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Research Article

Free Convective Fluctuating MHD Flow through Porous Media Past a Vertical Porous Plate with Variable Temperature and Heat Source

A. K. Acharya, G. C. Dash, and S. R. Mishra

Department of Mathematics, I.T.E.R, Siksha "O" Anusandhan University, Khandagiri, Bhubaneswar, Orissa 751030, India

Correspondence should be addressed to S. R. Mishra; satyaranjan_mshr@yahoo.co.in

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Free convective magnetohydrodynamics (MHD) flow of a viscous incompressible and electrically conducting fluid past a hot vertical porous plate embedded in a porous medium in the presence of heat source has been studied in this paper. The temperature of the plate varies both in space and time. The main objective of this paper is to study the effect of porosity of the medium coupled with the variation of plate temperature with regard to space and in time. The effect of pertinent parameters characterizing the flow has been presented through the graphs. It is important to record that the presence of porous media has no significant contribution to the flow characteristics and viscous dissipation compensates for the heating and cooling of the plate due to convective current.

1. Introduction

MHD flow with heat transfer has been a subject of interest of many researchers because of its varied application in science and technology. Such phenomena are observed in buoyancy induced motions in the atmosphere, water bodies, quasi-solid bodies such as earth, and so forth. Many industrial applications use magnetohydrodynamics (MHD) effects to resolve the complex problems that very often occurred in industries. The available hydrodynamics solutions include the effects of magnetic field which is possible as the most of the industrial fluids are electrically conducting. For example, liquid metal MHD takes its root in hydrodynamics of incompressible media which gains importance in the metallurgical industry, nuclear reactor, sodium cooling system, and every storage and electrical power generation (Stangeby [1], Lielausis [2], and Hunt and Moreu [3]). Free convective flows are of great interest in a number of industrial applications such as fiber and granular insulation and geothermal system. Buoyancy is also of importance in an environment where difference between land and air temperature can give rise to complicated flow patterns. The unsteady free convection flow past an infinite porous plate and semi-infinite plate were studied by Nanda and Sharma [4]. In their first paper they assumed the suction velocity at the plate varying in time as $t^{-1/2}$, where as in the second paper the plate temperature was assumed to oscillate in time about a constant nonzero mean. Free convective flow past a vertical plate has been studied extensively by Ostrach [5] and many others. The free convective heat transfer on vertical semi-infinite plate was investigated by Berezovsky et al. [6]. Martynenko et al. [7] investigated the laminar free convection from a vertical plate; see Figure 1 and Table 1.

The basic equations of incompressible MHD flow are nonlinear. But there are many interesting cases where the equations became linear in terms of the unknown quantities and may be solved easily. Linear MHD problems are accessible to exact solutions and adopt the approximations that the density and transport properties are constant. No fluid is incompressible but all may be treated as such whenever the pressure changes are small in comparison with the bulk modulus. Ferdows et al. [8] analysed free convection flow with variable suction in presence of thermal radiation. Alam et al. [9] studied Dufour and Soret effect with variable suction on unsteady MHD free convection flow along a porous plate. Majumder and Deka [10] gave an exact solution for MHD

Table 1

Curve	Gr	M	K_p	Pr	S	Re	Ec
I	5	0	100	0.71	0	2	0.01
II	5	2	100	0.71	0	2	0.01
III	5	2	100	0.71	1	2	0.01
IV	5	2	0.5	0.71	1	2	0.01
V	5	4	100	0.71	1	2	0.01
VI	10	2	100	0.71	1	2	0.01
VII	5	2	100	7	1	2	0.01
VIII	5	2	100	0.71	1	4	0.01
IX	5	2	100	0.71	1	2	0.02
X	5	2	0.5	7	1	2	0.01
XI	5	2	0.5	0.71	2	2	0.01
XII	5	4	0.5	0.71	1	2	0.01
XIII	−5	2	100	0.71	1	2	0.01

