of Hall parameter m at the centre of the plates and the reverse action is observed near the plates. However at low values of magnetic parameter M, Hall parameter m has low effects.

Nomenclature

B_0 – uniform transverse magnetic field, [G]
c – rate of stretching, [–]
$C(t)$ – time dependent constant, [–]
h – width of the channel, [m]
p – pressure, [Pa]
Re – stretching Reynolds number, [–]
$\bar{t}$ – time, [s]
U_0 – characteristic velocity of the upper plate [ms^{-1}]
u, v – velocity components, [ms^{-1}]
V_0 – suction velocity through upper plate, [ms^{-1}]
x – flow directional co-ordinate along the stretching sheet, [m]
y – distance normal to the stretching sheet, – [m]

Greek symbols

β – suction parameter, [–]
η – similarity variable, [–]
ν – kinematic viscosity, [m^{2}s^{-1}]
ρ – density of the fluid , [kgm^{-3}]
σ_e – electric conductivity, [Sm^{-1}]
ω – frequency, [Hz]

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