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Magnetoydrodynamic Flow of a Dusty Fluid through an Equilateral Triangular Channel

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Abstract: In this paper, the motion of an incompressible dusty fluid through an equilateral triangular channel placed under a transverse magnetic field has been studied by using the concerned equations of a straight channel after their modification for triangular channel with suitable conditions and then through Fourier series method, an analytical solution for the velocity distributions has been obtained for both the fluid and particle phase. The effects of various parameters associated with this flow problem such as magnetic field, dust-concentration, frequency of oscillations and dust-relaxation on the steady and unsteady part of velocity distributions are analyzed by plotting the graphs. Especially for transverse magnetic field, it has been found that steady and unsteady part of velocity distributions for both fluid and particle phase decrease with the increase of the Hartman number.

Keywords: Dusty fluid, MHD flows, Triangular -Channel, Magnetic field, Two-phase flow.

1. Introduction

The study of the flow of a dusty incompressible and electrically-conducting fluid through tube of various cross-sections in presence of magnetic field has many valuable practical applications in industries and engineering sciences as the efficiency and performance of many devices are affected by the presence of suspended solid particles contained by the fluid in magnetic field.

A great effort has been made to understand interaction between dusty fluid flow and magnetic field time to time by number of researchers. Saffman[1] investigated the effect of stability of laminar flow of dusty gas. Dube and Srivastava[2] derived the expression for the unsteady flow of a dusty viscous fluid by assuming uniform distribution of dust particles in a channel bounded by two parallel flat plates. Pateriya[3] discussed the unsteady viscous flow of fluids through electrical ducts Rukmangadachari[4] has studied the solution of dusty viscous flow through a cylinder of triangular cross-section. Das and Gupta[5] investigated the unsteady viscous flow of an incompressible fluid viscous liquid through an equilateral triangular channel in presence of magnetic- field. Chernyshov[6] obtained the exact solution for unsteady two dimensional problem of the motion of an incompressible viscous fluid in rigid tube of triangular cross-section.. Attia[7] studied MHD Hartman flow of a dusty fluid with exponential decaying pressure gradaint. Khare[8] explained the effect of magnetic field on mean velocity of flow in a channel placed in a magnetic field. Sandsoo Lim[9] discussed the MHD micropump with side-walled electrodes. Lee[10] made numerical study on electrohydrodynamic induction pumps using CFD modeling. Malekzadeh[11] studied the magnetic field effect on laminar heat transfer in a pipe for thermal entry region.

In the present study, the channel with equilateral triangular cross-section has considered for the motion of fluid. The fluid is assumed to be dusty, incompressible and electrically conducting while the particle phase is assumed be incompressible and electrically non-conducting Dust particle are assumed to be spherical in shape and of equal size and mass. The flow is induced by a decaying pressure gradient and other force of interactions has been ignored. The channel is placed under an applied transverse magnetic field while no electric field is applied and the induced magnetic field is neglected by assuming a very small magnetic Reynolds number. The motion of system has been observed for the fluid and particle phase separately. The differential equations so formed have been solved analytically with the established boundary conditions using different mathematical techniques and related expressions have been derived by considering parameters viz. Magnetic Field, Frequency-Parameter, Dust Relaxation Parameter and Dust Concentration Parameter. Choosing the numerical values for these parameters, the derived relations have been used to find the numerical values for the steady and unsteady part of velocity. Then the graphs have been drawn to analyze the results which are also examined on theoretical basis.

2. Formulation of the Problem

Consider the flow of a dusty viscous incompressible fluid through an equilateral triangular channel placed under transversely applied magnetic field taking the flow along the axis of the channel.

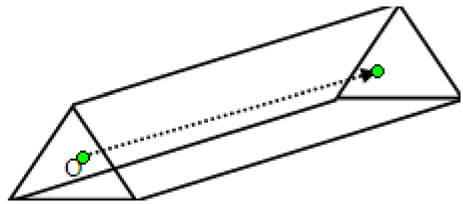

Fig.1 Shape of Channel

The governing equations of the motion of a dusty incompressible electricity conducting fluid in a straight channel under the influence of applied external transverse uniform magnetic field are given by

