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Oscillatory MHD Mixed Convection Boundary Layer Flow of Finite Dimension with Induced Pressure Gradient

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ABSTRACT

The purpose of present investigation is to deal with g-jitter forces of a time varing gravity field on unsteady hydromagnetic flow past a horizontal flat plate in the presence of a transverse magnetic field and the flow at the entrance also oscillates because of an applied pressue gradient. This problem deals with mixed convection driven by a combination of g-jitter and oscillating pressure gradient under the influence of an applied magnetic field. Analysis of this type find applications in space fluid system design and interpreting the experimental measurements in microgravity flow and heat transfer system.

Keywords: MHD flow; G-jitter forces; Critical Grashof number; Forced convection.

1. INTRODUCTION

Magneto hydrodynamic (MHD) mixed convection flow is the subject motivated by several important applications of fluid engineering, geothermal and aerospace science. To improve the efficiency of MHD energy systems, scientists and engineers are continuously involved with both analytical and numerical approaches to yield a considerable amount of new solutions to many different flow scenarios (Damseh 2006, Ghosh 1994, Pop *et al.* 2001, Datta and Jana 1977, Chen 2008 and Ghosh *et al.* 2011). MHD buoyancy driven mixed convection flow is of great interest to diverse new technological development on solar hydromagnetics with reference to a dynamo context of the Sun. A strong evidence of a vast magnetic field with the Sun in the presence of a magnetic mirror becomes relevant to the study of controlled thermonuclear fusion reaction of the Sun with reference to a turbulent dynamo mechanism of the Sun at the resonant level. In this situation, reflection occurs with the convective part of the surface of the Sun as the magnetic field increases abruptly in strength when a magnetic mirror with the Sun is taken into account. A charged oscillator exerts its influence of laser radiation due to a driving force so that an excitation frequency can lead to a resonant condition with a decisive importance to a dynamo mechanism of the Sun. This has been studied by Ghosh *et al.* (2013) and Ghosh (2014). In this context, MHD buoyancy driven mixed convection becomes important to a study of astrophysical flow in a microgravity field. Although MHD mixed convection flow with asymmetric heating of the wall has been studied by Ghosh and Nandi (2000), Ghosh and Bhattacharjee (2000), Ghosh *et al.* (2002), and Guria *et al.* (2007). Takhar *et al.* (1999) studied the influence of a magnetic field on unsteady free convection flow with the inclusion of the effects of heat transfer on a semi-infinite flat plate with an aligned magnetic field. Ghosh (1993) studied the transient magnetohydrodynamic viscous flow in a rotating parallel plate channel with oscillating pressure gradient for large frequency of oscillations at very small Ekman number (strong Coriolis force). Naroua (2006) studied magnetohydrodynamic convection driven by buoyancy force in a rotating heat generating fluid with Hall and ion slip current effects. Ghosh and Pop (2006) investigated in detail the magnetohydrodynamic effects on free convection boundary layer heat transfer from a finite plate of arbitrary inclination in a rotating environment permeated by a transverse magnetic field. Beg *et.al* (2009) studied steady hydromagnetic non-similar electrically conducting forced convection liquid metal boundary layer flow with induced magnetic field effects. Ghosh *et al.* (2010) developed a new approach on hydromagnetic free convection boundary layer flow of a moving layer past an infinite vertical flat plate under the influence of a transverse magnetic field showing the effect of Rayleigh flow. A recent study has been developed with g-jitter force to exert its influence on mixed convection flow with asymmetric heating of the wall in the presence of a magnetic field. This has been studied by Pan and Ben (1998).

