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MHD AND RADIATION EFFECTS ON AN OSCILLATORY FREE CONVECTIVE FLOW PAST A VERTICAL PLATE IN SLIP-FLOW REGIME WITH VARIABLE SUCTION AND PERIODIC PLATE TEMPERATURE

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Abstract

A study of radiative viscous, incompressible convection oscillatory flow of an electrically conducting Newtonian non-gray fluid past a vertical porous plate in sleep-flow regime with variable suction and periodic plate temperature in presence of uniform transverse magnetic field is presented. The fluid is assumed to be optically thin and the magnetic Reynolds number consider small enough to neglect the induced hydro magnetic effects. Analytical solutions of the coupled non-linear equations governing the flow and heat transfer and derived by using perturbation method with Eckert number $E(< 1)$ as perturbation parameter. The expressions for velocity field, temperature field, skin friction in the direction of the flow and coefficients of heat transfer at the plate have been obtained and their numerical values for different values of the parameters involved in the problem have been demonstrated in graphs.

1. Introduction

MHD (Magneto hydrodynamics) flows and heat transfer have become more important in recent years because of its varied agricultural engineering

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and petroleum industries. Recently considerable attention has also been focused on new applications of magneto-hydrodynamics (MHD) and heat transfer such as metallurgical processing, plasma propulsion in astronautics, nuclear reactor thermal dynamics and ionized-geothermal energy system etc. The present form of MHD is due to the pioneer contributions of several notable authors like Alfven [1], Cowling [2], Shercliff [3], Ferraro and Plumpton [4] and Crammer and Pai [5].

The problems of interaction of free convection with thermal radiation of viscous incompressible MHD unsteady flow past infinite vertical plate are being studied now a days due to many applications of such problems in Astrophysics, Geophysical and different Engineering fields. The heating of rooms and buildings by use of radiators is an example of heat transfer through electromagnetic waves. Radiative convective flows are encountered in many industrial and environment process like heating and cooling chambers, evaporation from large open water reservoirs, astrophysical flows and solar power technology. Due to importance of the above physical aspects, several authors have carried out model studies on the problems of free convective flows of viscous incompressible fluid under different flow geometries taking into account of thermal radiation. Some of them are Tak and Kumar [6], Mahamed et al. [7], Makinde [8], Ganesan et al. [9], Ahmed [10] and Ahmed and Sarmah [11]. Samad and Rahman [12] presented a thermal radiation interaction with unsteady MHD flow past a vertical porous plate immersed in a porous medium. Orhan and Ahmet [13] studied the radiation effect on MHD mixed convection flow about a permeable vertical plate.

Recently Ahmed et al. [14] have studied the radiation effect with thermal diffusion on a MHD flow past an impulsively started vertical plate with ramped temperature by adopting Cogley-Vincentine-Gilles equilibrium model [15]. The objective of the present work is to study the effects of magnetic field and thermal radiation on a free convective flow past a vertical plate in sleep-flow regime with variable suction and periodic plate temperature. This is an extension to the work of Ahmed and Kalita [16] to consider the effect of radiation.

2. Mathematical Formulation

We consider the unsteady oscillatory free convective flow of an electrically conducting, viscous and incompressible fluid past a vertical plate in slip-flow regime with variable suction and periodic plate temperature under the influence of uniform transverse magnetic field. We introduce a coordinate system $(\bar{x}, \bar{y}, \bar{z})$ with x-axis is taken along the upward vertical plate and y axis perpendicular to it directed to the fluid region and z-axis along the width of the plate. Since the plate is of infinite length therefore all the physical quantities except the pressure p are independent of x. Let $\bar{q}(\bar{u}, 0, 0)$ denote the fluid velocity and $\overline{B}(0, B, 0)$ be the applied magnetic field at the point $(\bar{x}, \bar{y}, \bar{z}, \bar{t})$ in the fluid.