(1) $$\frac{\partial u}{\partial t}+\left(u\nabla\right)u=-\frac{\nabla p}{\rho}+\nu\nabla^{2}u+\frac{KN.}{\rho}\left(v-u\right)+\mu_{e}\ \left(J\times H\right),$$

(2) $$m\left[\frac{\partial v}{\partial t}+\left(v.\nabla\right)\nabla\right]=K\left(u-v\right).$$

(3) $$\nabla.u=\nabla.v=0,$$

(4) $$\frac{\partial N}{\partial t}+\nabla.\left(Nv\right)=0.$$

After simplifying, the equations (1) and (2) can be written as

(5) $$\frac{\partial u}{\partial t}=\frac{1}{\rho}\left(-\frac{\partial p}{\partial z}\right)+\upsilon\left(\frac{\partial^{2}u}{\partial x^{2}}+\frac{\partial^{2}u}{\partial y^{2}}\right)+\frac{KN}{\rho}\left(v-u\right)-\frac{\sigma}{\rho}\left(B_{0}^{2}u\right),$$

(6) $$\frac{\partial v}{\partial t}=\frac{1}{\tau}\left(u-v\right),$$

where u : the axial velocity of fluid, v : the axial velocity of dust particles, p : pressure, K : the Stokes's resistance coefficient, m : mass of each particle, N : number density of particles assumed to be constant, ν : kinematic viscosity, ρ : density of fluid, μ_e : Permeability, σ : Electrical conductivity, H : strength of magnetic field, B_0 : Magnetic field, J : current density, $\tau=\frac{m}{K}$ (Relaxation time for dust particle), $f=\frac{mN}{\rho}$ (Mass concentration parameter of the dust particle). The first term represents pressure gradient, second term viscosity, third term the force due to relative

motion between fluid and dust particle and last term represents Lorentz force in the above equations.
(7) The boundary conditions are $u = 0$ and $v = 0$ on the boundary of the channel
The flow is induced by a pressure gradient of the form

$$(8) \qquad -\frac{1}{\rho}\frac{\partial p}{\partial z} = A\left(1+\varepsilon e^{i\omega t}\right),$$

where ω is the frequency of the oscillation, A being a constant and ε is a dimensionless small quantity.
The following non-dimensional variables have been introduced to derive the dimensionless form of the equations from (5) to (8) to get the equations (9) as

$$\left.\begin{array}{l} u = u_1 u^*, \quad v = u_1 v^*, \ x = ax^*, \ y = ay^*, \ z = az^*, \ \tau = \dfrac{a}{u_1}\tau^*, \ p = \rho u_1^2 p^* \\ R = \dfrac{au_1}{\nu}, \ t = \dfrac{a}{u_1}t^*, \ M = B_0 a\sqrt{\dfrac{\sigma}{\rho\nu}}, \ f = \dfrac{mN}{\rho}, \ \tau = \dfrac{m}{K}, \ \omega^* = \dfrac{\omega a}{u_1}, A^* = \dfrac{Aa}{u_1^2} \end{array}\right\}$$

where M is the Hartman Number.
Putting them in equation (5), (6) and (8), the non-dimensional forms of these equations can be written as (the asterisks have been dropped for convenience)

$$(10) \qquad \frac{\partial u}{\partial t} = \left(-\frac{\partial P}{\partial z}\right) + \frac{1}{R}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \frac{f}{\tau}(v-u) - \frac{M^2}{R}u,$$

$$(11) \qquad \tau\frac{\partial v}{\partial t} = (u - v),$$

$$(12) \qquad -\frac{\partial p}{\partial z} = A\left(1+\varepsilon e^{i\omega t}\right).$$

Corresponding non dimensional initial and boundary conditions become

$$(13) \qquad t \le 0, \qquad \left.\begin{array}{l} u(x,y,t) = 0 \\ v(x,y,t) = 0 \end{array}\right\} \text{ everywhere in the channel}$$

(14) $t > 0,\qquad \left.\begin{aligned} u(x,y,t) &= 0 \\ v(x,y,t) &= 0 \end{aligned}\right\}$ on the boundary of the channel

We transform the equations (10) to trilinear co-ordinate system. Let *PQR* be the equilateral triangular tube and *O* is its centroid taken as origin. The lines perpendicular and parallel to *QR* are taken as x-axis and y-axis. Let 2a be the length of each side of the triangle and r be radius of in-circle. Let p_1, p_2 and p_2 are the perpendicular from any point within the triangle on the sides, QR, RP and PQ respectively.