The purpose of present investigation is to deal with the study of an oscillating mixed convection boundary layer flow driven by g-jitter forces associated with microgravity field with a decisive importance to a magnetic field. We consider g-jitter forces of a time varying gravity field on unsteady hydromagnetic flow past a horizontal flat plate in the presnce of a transverse magnetic field and the flow entrance also oscillates because of an applied pressure gradient. The g-jitter field varies harmonically with time. Oscillating mixed convection driven by g-jitter forces associated with microgravity and magnetic field effect on convection is investigated. In a realistic situation, the co-relation of unsteadiness and g-jitter force becomes relevant to a time varying gravity field driven by a time harmonic g-jitter components with a frequency of oscillation and the flow at the entrance also oscillates because of an applied pressure gradient. The time varying gravity field will generate an oscillatory free convection velocity field. This is combined with forced oscillating flow driven by a pressure gradient. For a g-jitter driven flow in a cavity that bears direct relevance to crystal growth in space; the net mass flow rate in the system is zero. The problem deals with mixed convection driven by a combination of g-jitter and oscillating pressure gradient under the influence of an applied magnetic field. Analysis of this type find applications in space fluid system design and interpreting the experimental measurements in microgravity flow and heat transfer system.

2. FORMULATION OF THE PROBLEM AND ITS SOLUTION

Consider an unsteady MHD flow of a viscous incompressible electrically conducting fluid past a horizontal flat plate of finite dimension, directed along the positive x-axis, in the presence of an applied uniform transverse magnetic field. This model is considered by representing the flow system of a flat plate with significant effect of pressure gradient. The flow is driven by a g-jitter field in the presence of a transverse magnetic field. In such a situation, a time varying gravity field driven by a time harmonic g-jitter forces and the flow at the entrance will also oscillate because of an applied pressure gradient. It is assumed that the plate is isothermal where the constant surface temperature T_W of the plate is exposed to the fluid. The temperature of the surrounding fluid is T_0 at a distance from the plate. A layer of the ascending heated fluid appears at the plate. x-axis is taken at the leading edge of the plate and the y-axis is oriented in the direction perpendicular to its surface. A uniform magnetic flux B_0 is applied parallel to y-axis (see Fig.1).

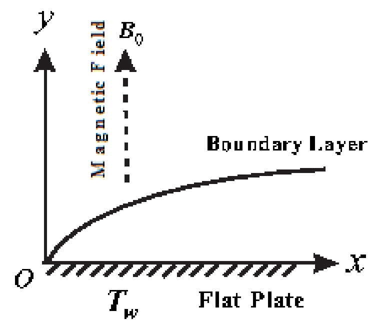

Fig. 1. Geometry of the problem.

Following Lewandowski (1991) and Ghosh *et al.* (2010) we assume that in the moving layer, temperature varies under the following condition:

$$\theta(\eta)=\frac{T-T_0}{T_W-T_0}=\left(1-\frac{y}{\delta}\right)^2. \tag{1}$$

This has also been described by Isachenko *et al.* (1969) in their monograph, where $\psi=T-T_0$ and $\psi_w=T_w-T_0$. In the present investigation, the temperature profile can be described in the moving layer with reference to $T_W-T_0=\text{constant}$.

Under the assumption (1), the following boundary conditions are satisfied

$$\psi=\psi_w \quad \text{at} \quad y=0\,,\quad \psi=0 \quad \text{at} \quad y=\delta \tag{2}$$

The unsteady MHD momentum conservation equation in the component form

$$\frac{\partial u'}{\partial t'}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\frac{\partial^2 u'}{\partial y^2}-\frac{\sigma B_0^2}{\rho}u' \tag{3}$$

$$0=-\frac{1}{\rho}\frac{\partial p}{\partial y}+g(t')\beta(T-T_0) \tag{4}$$

From (1) and (4), we have

$$\frac{\partial p}{\partial x}=\rho g(t')\beta(T_W-T_0)\left(\frac{y^2}{\delta^2}-\frac{2}{3}\frac{y^3}{\delta^3}\right)\frac{\partial\delta}{\partial x}+\frac{d}{dx}C\left(x\right) \tag{5}$$

We assume that at the leading edge of the plate the boundary layer growth is constant. Due to symmetry of the boundary layer growth, we have taken

$$\frac{\partial\delta}{\partial x}=\text{Constant}=H\ \text{(say)}. \tag{6}$$

Then equation (5) transformed into

$$\frac{\partial p}{\partial x}=\rho g(t')\beta(T_W-T_0)\left(\frac{y^2}{\delta^2}-\frac{2}{3}\frac{y^3}{\delta^3}\right)H+\frac{dC}{dx} \tag{7}$$