Our investigation is restricted to the following assumption

(1) All fluid properties are considered constant except the influence of the variation in density in the buoyancy force term.

(2) The viscous and ohmic dissipation of energy are negligible.

(3) The magnetic Reynolds Number is so small that the induced magnetic field can be neglected in comparison to the applied magnetic field.

(4) The plate is electrically non-conducting.

(5) The radiation heat flux in the direction of the plate velocity is considered negligible in comparison to that in normal direction.

(6) No external electric field is applied for which the polarization voltage is negligible leading to $\vec{E} = 0$.

The present flow configuration is shown in figure1

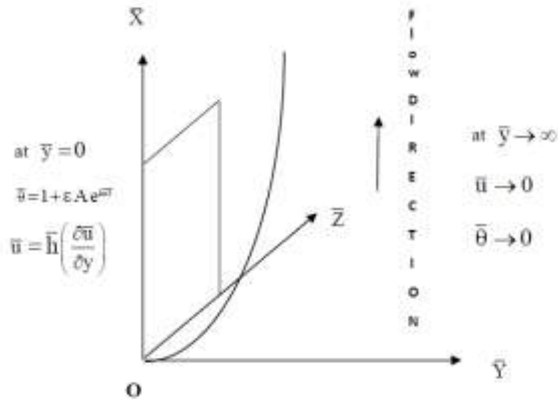

Figure 1. Flow configuration of the problem.

The equations governing the flow are

Equation of continuity

$$\frac{\partial \bar{v}}{\partial \bar{y}} = 0 \Rightarrow \bar{v} = -v_0(1 + \varepsilon A e^{i\bar{\omega}\bar{t}}) \tag{2.1}$$

where v_0 and A being constants.

Momentum equation

$$\frac{\partial \bar{u}}{\partial \bar{t}} - v_0(1 + \varepsilon A e^{i\bar{\omega}\bar{t}})\frac{\partial \bar{u}}{\partial \bar{y}} = g\beta(\bar{T} - \bar{T}_\infty) + \upsilon \frac{\partial^2 \bar{u}}{\partial \bar{y}^2} - \frac{\sigma B_0^2}{\rho}\bar{u} \tag{2.2}$$

Energy equation

$$\rho c_p\left[\frac{\partial \bar{T}}{\partial \bar{t}} - v_0(1 + \varepsilon A e^{i\bar{\omega}\bar{t}})\frac{\partial \bar{T}}{\partial \bar{y}}\right] = k\frac{\partial^2 \bar{T}}{\partial \bar{y}^2} + \upsilon\rho\left(\frac{\partial \bar{u}}{\partial \bar{y}}\right)^2 - \frac{\partial \bar{q}_r}{\partial \bar{y}} \tag{2.3}$$

(Neglecting the higher powers of $\bar{u}$)

The boundary conditions are

$$\text{at } \bar{y} = 0; \bar{u} = \bar{h}\left(\frac{\partial \bar{u}}{\partial \bar{y}}\right), \bar{T} = \bar{T}_w + \varepsilon(\bar{T} = \bar{T}_w)e^{i\bar{\omega}\bar{t}}$$

$$\text{at } \bar{y} \to \infty; \bar{u} = 0, \bar{T} = \bar{T}_\infty \tag{2.4}$$

We assume that the medium is optically thin with relatively low density.

Following the Cogly-Vincentine-Gilles equilibrium model, we have

$$\frac{\partial \bar{q}_r}{\partial \bar{y}} = 4(\bar{T} - \bar{T}_\infty)\int_0^\infty K_w \left(\frac{\partial e_b}{\partial \bar{T}}\right)_w d\lambda = 4\bar{I}(\bar{T} - \bar{T}_\infty) \tag{2.5}$$