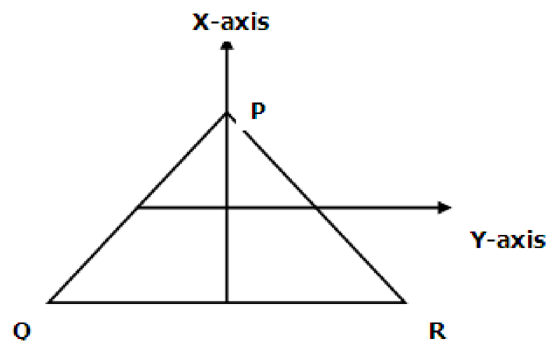

Fig. 2

The equations (15) are

Therefore $$\left.\begin{aligned} p_1 &= r - x \\ p_2 &= r + \frac{x}{2} - \frac{\sqrt{3}}{2}y \\ p_3 &= r + \frac{x}{2} + \frac{\sqrt{3}}{2}y \end{aligned}\right\}$$

(16) with $$p_1 + p_2 + p_3 = \sqrt{3}\,a$$

Now from equations (15) and (16), we have

(17) $$\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \equiv \frac{\partial^2}{\partial p_1^2} + \frac{\partial^2}{\partial p_2^2} + \frac{\partial^2}{\partial p_3^2} - \frac{\partial^2}{\partial p_1 \partial p_2} - \frac{\partial^2}{\partial p_2 \partial p_3} - \frac{\partial^2}{\partial p_3 \partial p_1}.$$

Under the transformation of equation (17), the equation (10) becomes

$$(18)\quad \frac{\partial u}{\partial t}=\left(-\frac{\partial P}{\partial z}\right)+\frac{1}{R}\left(\frac{\partial^2 u}{\partial p_1^2}+\frac{\partial^2 u}{\partial p_2^2}+\frac{\partial^2 u}{\partial p_3^2}-\frac{\partial^2 u}{\partial p_1 \partial p_2}-\frac{\partial^2 u}{\partial p_2 \partial p_3}-\frac{\partial^2 u}{\partial p_3 \partial p_1}\right)+\frac{f}{\tau}(v-u)-\frac{M^2}{R}u$$

and the boundary conditions are given by equations (19)

$$\left.\begin{array}{lll} (i)\ \ t \le 0, & u=v=0, & \text{everywhere in channel} \\ (ii)\ \ t>0, & u=v=0 \ \text{ at } \ p_1=0,\ p_2=0 \ \text{and} \ p_3=0 & \end{array}\right\} .$$

Solution: In the view of given conditions, we can assume the solutions for u and v in form

$$(20)\quad u(p_1,p_2,p_3,t)=A\left\{u_0(p_1,p_2,p_3)+\varepsilon u_1(p_1,p_2,p_3)\, e^{i\omega t}\right\}$$

$$(21)\quad v(p_1,p_2,p_3,t)=A\left\{v_0(p_1,p_2,p_3)+\varepsilon v_1(p_1,p_2,p_3) e^{i\omega t}\right\}$$

where u_0 and v_0 are the steady part and $u_1$and v_1 are the unsteady parts of the entries.
The corresponding boundary conditions changes to

$$(22)\quad u_0=0, u_1=0, v_0=0 \ \text{and} \ v_1=0 \ \text{at} \quad p_1=0, p_2=0 \, \text{and} \, p_3=0 \ .$$

Putting the value of u and v and different derivatives of u from (20) and (21) in equation (18) and equating separately the terms free from $\varepsilon e^{i\omega t}$ and the coefficients of $\varepsilon e^{i\omega t}$, we get following two equations

$$(23)\qquad \frac{\partial^2 u_0}{\partial p_1^2}+\frac{\partial^2 u_0}{\partial p_2^2}+\frac{\partial^2 u_0}{\partial p_3^2}-\frac{\partial^2 u_0}{\partial p_1 \partial p_2}-\frac{\partial^2 u_0}{\partial p_2 \partial p_3}-\frac{\partial^2 u_0}{\partial p_3 \partial p_1}+\frac{Rf}{\tau}\left(v_0-u_0\right)-M^2 u_0=-R\,,$$

$$(24)\quad \frac{\partial^2 u_1}{\partial p_1^2}+\frac{\partial^2 u_1}{\partial p_2^2}+\frac{\partial^2 u_1}{\partial p_3^2}-\frac{\partial^2 u_1}{\partial p_1 \partial p_2}-\frac{\partial^2 u_1}{\partial p_2 \partial p_3}-\frac{\partial^2 u_1}{\partial p_3 \partial p_1}+\frac{Rf}{\tau}\left(v_1-u_1\right)-M^2 u_1+R-Ru_1 i\omega=0.$$