The velocity and temperature boundary conditions are

$$u'=0 \text{ at } y=0,\ u'=0 \text{ at } y=\delta, \tag{8}$$

$$\psi=\psi_w \text{ at } y=0,\ \psi=0 \text{ at } y=\delta.$$

where $u', \nu, \delta, g_0, \sigma, \rho, p, B_0$ are, respectively, the velocity component in x-direction, kinematic viscosity, boundary layer thickness, gravitational acceleration, electrical conductivity, fluid density, pressure and magnetic flux density.

Assume that

$$u'=u(y)e^{i\omega' t'},\ g(t')=g_0 e^{i\omega' t'},\ p=p_0 e^{i\omega' t'}, \tag{9}$$

where g_0 is the gravitational acceleration and t' is the time.

Introduce the non-dimensional variables

$$\eta=\frac{y}{\delta},\ F=\frac{u\delta}{\nu},\ \omega=\frac{\omega'\delta^2}{\nu},\ t=\frac{t'\nu}{\delta^2} \tag{10}$$

Combining equations (7) and (3) together with Eq. (5) subject to (9) the following equation can be obtained in a dimensionless form with reference to (10)

$$i\omega F=-Gr(\eta^2-\frac{2}{3}\eta^3)H+p_0+\frac{\partial^2 F}{\partial\eta^2}-M^2F, \tag{11}$$

where $Gr=g_0\beta(T_w-T_0)\delta^3/\nu^2$ is the Grashof number, $M^2=B_0^2\delta^2(\sigma/\rho\nu)$ is the Hartmann number and $p_0=\frac{\delta^3}{\rho\nu^2}\left\{-\frac{d}{dx}C\right\}$ is the dimensionless pressure gradient.

The corresponding velocity boundary conditions are

$$F=0 \text{ at } \eta=0 \text{ and } F=0 \text{ at } \eta=1 \tag{12}$$

The corresponding temperature boundary conditions are

$$\theta=1 \text{ at } \eta=0 \text{ and } \theta=0 \text{ at } \eta=1 \tag{13}$$

Equation (11) together with the boundary conditions (12) and (13) can be solved and the solution is

$$\begin{aligned}F(\eta)=&\frac{p_0}{(\alpha+i\beta)^2}\left[1-\frac{\sinh(\alpha+i\beta)\eta}{\sinh(\alpha+i\beta)}-\frac{\sinh(\alpha+i\beta)(1-\eta)}{\sinh(\alpha+i\beta)}\right]\\&+2GrH\left[\frac{1}{(\alpha+i\beta)^4}\left\{(2\eta-1)-\frac{\sinh(\alpha+i\beta)\eta}{\sinh(\alpha+i\beta)}+\frac{\sinh(\alpha+i\beta)(1-\eta)}{\sinh(\alpha+i\beta)}\right\}\right.\\&\left.+\frac{1}{6}\frac{1}{(\alpha+i\beta)^2}\left\{(2\eta^3-3\eta^2)+\frac{\sinh(\alpha+i\beta)\eta}{\sinh(\alpha+i\beta)}\right\}\right],\end{aligned} \tag{14}$$

where

$$\alpha,\beta=\frac{1}{\sqrt{2}}\left[(M^4+\omega^2)^{1/2}\pm M^2\right]^{1/2}. \tag{15}$$

With the help of (14), (10) and (9), one can easily obtained the value of $F_1(\eta)\left(=\frac{u'\delta}{\nu}\right)$, where $F_1(\eta,t)$ is given by

$$F_1(\eta,t)=F(\eta)e^{i\omega t}. \tag{16}$$

The pressure gradient p_0 is determined by requiring that flow satisfies the following condition

$$\int_0^1 F(\eta)d\eta=1 \tag{17}$$

Equation (17) is valid when the rate of mass flow is constant.