Thus with the help of equation (2.5), equation (2.3) can be rewritten as

$$\rho c_p \left[\frac{\partial \bar{T}}{\partial \bar{t}} - v_0(1 + \varepsilon A e^{i\bar{\omega}\bar{t}})\frac{\partial \bar{T}}{\partial \bar{y}}\right] = k\frac{\partial^2 \bar{T}}{\partial \bar{y}^2} + \upsilon\rho\left(\frac{\partial \bar{u}}{\partial \bar{y}}\right)^2 - 4\bar{I}(\bar{T} - \bar{T}_\infty) \tag{2.6}$$

We introduce the following non-dimensional variables and similarity parameters to normalized the flow model

$$y = \frac{\bar{y}v_0}{\upsilon},\ t = \frac{\bar{t}v_0^2}{\upsilon},\ \omega = \frac{\upsilon\bar{\omega}}{v_0^2},\ u = \frac{\bar{u}}{v_0},\ P\frac{\mu c_p}{\lambda},\ F\frac{4I\upsilon^2}{kv_0^2},$$

$$\theta = \frac{\bar{T} - \bar{T}_\infty}{\bar{T}_w - \bar{T}_\infty},\ E = \frac{v_0^2}{c_p(\bar{T}_w - \bar{T}_\infty)}$$

$$G = \frac{g\beta\upsilon(\bar{T} - \bar{T}_\infty)}{v_0^3},\ M = \frac{\sigma B_0^2\upsilon}{\rho v_0^2},\ h = \frac{v_0\bar{h}}{\upsilon}$$

All the physical quantities are defined in Nomenclature

The non-dimensional equations with boundary conditions are

$$\frac{\partial u}{\partial t} - (1 + \varepsilon A e^{i\omega t})\frac{\partial u}{\partial y} = G\theta + \frac{\partial^2 u}{\partial y^2} - Mu \tag{2.7}$$

$$P\frac{\partial \theta}{\partial t} - P(1 + \varepsilon A e^{i\omega t})\frac{\partial \theta}{\partial y} = \frac{\partial^2 \theta}{\partial y^2} + EP\left(\frac{\partial u}{\partial y}\right)^2 - F\theta \tag{2.8}$$

subject to boundary conditions

$$\left.\begin{array}{l} y = 0; u = h\dfrac{\partial u}{\partial y},\ \theta = 1 + \varepsilon \mathrm{A}e^{\mathrm{i}\omega \mathrm{t}} \\ \mathrm{y} \to \infty; \mathrm{u} \to 0,\ \theta \to 0 \end{array}\right\} \tag{2.9}$$

3. Method of solution

Assuming the small amplitude oscillation $(\varepsilon \ll 1)$, we represent the velocity u and temperature θ, near the plate as

$$\left.\begin{aligned} u &= u_0(y) + \varepsilon e^{i\omega t} u_1(y) + O(\varepsilon^2) \\ \theta &= \theta_0(y) + \varepsilon e^{i\omega t} \theta_1(y) + O(\varepsilon^2) \end{aligned}\right\} \tag{3.1}$$

Substituting from (3.1) in (2.8) and (2.9) and by equating the harmonic terms and neglecting the higher powers of ε, the following equations are obtained

$$u_0'' = u_0' - Mu_0 = -G\theta_0 \tag{3.2}$$

$$u_1'' = u_1' - (i\omega + M)u_1 = -G\theta_1 - Au_0' \tag{3.3}$$

$$\theta_0'' + P\theta_0' - F\theta_0 = -EPu_0'^2 \tag{3.4}$$

$$\theta_1'' + P\theta_1' - (F + i\omega P)\theta_1 = -AP\theta_0' - 2EPu_0'u_1' \tag{3.5}$$

The corresponding boundary conditions are

$$\left.\begin{aligned} & y = 0; u_0 = h\frac{\partial u_0}{\partial y}, \theta_0 = 1, u_1 = h\frac{\partial u_1}{\partial y}, \theta_1 = 1 \\ & y \to \infty; u_0 \to 0, \theta_0 \to 0, u_1 \to 0, \theta_1 \to 0 \end{aligned}\right\} \tag{3.6}$$

where, dashes denote differentiation with respect to y.