Again putting the value of u and v and different derivatives of v from (20) and (21) in equation (11) and equating separately the terms free from $\varepsilon e^{i\omega t}$ and the coefficients of $\varepsilon e^{i\omega t}$, we get following two equations

$$\text{(25)}\quad \frac{1}{\tau}\left(u_0 - v_0\right) = 0 \Rightarrow\ u_0 = v_0\,,$$

$$\text{(26)}\quad v_1 = \frac{1}{(1+i\omega\tau)}u_1.$$

It may be noted here that in fully developed flow, the steady part of fluid and the particle velocity are the same.

From equation (25) in (23) and from equation (26) in (24), we get following two equations

$$\text{(27)}\quad \frac{\partial^2 u_0}{\partial p_1^2} + \frac{\partial^2 u_0}{\partial p_2^2} + \frac{\partial^2 u_0}{\partial p_3^2} - \frac{\partial^2 u_0}{\partial p_1 \partial p_2} - \frac{\partial^2 u_0}{\partial p_2 \partial p_3} - \frac{\partial^2 u_0}{\partial p_3 \partial p_1} - M^2 u_0 = -R$$

$$\text{(28)}\quad \frac{\partial^2 u_1}{\partial p_1^2} + \frac{\partial^2 u_1}{\partial p_2^2} + \frac{\partial^2 u_1}{\partial p_3^2} - \frac{\partial^2 u_1}{\partial p_1 \partial p_2} - \frac{\partial^2 u_1}{\partial p_2 \partial p_3} - \frac{\partial^2 u_1}{\partial p_3 \partial p_1} - R\omega\left(C_1 + iC_2\right)u_1 = -R$$

$$\text{(29)}\quad \text{where}\quad C_1 = \left(\frac{M^2}{\omega R} + \frac{f\omega\tau}{1+\omega^2\tau^2}\right),\ \text{and}\ C_2 = \left\{1 + \frac{f}{1+\omega^2\tau^2}\right\}.$$

Let assume the solution of the equation (27) and (28) satisfying the boundary conditions of equation (22) as;

$$\text{(30)}\quad u_0 = \sum_{n=1}^{\infty}\alpha_n\left(\sin\frac{2n\pi}{\sqrt{3}\,a}p_1 + \sin\frac{2n\pi}{\sqrt{3}\,a}p_2 + \sin\frac{2n\pi}{\sqrt{3}\,a}p_3\right)\ ,$$

$$\text{(31)}\quad u_1 = \sum_{n=1}^{\infty}\beta_n\left(\sin\frac{2n\pi}{\sqrt{3}\,a}p_1 + \sin\frac{2n\pi}{\sqrt{3}\,a}p_2 + \sin\frac{2n\pi}{\sqrt{3}\,a}p_3\right).$$

Substituting the value of u_0, u_1 and different derivatives of u_0, u_1 from equation (30) and (31) in equation (27) and (28) we get following two equations

$$(32)\quad \sum_{n=1}^{\infty} \alpha_n \left(\sin\frac{2n\pi}{\sqrt{3}\,a} p_1 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_2 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_3 \right) M^2 = R \;,$$

$$(33)\quad \sum_{n=1}^{\infty} \beta_n \left(\sin\frac{2n\pi}{\sqrt{3}\,a} p_1 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_2 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_3 \right) \omega\left(C_1 + iC_2\right) = 1 \;.$$

Since $P_1 + P_2 + P_3 = \sqrt{3}\,a$, we can write

$$(34)\quad R = \frac{R}{\sqrt{3}\,a}\left\{\left(\sqrt{3}\,a - 2p_1\right) + \left(\sqrt{3}\,a - 2p_2\right) + \left(\sqrt{3}\,a - 2p_3\right)\right\}.$$