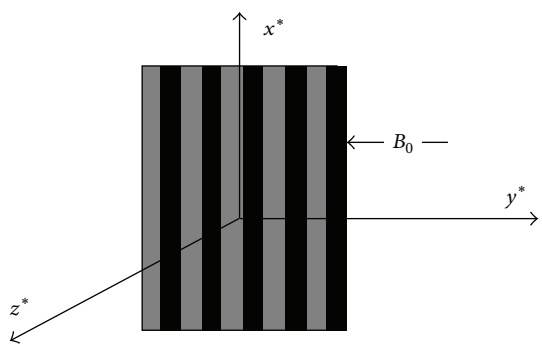

Figure 1

flow past an impulsively started infinite vertical plate in the presence of thermal radiation. Muthucumaraswamy et al. [11] studied unsteady flow past an accelerated infinite vertical plate with variable temperature and uniform mass diffusion. Recently, Dash et al. [12] have studied free convective MHD flow of a viscoelastic fluid past an infinite vertical porous plate in a rotating frame of reference in the presence of chemical reaction. Recently Mishra et al. [13] have studied free convective fluctuating MHD flow through porous media past a vertical porous plate with variable temperature.

In the present study we have set the flow through porous media with uniform porous matrix with suction and blowing at the plate surface besides the free convective MHD effects and fluctuating surface temperature. From the established result it is clear that the suction prevents the imposed nontorsional oscillations spreading away from the oscillating surface (disk) by viscous diffusion for all values of frequency of oscillations. On the contrary the blowing promotes the spreading of the oscillations far away from the disk and hence the boundary layer tends to be infinitely thick when the disk is forced to oscillate with resonant frequency. In other words, in case of blowing and resonance the oscillatory boundary layer flows are no longer possible.

Therefore, the present study aims at finding a meaningful solution for a nonlinear coupled equation to bring out the effects of suction/blowing with varying spanwise cosinusoidal time dependent temperature in the presence of uniform porous matrix in a free convective magnetohydrodynamic flow past a vertical porous plate.

2. Formulation of the Problem

An unsteady flow of a viscous incompressible electrically conducting fluid through a porous medium past an insulated, infinite, hot, porous plate lying vertically on the $x^* - z^*$ plane is considered. The x^*-axis is oriented in the direction of the buoyancy force and y^*-axis is taken perpendicular to the plane of the plate. A uniform magnetic field of strength B_0 is applied along the y^*-axis. Let (u^*, v^*, w^*) be the component of velocity in the direction (x^*, y^*, z^*), respectively. The plate being considered infinite in x^* direction; hence all the physical quantities are independent of x^*. Thus, following Acharya and Padhy [14], w^* is independent of z^* and the equation of continuity gives $v^* = -V$ (constant) throughout.

We assume the spanwise cosinusoidal temperature of the form

$$T = T^* + \varepsilon\left(T_0^* - T_\infty^*\right)\cos\left(\frac{\pi z^*}{l} - \omega^* t^*\right). \tag{1}$$

The mean temperature T^* of the plate is supplemented by the secondary temperature $\varepsilon(T_0^* - T_\infty^*)\cos(\pi z^*/l - \omega^* t^*)$ varying with space and time. Under the usual Boussinesq approximation the free convective flow through porous media is governed by the following equations:

$$\begin{aligned}
\frac{\partial u^*}{\partial t^*} - V\frac{\partial u^*}{\partial y^*} &= \upsilon\left(\frac{\partial^2 u^*}{\partial y^{*2}} + \frac{\partial^2 u^*}{\partial z^{*2}}\right) \\
&\quad + g\beta\left(T^* - T_\infty^*\right) - \frac{\sigma B_0^2 u^*}{\rho} - \frac{\upsilon u^*}{K_p^*}, \\
\frac{\partial T^*}{\partial t^*} - V\frac{\partial T^*}{\partial y^*} &= \frac{K}{\rho C_P}\left(\frac{\partial^2 T^*}{\partial y^{*2}} + \frac{\partial^2 T^*}{\partial z^{*2}}\right) \\
&\quad + \frac{\mu}{\rho C_P}\left(\left(\frac{\partial u^*}{\partial y^*}\right)^2 + \left(\frac{\partial u^*}{\partial z^*}\right)^2\right) \\
&\quad - S^*\left(T^* - T_\infty^*\right).
\end{aligned} \tag{2}$$

The boundary conditions are given by

$$\begin{aligned}
&y^* = 0 : u^* = 0, \qquad v^* = -V\,(\text{Const.}), \\
&T^* = T_0^* + \varepsilon\left(T_0^* - T_\infty^*\right)\cos\left(\frac{\pi z^*}{l} - \omega^* t^*\right), \\
&y^* \longrightarrow \infty : u^* \longrightarrow 0, \quad T^* \longrightarrow T_\infty^*.
\end{aligned} \tag{3}$$