The equations (3.2) to (3.5) are still coupled for the variables u_0, u_1, θ_0 and θ_1. To solve them we note that θ_1. for all incompressible fluids and assume that

$$\left.\begin{aligned} & u_0 = u_{00} = Eu_{01} + O(E^2); u_1 = u_{10} + Eu_{11} + O(E^2) \\ & \theta_0 = \theta_{00} + E\theta_{01} + O(E^2); \theta_1 = \theta_{10} + E\theta_{11} + O(E^2) \end{aligned}\right\} \tag{3.7}$$

Substituting from (3.7) in the equations (3.2) to (3.5) and equating the terms independent of E and coefficient of E in each equation and neglecting higher powers of E the following equations are obtained

$$u_{00}'' + u_{00}' - Mu_{00} = -G\theta_{00} \tag{3.8}$$

$$u_{01}'' + u_{01}' - Mu_{01} = -G\theta_{01} \tag{3.9}$$

$$u_{10}'' + u_{10}' - (i\omega + M)u_{10} = -Au_{00}' - G\theta_{10} \tag{3.10}$$

$$u''_{11} + u'_{11} - (i\omega - M)u_{11} = -G\theta_{11} - Au_{01} \tag{3.11}$$

$$\theta''_{00} + P\theta'_{00} - F\theta_{00} - = 0 \tag{3.12}$$

$$\theta''_{01} - P\theta'_{01} - F\theta_{01} = -Pu'^{2}_{00} \tag{3.13}$$

$$\theta''_{10} + P\theta'_{10} - P(F + i\omega)\theta_{10} = -AP\theta'_{00} \tag{3.14}$$

$$\theta''_{11} + P\theta'_{11} - (F + i\omega)\theta_{11} = -AP\theta'_{01} - 2Pu'_{00}u'_{10} \tag{3.15}$$

subject to boundary conditions

$$\text{at } y = 0, \begin{Bmatrix} u_{00} = h\dfrac{\partial u_{00}}{\partial y},\ u_{01} = h\dfrac{\partial u_{01}}{\partial y},\ u_{10} = h\dfrac{\partial u_{10}}{\partial y},\ u_{11} = h\dfrac{\partial u_{11}}{\partial y} \\ \theta_{00} = 1,\ \theta_{01} = 0,\ \theta_{10} = 1,\ \theta_{11} = 0 \end{Bmatrix} \tag{3.16}$$

$$y = 0, \begin{Bmatrix} u_{00} \to 0,\ u_{01} \to 0,\ u_{10} \to 0,\ u_{11} \to 0 \\ \theta_{00} \to 0,\ \theta_{01} \to 0,\ \theta_{10} \to 0,\ \theta_{11} \to 0 \end{Bmatrix} \tag{3.17}$$

Solving these equations from (3.8) to (3.15) with the help of boundary conditions (3.16) and (3.17) we get

$$\theta_{00}(y) = e^{-\lambda_1 y} \tag{3.18}$$

$$u_{00}(y) = A_1 e^{-\lambda_1 y} + A_2 e^{-\lambda_2 y} \tag{3.19}$$

$$\theta_{01}(y) = A_6 e^{-\lambda_1 y} + A_3 e^{-2\lambda_1 y} + A_4 e^{-2\lambda_2 y} + A_5 e^{-(\lambda_1 + \lambda_2)y} \tag{3.20}$$

$$u_{01}(y) = A_{11} e^{-\lambda_2 y} + A_7 e^{-\lambda_3 y} + A_8 e^{-2\lambda_1 y} + A_9 e^{-2\lambda_2 y} + A_{10} e^{-(\lambda_1 + \lambda_2)y} \tag{3.21}$$