Expressing $\left(\sqrt{3}\,a - 2p_1\right)$ etc. as Fourier's sine series, we get

$$(35)\quad \sum_{n=1}^{\infty} \left(\sin\frac{2n\pi}{\sqrt{3}\,a} p_1 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_2 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_3 \right) \frac{2}{\pi} = 1.$$

From equation (35) in equations (32) and (33), we have

$$(36)\quad \alpha_n = \frac{2R}{\pi\, n\, M^2},$$

$$(37)\quad \beta_n = \frac{2}{\pi\, n\, \omega\left(C_1 + iC_2\right)}.$$

Hence the solution of equations (27) and (28) is

$$(38)\quad u_0 = \sum_{n=1}^{\infty} \frac{2R}{\pi\, n\, M^2} \left(\sin\frac{2n\pi}{\sqrt{3}\,a} p_1 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_2 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_3 \right) \text{ and}$$

$$(39)\quad v_0 = \sum_{n=1}^{\infty} \frac{2R}{\pi\, n\, M^2} \left(\sin\frac{2n\pi}{\sqrt{3}\,a} p_1 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_2 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_3 \right).$$

Also

$$(40)\quad u_1 = \sum_{n=1}^{\infty} \frac{2}{\pi n \omega (C_1 + iC_2)} \left(\sin\frac{2n\pi}{\sqrt{3}\,a} p_1 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_2 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_3 \right).$$

Hence

$$(41)\quad v_1 = \sum_{n=1}^{\infty} \frac{2}{\pi n (1 + i\omega\tau) \omega (C_1 + iC_2)} \left(\sin\frac{2n\pi}{\sqrt{3}\,a} p_1 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_2 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_3 \right).$$

From equations (38), (39) and (40), (41), we get

$$(42)\quad u = A\left\{ \begin{aligned} &\sum_{n=1}^{\infty} \frac{2R}{\pi n M^2} \left(\sin\frac{2n\pi}{\sqrt{3}\,a} p_1 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_2 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_3 \right) \\ &+ \varepsilon \sum_{n=1}^{\infty} \frac{2}{\pi n \omega (C_1 + iC_2)} \left(\sin\frac{2n\pi}{\sqrt{3}\,a} p_1 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_2 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_3 \right) e^{i\omega t} \end{aligned} \right\}$$

$$(43)\quad v = A\left\{ \begin{aligned} &\sum_{n=1}^{\infty} \frac{2R}{\pi n M^2} \left(\sin\frac{2n\pi}{\sqrt{3}\,a} p_1 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_2 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_3 \right) \\ &+ \varepsilon \sum_{n=1}^{\infty} \frac{2}{\pi n (1 + i\omega\tau) \omega (C_1 + iC_2)} \left(\sin\frac{2n\pi}{\sqrt{3}\,a} p_1 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_2 + \sin\frac{2n\pi}{\sqrt{3}\,a} p_3 \right) e^{i\omega t} \end{aligned} \right\}$$