Introducing the following nondimensional quantities in (2), and (3):

$$u = \frac{vu^*}{lV^2}, \qquad t = \frac{\omega v}{l^2}t^*, \qquad y = \frac{y^*}{l},$$
$$z = \frac{z^*}{l}, \qquad T = \frac{T^* - T^*_\infty}{T^*_0 - T^*_\infty}, \qquad \mathrm{Ec} = \frac{V^2}{C_p\left(T^*_0 - T^*_\infty\right)},$$
$$\mathrm{Re} = \frac{lV}{v}, \qquad M^2 = \frac{B_0^2 l^2 \sigma}{\mu}, \qquad \mathrm{Gr} = \frac{g\beta v}{V^3}\left(T^*_0 - T^*_\infty\right),$$
$$\mathrm{Pr} = \frac{k}{\mu C_p}, \qquad S = \frac{S^* l}{V}, \tag{4}$$

we get

$$\omega\frac{\partial u}{\partial t} - \mathrm{Re}\frac{\partial u}{\partial y} = \left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) + \mathrm{ReGr}T - \left(M^2 + \frac{1}{K_P}\right)u, \tag{5}$$

$$\omega\mathrm{Pr}\frac{\partial T}{\partial t} - \mathrm{PrRe}\frac{\partial T}{\partial y} = \left(\frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \mathrm{PrRe}^2\mathrm{Ec}\left(\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial z}\right)^2\right) - ST, \tag{6}$$

with corresponding boundary conditions:

$$y = 0 : u = 0, \qquad T = 1 + \varepsilon\cos(\pi z - t),$$
$$y \longrightarrow \infty : u \longrightarrow 0, \quad T \longrightarrow 0. \tag{7}$$

Since the amplitude, $\varepsilon(\ll 1)$, of the plate temperature is very small, we represent the velocity and temperature in the neighborhood of the plate as

$$u(y,z,t) = u_0(y) + \varepsilon u_1(y,z,t) + o\left(\varepsilon^2\right),$$
$$T(y,z,t) = T_0(y) + \varepsilon T_1(y,z,t) + o\left(\varepsilon^2\right). \tag{8}$$

Comparing the coefficients of like powers of ε after substituting (8) in (5) and (6), we get the following zeroth order equations:

$$\frac{\partial^2 u_0}{\partial y^2} + \mathrm{Re}\frac{\partial u_0}{\partial y} - \left(M^2 + \frac{1}{K_P}\right)u_0 = -\mathrm{ReGr}T_0,$$
$$\frac{\partial^2 T_0}{\partial y^2} + \mathrm{PrRe}\frac{\partial T_0}{\partial y} - ST_0 = -\mathrm{PrRe}^2 E_c\left(\frac{\partial u_0}{\partial y}\right)^2. \tag{9}$$

The E_c, the Eckert number, is a measure of the dissipation effects in the flow. Since this grows in proportion to the square of the velocity it can be neglected for small velocity [15].

For solving the above coupled equations we use the following perturbed equations with perturbation parameter E_c, (Eckert number):

$$u_0 = u_{01} + \mathrm{Ec}u_{02} + o\left(\mathrm{Ec}^2\right),$$
$$T_0 = T_{01} + \mathrm{Ec}T_{02} + o\left(\mathrm{Ec}^2\right). \tag{10}$$

Substituting (10) into (9) we get the following zeroth and first order equations of E_c:

$$\frac{\partial^2 u_{01}}{\partial y^2} + \mathrm{Re}\frac{\partial u_{01}}{\partial y} - \left(M^2 + \frac{1}{K_P}\right)u_{01} = -\mathrm{ReGr}T_{01},$$
$$\frac{\partial^2 T_{01}}{\partial y^2} + \mathrm{PrRe}\frac{\partial T_{01}}{\partial y} - ST_{01} = 0,$$
$$\frac{\partial^2 u_{02}}{\partial y^2} + \mathrm{Re}\frac{\partial u_{02}}{\partial y} - \left(M^2 + \frac{1}{K_P}\right)u_{02} = -\mathrm{ReGr}T_{02},$$
$$\frac{\partial^2 T_{02}}{\partial y^2} + \mathrm{PrRe}\frac{\partial T_{02}}{\partial y} - ST_{02} = -\mathrm{PrRe}^2\left(\frac{\partial u_{01}}{\partial y}\right)^2. \tag{11}$$