$$\theta_{10}(y) = B_1 e^{-\lambda_1 y} + B_2 e^{-\lambda_3 y} \tag{3.22}$$

$$u_{10}(y) = B_6 e^{-\lambda_4 y} + B_3 e^{-\lambda_1 y} + B_4 e^{-\lambda_2 y} + B_5 e^{-\lambda_3 y} \tag{3.23}$$

$$\theta_{11}(y) = B_{23} e^{-\lambda_3 y} + B_{15} e^{-\lambda_1 y} + B_{16} e^{-2\lambda_1 y} + B_{17} e^{-(\lambda_1 + \lambda_2)y} + B_{18} e^{-2\lambda_2 y}$$
$$+ B_{19} e^{-(\lambda_1 + \lambda_2)y} + B_{20} e^{-(\lambda_1 + \lambda_3)y} + B_{21} e^{-(\lambda_2 + \lambda_4)y} + B_{22} e^{-(\lambda_2 + \lambda_3)y} \tag{3.24}$$

$$u_{11}(y) = B_{34} e^{-\lambda_4 y} + B_{24} e^{-\lambda_1 y} + B_{25} e^{-\lambda_2 y} + B_{26} e^{-\lambda_3 y} + B_{27} e^{-2\lambda_1 y}$$

$$+ B_{28}e^{-2\lambda_2 y} + B_{29}e^{-(\lambda_1+\lambda_2)y} + B_{30}e^{-(\lambda_1+\lambda_3)y} + B_{31}e^{-(\lambda_2+\lambda_3)y}$$

$$+ B_{32}e^{-(\lambda_2+\lambda_4)y} + B_{33}e^{-(\lambda_1+\lambda_4)y} \tag{3.25}$$

Now substituting equations (3.18) to (3.25) in equation (3.1) and splitting into real and imaginary parts we get the expressions for the velocity and temperature profiles in the following form

$$u(y, t) = u_{00}(y) + Eu_{01}(y) + \varepsilon\{(u_{10}^R + Eu_{11}^R)\cos\omega t - (u_{10}^I + Eu_{11}^I)\sin\omega t\}$$

$$\theta(y, t) = \theta_{00}(y) + E\theta_{01}(y) + \varepsilon\{(\theta_{10}^R + E\theta_{11}^R)\cos\omega t - (\theta_{10}^I + E\theta_{11}^I)\sin\omega t\}$$

where, superscripts R and I respectively represent the real and imaginary parts and

$$\lambda_1 = \frac{P + \sqrt{P^2 + 4F}}{2}, \; \lambda_2 = \frac{1 + \sqrt{1 + 4M}}{2}, \; \lambda_3 = \frac{P + \sqrt{(P^2 + 4F) + i(4\omega P)}}{2},$$

$$\lambda_3 = \frac{1 + \sqrt{(1 + 4M) + i(4\omega)}}{2}$$

The other constants $A_1, A_2, A_3, \ldots, A_{11}$ (real) and $B_1, B_2, B_3, \ldots, B_{34}$ (complex) are obtained but not presented here for the sake of brevity.

4. Coefficient of Skin-Friction

The coefficient of skin friction in the non-dimensional form at the plate is given by

$$\tau = \left.\frac{\partial u}{\partial y}\right]_{y=0} = \left.\frac{\partial u_0}{\partial y} + \varepsilon e^{i\omega t}\frac{\partial u_1}{\partial y}\right]_{y=0}$$

$$= \left[\frac{\partial}{\partial y}\{u_{00} + Eu_{01}\}\right]_{y=0} + \varepsilon(\cos\omega t + i\sin\omega t)\left[\frac{\partial}{\partial y}\{u_{10} + Eu_{11}\}\right]_{y=0}$$