The expression of p_0 can be determined by using (17) together with the equation (14)

$$p_0=\frac{(\alpha+i\beta)^2}{1+D}+\frac{1}{6}H\,Gr \tag{18}$$

where $D=\frac{2[1-\cosh(\alpha+i\beta)]}{(\alpha+i\beta)\sinh(\alpha+i\beta)}$.

If the rate of mass flow is zero, then the expression for pressure gradient (18) reduces to

$$p_0=\frac{1}{6}H\,Gr \tag{19}$$

On using (18), Eq. (16) becomes

$$\begin{aligned}F_1(\eta,t)=&\left[\left\{\frac{1}{1+D}+\frac{1}{6(\alpha+i\beta)^2}Gr\,H\right\}\left\{1-\cosh(\alpha+i\beta)\eta+(\cosh(\alpha+i\beta)-1)\frac{\sinh(\alpha+i\beta)\eta}{\sinh(\alpha+i\beta)}\right\}\right.\\&+Gr\,H\left\{\frac{2}{(\alpha+i\beta)^4}\left\{(2\eta-1)+\cosh(\alpha+i\beta)\eta-(1+\cosh(\alpha+i\beta))\frac{\sinh(\alpha+i\beta)\eta}{\sinh(\alpha+i\beta)}\right\}\right.\\&\left.\left.+\frac{1}{3}\frac{1}{(\alpha+i\beta)^2}\left\{2\eta^3-3\eta^2+\frac{\sinh(\alpha+i\beta)\eta}{\sinh(\alpha+i\beta)}\right\}\right\}\right]e^{i\omega t}\end{aligned} \tag{20}$$

If the mass flow rate is zero, the equation (20) can be transformed into pure free convection flow. Using (19) the equation (16) turns into

$$\begin{aligned}F_1(\eta,t)=Gr\,H\Bigg[&\frac{1}{6(\alpha+i\beta)^2}\left\{1-\cosh(\alpha+i\beta)\eta+(\cosh(\alpha+i\beta)-1)\frac{\sinh(\alpha+i\beta)\eta}{\sinh(\alpha+i\beta)}\right\}\\&+\frac{2}{(\alpha+i\beta)^4}\left\{(2\eta-1)+\cosh(\alpha+i\beta)\eta\right.\end{aligned}$$

$$-\left(1+\cosh(\alpha+i\beta)\right)\frac{\sinh(\alpha+i\beta)\eta}{\sinh(\alpha+i\beta)}\Bigg\}$$

$$+\frac{1}{3}\frac{1}{(\alpha+i\beta)^2}\left\{2\eta^3-3\eta^2+\frac{\sinh(\alpha+i\beta)\eta}{\sinh(\alpha+i\beta)}\right\}\Bigg]e^{i\omega t} \tag{21}$$

In the absence of Grashof number $(Gr=0)$ this gives pure forced convection flow. Then equation (20) turns into

$$F_1(\eta,t)=\frac{1}{1+D}\Big[1-\cosh(\alpha+i\beta)\eta$$

$$+\left(\cosh(\alpha+i\beta)-1\right)\frac{\sinh(\alpha+i\beta)\eta}{\sinh(\alpha+i\beta)}\Bigg]e^{i\omega t} \tag{22}$$

3. RESULTS AND DISCUSSION

To determine the physical insight into the MHD flow pattern the velocity distributions are depicted graphically in Figs.2-5 for several values of M^2, Gr, ω and ωt. It is evident from