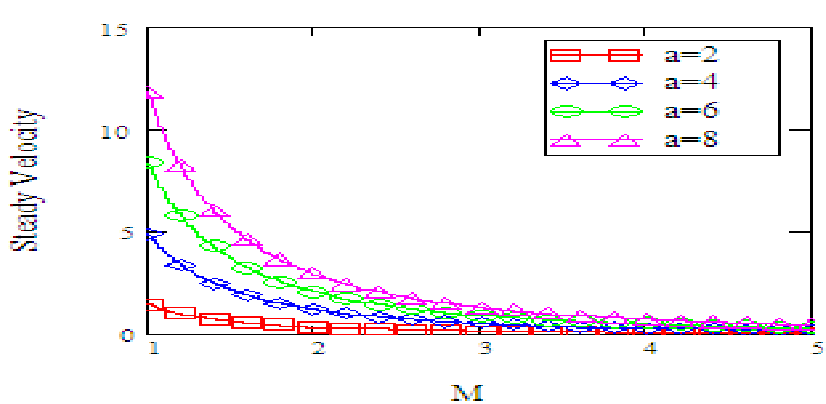

Fig. 3

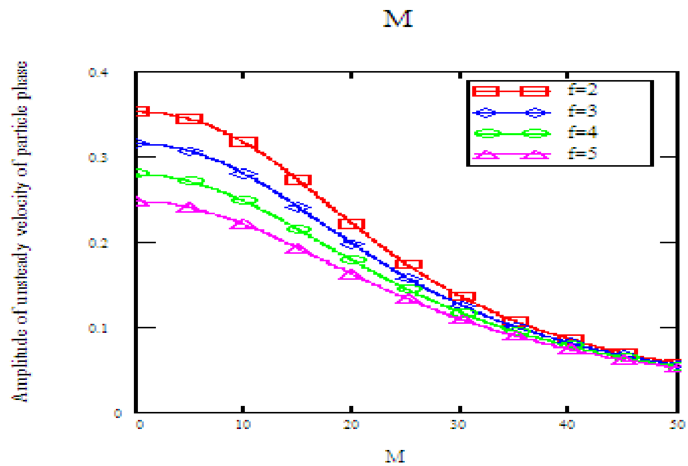

Fig. 4

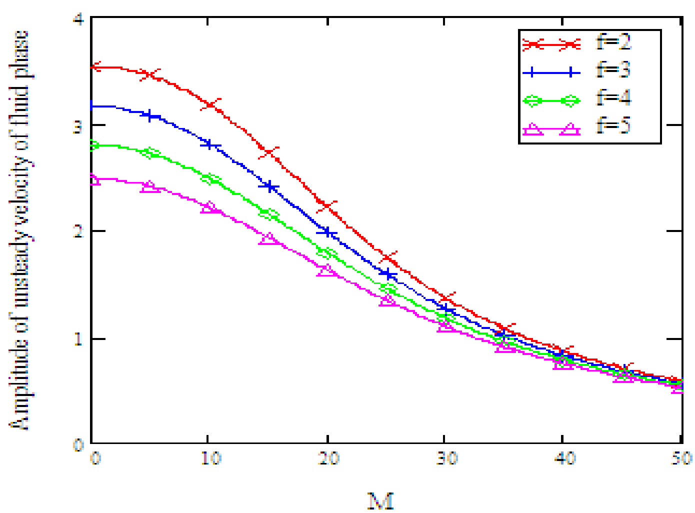

Fig. 5

3. Discussion of Results

The above equations are used to find numerical computation for various values of the parameters to analyze their effect on the steady and unsteady part of the velocity distributions for both fluid and particle phase. Figure 3 shows the profile of the steady part of the fluid velocity against M between $M=1$ and $M=5$ for various values of 'a'. The graph are plotted for a= (2,4,6,8), (x,y)=(0,0), R=100 and t=32. From the graph it is observed that

the steady velocity decreases as the cross-sections area provides more free space for the motion which results in increasing u_0 and hence v_0.
Figures (4) and (5) show the profile of unsteady part of the fluid and particle velocity against *M* between *M=10* and *M=50* for various values of *f*. The graph are plotted for f = (2,3,4,5), (*x*,*y*)=(0,0), R =100, $\omega = 2.5$, $\tau = 1.5$ and *t*=3.
From the graph it is observed that the amplitude of unsteady velocity of both phases decreases with increase of *f*. Physically the fluid density ρ decreases with increase in mass concentration parameter *f* which, in turn, would increase of the velocity. Also imposition of magnetic field decreases the velocity and at large value of *M* , it tends to a steady states for the both phases but amplitude of unsteady velocity for particle phase is less than that of fluid phase as fluid phase provides the medium for motion of particle phase.

4. Conclusion

From the figures 3-5 and theoretical investigation of MHD flow of dusty fluid through triangular channel, it is observed that the steady part of flow of the fluid and particle phase are the same and decreases with increase in Hartman number and cross-section area of the channel. It is also found that the value of Reynolds number has no effects on the fully developed velocity profile. Its further study shows that as mass concentration of dust particle increases, the amplitude of unsteady part of velocities of both the phase decreases and this discernment is increased due to increment of magnetic field. The amplitude of the unsteady part of the velocities of fluid and particle phases increase with decrease of frequency of oscillation. It is also observed that as relaxation time of dust particles increases, the amplitude of unsteady velocity of fluid phase increases while amplitude of particle phase decreases but when τ decreases and tends to zero, the amplitudes of velocities of fluid and particle phase become the same.

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