5. Rate of Heat Transfer (Heat Flux)

The rate of heat transfer (Nusselt Number) between the fluid and the plate is given by

$$N_u = \left.\frac{\partial\theta}{\partial y}\right]_{y=0} = \left.\frac{\partial\theta_0}{\partial y} + \varepsilon e^{i\omega t}\frac{\partial\theta_1}{\partial y}\right]_{y=0}$$

$$= \left[\frac{\partial}{\partial y}\{\theta_{00} + E\theta_{01}\}\right]_{y=0} + \varepsilon(\cos\omega t + i\sin\omega t)\left[\frac{\partial}{\partial y}\{\theta_{10} + E\theta_{11}\}\right]_{y=0}$$

6. Results and Discussion

In order to get physical insight into the problem the numerical values of velocity distribution, temperature distribution, skin friction, rate of heat transfer in terms of Nusselt number have been obtained and they are demonstrated graphically.

For the purpose of discussing the effects of various parameters on the flow behavior near the plate, numerical calculations have been carried out for different values of M, F, G, ωt and for fixed values of P, E, ε, A and ω. Throughout our investigation the Prandtl number P is taken to be equal to 0.71 which corresponds to the air at $20^\circ C$. The values of Eckert number E is assumed to be 0.01. The values of small reference parameter ε, frequency ω, suction parameter A are taken 0.001, 1, 2 respectively. In our investigation, Grashof number for heat transfer $Gr > 0$ corresponds to externally cooled plate.

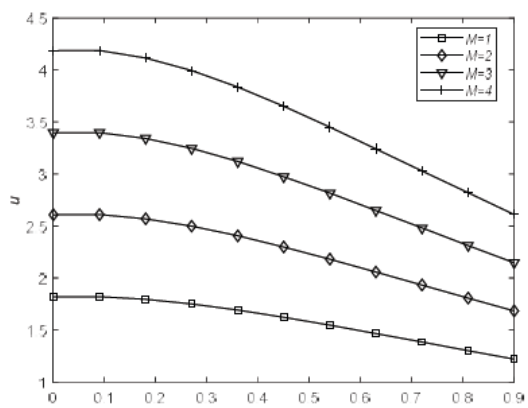

Figure 2. Velocity u versus y for various values of Hartman Number M When $A = 0.4$, $E = 0.01$, $G = 5$, $P = 0.71$, $\omega = 3$, $\omega t = \pi/6$, $h = .4$, $F = 9$, $\varepsilon = 0.001$.

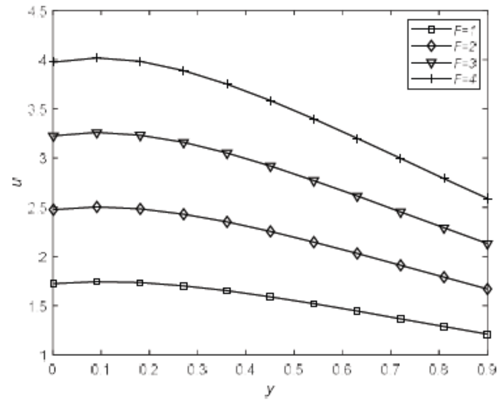

Figure 3. Velocity u versus y for various values of Thermal radiation parameter F When $A = 0.4$, $E = 0.01$, $G = 5$, $P = 0.71$, $\omega = 3$, $\omega t = \pi/6$, $h = .4$, $M = 4$, $\varepsilon = 0.001$.

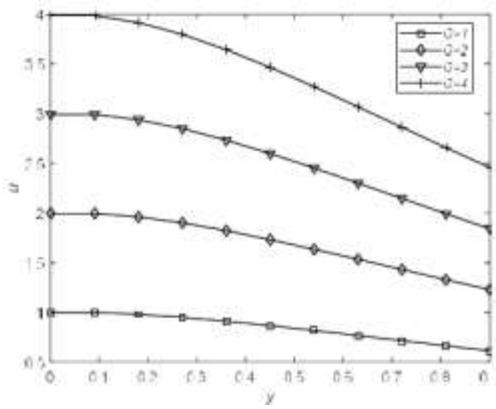

Figure 4. Velocity u versus y for various values of G, when $A = 0.4$, $E = 0.01$, $M = 4$, $P = 0.71$, $\omega = 3$, $\omega t = \pi/6$, $h = .4$, $F = 9$, $\varepsilon = 0.001$.