Figs.2-5 that the profiles are parabolic in nature and maximum peak of the profile occurs at the central section of the boundary layer region. Due to the symmetry of the boundary layer region the profiles are of parabolic in nature at the central region. Fig.2 shows that the fluid velocity decreases with an increase in M^2 in the region $0.27 \le \eta \le 0.70$. This happens due to setting up of Lorentz force in the presence of a transverse magnetic field, which impedes fluid velocity. In addition, there exists a flow reversal at the two ends of the boundary layer region. This happens in the case of a flow reversal under the influence of an induced pressure gradient when the decelerated fluid particle is to be forced outward and the fluid velocity increases near the two ends of the boundary layer region with an increase in M^2 in the regions $0 \le \eta < 0.27$ and $0.70 < \eta \le 1$. Fig.3 demonstrates that a flow reversal occurs at the two ends of the boundary layer region with a decisive importance to induced pressure gradient. Also, an increase in free convection parameter i.e. Grashof number Gr that leads to increase the fluid velocity in the region $0 \le \eta < 0.5$ and it decreases in the region $0.5 \le \eta \le 1$. This trend is due to the fact that the positive Grashof number Gr acts like a favourable pressure gradient which accelerates the flow in the boundary layer region. It is noticed from Fig.4 that in the central section of the boundary layer region the fluid velocity increases with an increase in frequency parameter ω and the occurrence of flow reversal at the two ends of the boundary layer region leads to decrease the fluid velocity with an increase in frequency parameter ω in the regions $0 \le \eta < 0.27$ and $0.70 < \eta \le 1$. It is interesting to note that the fluid velocity vanishes at the critical distances $\eta = 0.27$ and $\eta = 0.70$ from the plate. Fig.5 indicates that the fluid velocity decreases with an increase in phase angle ωt. This happens in the case of stability criteria when the phase angle determines the critical value for retarding the fluid velocity so that the flow becomes stable where no flow reversal occurs at the boundary of the plate.

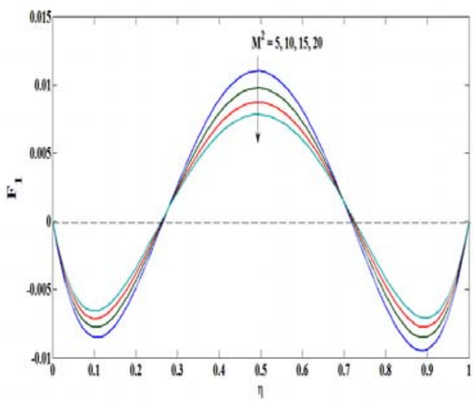

Fig. 2. Velocity profiles for M^2 when $Gr = 5$, $\omega = 2$ and $\omega t = \pi/2$.

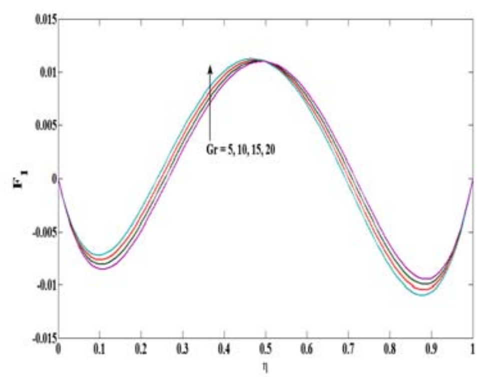

Fig. 3. Velocity profiles for Gr when $M^2 = 5$, $\omega = 2$ and $\omega t = \pi/2$.

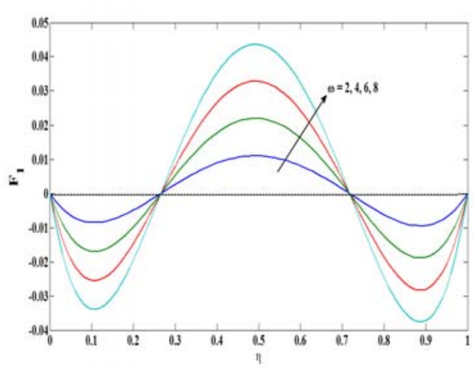

Fig. 4. Velocity profiles for ω when $M^2 = 5$, $Gr = 5$ and $\omega t = \pi/2$.