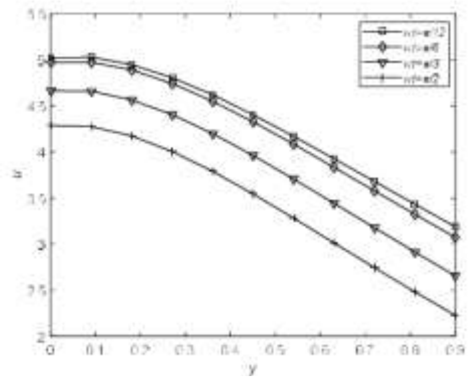

Figure 5. Velocity u versus y for various values of Frequency parameter ωt, when $A = 0.4, E = 0.01, G = 5, P = 0.71, \omega = 3, F = 9, h = 4, M = 4, \varepsilon = 0.001$.

Figures (2)-(5) depict the change of behavior of velocity profile u against y under the effects of Hartman number M, radiation parameter F, Grashof number G and frequency parameter ωt. From these figures we observe that fluid motion is accelerated due to the effects of magnetic force, thermal radiation and bouncy force. But due to increase values of ωt (phase angle), the fluid velocity is retarded.

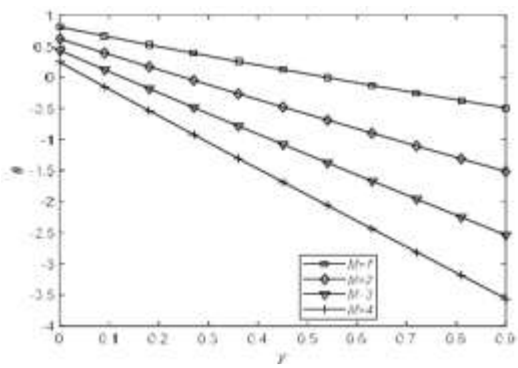

Figure 6. Temperature θ versus y for various values of M, when $A = 0.4,\ E = 0.01,\ G = 5,\ P = 0.71,\ \omega = 3,\ \omega t = \pi/6,\ h = .4,\ F = 9,\ \varepsilon = 0.001$.

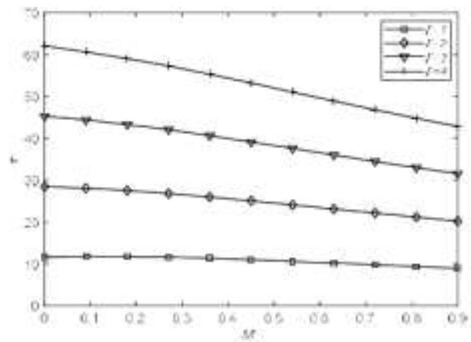

Figure 7. Skin friction τ versus M, for various values of F when $A = 0.4$, $E = 0.01$, $G = 5$, $P = 0.71$, $\omega = 3$, $\omega t = \pi/6$, $h = .4$, $\varepsilon = 0.001$.

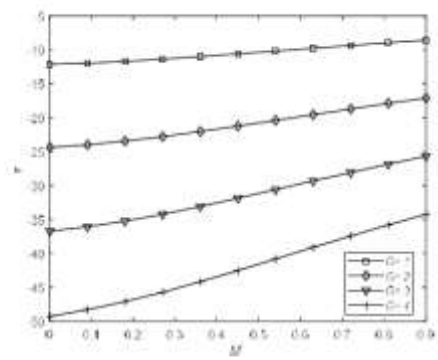

Figure 8. Skin friction τ versus M for various values of G, when $A = 0.4$, $E = 0.01$, $P = 0.71$, $\omega = 3$, $\omega t = \pi/6$, $h = .4$, $\varepsilon = 0.001$.

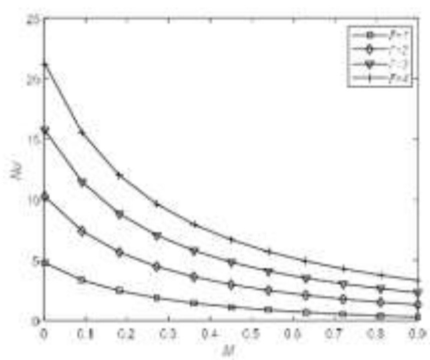

Figure 9. Nusselt Number Nu versus M for various values of F, when $A = 0.4$, $E = 0.01$, $P = 0.71$, $\omega = 3$, $\omega t = \pi/6$, $h = .4$, $G = 5$, $\varepsilon = 0.001$.

Figure (6) corresponds to the change of behavior of temperature against y under the effect of Hartmann Number M. It is inferred from the figure that an increase in magnetic force leads the temperature to decrease. The variation of skin friction τ at the plate $y = 0$ against Hartmann Number M for different values of F and G are demonstrated in figures (7) and (8). It is seen from the figure (7) that skin friction at the plate $y = 0$ is increased due to radiation. Again from the figure (8) it is clear that due to increase of G (low viscous force or high bouncy force), the magnitude of drag force is increased. From both figures it is cleared that due to applied magnetic field viscous drag falls slowly as it magnitude is concerned.

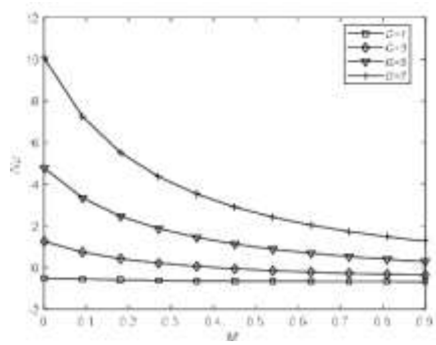

Figure 10. Nusselt Number Nu versus M for various values of Grashof Number G, when $A = 0.4$, $E = 0.01$, $P = 0.71$, $\omega = 3$, $\omega t = \pi/6$, $h = .4$, $F = 9$, $\varepsilon = 0.001$.

Figures (9) and (10) exhibit how the Nusselt number Nu at the plate is affected by the parameters M, F and G. This figure clearly establishes the fact that Nu rises due to the effect of radiation and bouncy force. It is also inferred from the figure (9) that due to strength of the magnetic field heat flux is decreases. It is cleared from the figure (10) that for small value of G (high viscous force or low bouncy force), there is no effect of magnetic field on heat flux.

7. Conclusions

1. Fluid velocity increases due to thermal radiation and bouncy force.

2. Temperature falls due to applied magnetic field.

3. Drag force at the plate increases due to effect of radiation.

4. Heat flux rises due to effect of radiation and bouncy force.

8. Nomenclature

A	Suction parameter	K_w	Absorption coefficient
B_0	Applied magnetic field	q_r	Radiative heat flux
Cp	Specific heat at constant pressure	$\overline{T}$	Temperature of the fluid near the plate
E	Eckert number		
G	Grashof number	$\overline{T}_w$	Temperature of the plate
g	Acceleration due to gravity	$\overline{T}_\infty$	Temperature at main stream fluid
h	Rarefaction parameter	t	time
P	Prandtl number	$\bar{t}$	time
M	Hartman number	t	velocity component in x-direction
F	Thermal radiation parameter	u	dimensionless velocity
k	thermal conductivity	$\bar{x}$	Coordinate along the plate
$\bar{y}$	Coordinate normal to the plate		
x	Dimensionless coordinate along the plate		
y	Dimensionless coordinate normal to the plate		

Greek symbols

β coefficient of thermal expansion

ρ fluid density

υ kinematics viscosity

ω frequency parameter

τ Dimensionless skin friction

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