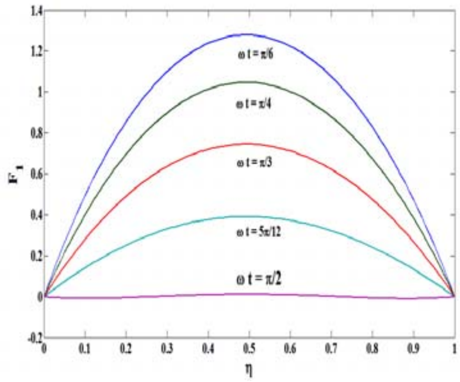

Fig. 5. Velocity profiles for ωt when $M^2 = 5$, $Gr = 5$ and $\omega = 2$.

We shall now discuss a few particular cases of interest.

Case I: In the case of a horizontal flat plate, the point of separation is determined by $\left(\frac{dF}{d\eta}\right)_{\eta=0} = 0.$

The mean value of the boundary layer thickness increases on the length of its growth. Due to symmetry of the boundary layer thickness, the length of its growth is constant. Since the curvature of the velocity profile depends on pressure gradient it is stated that in the absence of pressure gradient, the length of its boundary layer growth is zero. Therefore

$$\frac{d\delta}{dx} = H = 0 \tag{23}$$

Hence equation (17) reduces to

$$p_0 = \frac{(\alpha + i\beta)^2}{1 + D} \tag{24}$$

Using (23) and (24), the equation (16) becomes equivalent to (22) (Pure forced convection).

Case II: In the limiting case of a pure free convection ($p_0 = 0$) the equation (16) turns into

$$F_1(\eta,t) = Gr\,H\Bigg[\frac{2}{(\alpha+i\beta)^4}\Big\{(2\eta-1)+\cosh(\alpha+i\beta)\eta - (1+\cosh(\alpha+i\beta))\frac{\sinh(\alpha+i\beta)\eta}{\sinh(\alpha+i\beta)}\Big\} + \frac{1}{3}\frac{1}{(\alpha+i\beta)^2}\Big\{(2\eta^3-3\eta^2)+\frac{\sinh(\alpha+i\beta)\eta}{\sinh(\alpha+i\beta)}\Big\}\Bigg]e^{i\omega t} \tag{25}$$

The physical quantity of engineering significance is the shear stress (skin friction) at the plate. Using equation (16), the non-dimensional shear stress at the plate is given by

$$\tau_x = \left(\frac{dF_1}{d\eta}\right)_{\eta=0}$$

$$= \Bigg[\frac{p_0\{\cosh(\alpha+i\beta)-1\}}{(\alpha+i\beta)\sinh(\alpha+i\beta)} + Gr\,H\Big\{\frac{2}{(\alpha+i\beta)^4}\Big\{2-\frac{(\alpha+i\beta)(1+\cosh(\alpha+i\beta))}{\sinh(\alpha+i\beta)}\Big\} + \frac{1}{3}\frac{1}{(\alpha+i\beta)}\frac{1}{\sinh(\alpha+i\beta)}\Big\}\Bigg]e^{i\omega t} \tag{26}$$

Numerical results of the shear stress at the plate are presented graphically in Figs.6-8 for several values of Gr, ω and ωt. It is seen from Fig.6 that the shear stress at the plate decreases with an increase in either magnetic parameter M^2 or Grashof number Gr. Figs.7 and 8 show that the shear stress at the plate increases with an increase in either frequency parameter ω or phase angle ωt.

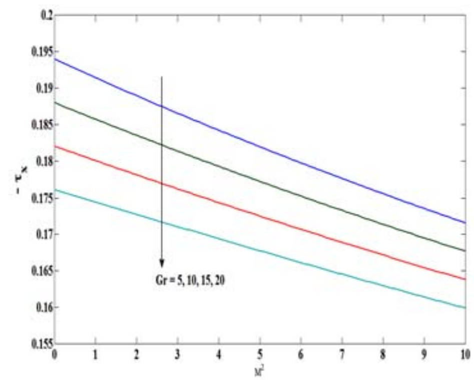

Fig. 6. Shear stress for Gr when $\omega = 2$ and $\omega t = \pi/2$.

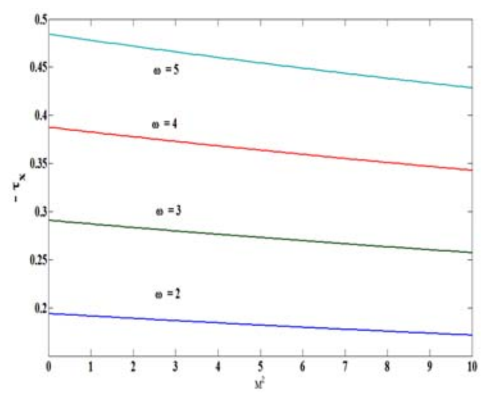

Fig. 7. Shear stress for ω when $Gr = 5$ and $\omega t = \pi/2$.

The critical Grashof number for which there is no flow reversal with reference to $\left(\frac{dF}{d\eta}\right)_{\eta=0} = 0$. Then we have

$$Gr\,H = \frac{1}{1+D}\frac{C_2}{C_4} \tag{27}$$

where

$$C_1 = \left[1+\cosh(\alpha+i\beta)\right]\frac{\alpha+i\beta}{\sinh(\alpha+i\beta)}$$

$$C_2 = \left[\cosh(\alpha+i\beta)-1\right]\frac{\alpha+i\beta}{\sinh(\alpha+i\beta)} \quad (28)$$

$$C_3 = \cosh(\alpha+i\beta)-\frac{2}{3}$$

$$C_4 = \frac{2(2-C_1)}{(\alpha+i\beta)^4}+\frac{C_3}{(\alpha+i\beta)\sinh(\alpha+i\beta)}$$

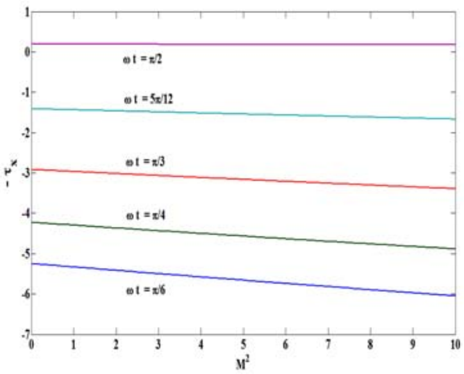

Fig. 8. Shear stress for ωt when $Gr = 5$ and $\omega = 2$.

It is numerically verified that no flow reversal occurs at the plate $\eta=0$. Fig.9 shows that the critical Grashof number increases with an increase in either frequency parameter ω or magnetic parameter M^2.

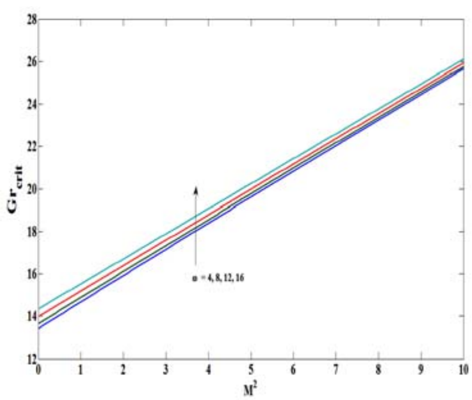

Fig. 9. Critical Grashof number for ω.

4. CONCLUSION

The present investigation is subjected to a study of an oscillating mixed convection boundary layer flow driven by g-jitter forces associated with microgravity field under the influence of an applied magnetic field with induced pressure gradient. The g-jitter field varies harmonically with time. The time varying gravity field emerges the backbone of an oscillatory free convection velocity field. This is combined with the forced oscillating flow driven by a pressure gradient. It is evident from numerical result that the influence of a magnetic force leads to fall the velocity at the central section of the boundary layer region while there exists a flow reversal at the two ends of the boundary layer region. The effect of Grashof number corresponds to a free convection flow in the presence of a pressure gradient to accelerate the flow in the boundary layer region. It is interesting to note that the phase angle determines the critical value for retarding the fluid velocity. The effect of skin friction at the plate plays a significant role on increasing the magnetic force. It is stated that critical Grashof number leads to a stabilizing influence on the flow field.

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