The corresponding boundary conditions are:

$$y = 0; \quad u_{01} = 0, \quad T_{01} = 1,$$
$$u_{02} = 0, \quad T_{02} = 0,$$
$$y \longrightarrow \infty; \quad u_{01} = 0, \quad T_{01} = 0,$$
$$u_{02} = 0, \quad T_{02} = 0. \tag{12}$$

The solutions of (11) under the boundary conditions (12) are

$$u_{01}(y) = A_1\left(e^{-m_1 y} - e^{-m_2 y}\right),$$
$$\theta_{01}(y) = e^{-m_1 y},$$
$$u_{02}(y) = A_{10}e^{-m_2 y} + A_6 e^{-m_1 y} + A_7 e^{-2m_1 y} + A_9 e^{-2m_2 y} + A_{10}e^{-(m_1+m_2)y},$$
$$\theta_{02}(y) = A_5 e^{-m_1 y} + A_2 e^{-2m_1 y} + A_3 e^{-2m_2 y} + A_4 e^{-(m_1+m_2)y}. \tag{13}$$

The terms of the coefficient of ε give the following first order equations:

$$\omega\frac{\partial u_1}{\partial t} - \mathrm{Re}\frac{\partial u_1}{\partial y} = \left(\frac{\partial^2 u_1}{\partial y^2} + \frac{\partial^2 u_1}{\partial z^2}\right) + \mathrm{GrRe}T_1 - \left(M^2 + \frac{1}{K_P}\right)u_1,$$
$$\omega\mathrm{Pr}\frac{\partial T_1}{\partial t} - \mathrm{PrRe}\frac{\partial T_1}{\partial y} = \left(\frac{\partial^2 T_1}{\partial y^2} + \frac{\partial^2 T_1}{\partial z^2}\right) - ST_1 + \mathrm{PrRe}^2 T_1\frac{\partial u_0}{\partial y}\frac{\partial u_1}{\partial y}. \tag{14}$$

In order to solve (14), it is convenient to adopt com-plex functions for velocity and temperature profile as

$$u_1(y,z,t) = \phi(y)e^{i(\pi z - t)},$$
$$T_1(y,z,t) = \psi(y)e^{i(\pi z - t)}. \tag{15}$$

The solutions obtained in terms of complex functions, the real parts of which have physical significance.

Now, substituting (15) into (14) we get the following coupled equations:

$$\begin{aligned}&\frac{\partial^2\phi}{\partial y^2}+\mathrm{Re}\,\frac{\partial\phi}{\partial y}\\&\quad+\left[\omega i-\pi^2-\left(M^2+\frac{1}{K_P}\right)\right]\phi=-\mathrm{ReGr}\psi(y),\\&\frac{\partial^2\psi}{\partial y^2}+\mathrm{PrRe}\frac{\partial\psi}{\partial y}\\&\quad+\left(\omega\mathrm{Pr}i-\pi^2-S\right)\psi=-2\mathrm{RePr}\frac{\partial u_0}{\partial y}\frac{\partial\phi}{\partial y}.\end{aligned}\tag{16}$$

Again, to uncouple above equations we assume the following perturbed forms with the same reasoning mentioned above:

$$\begin{aligned}\phi&=\phi_0+\mathrm{Ec}\phi_1+o\left(\mathrm{Ec}^2\right),\\\psi&=\psi_0+\mathrm{Ec}\psi_1+o\left(\mathrm{Ec}^2\right).\end{aligned}\tag{17}$$

Substituting (17) into (16) and equating the coefficient of like powers of Ec we get the subsequent equations:

$$\begin{aligned}&\frac{\partial^2\phi_0}{\partial y^2}+\mathrm{Re}\,\frac{\partial\phi_0}{\partial y}\\&\quad+\left[\omega i-\pi^2-\left(M^2+\frac{1}{K_P}\right)\right]\phi_0=-\mathrm{ReGr}\psi_0(y),\end{aligned}\tag{18}$$

$$\frac{\partial^2\psi_0}{\partial y^2}+\mathrm{PrRe}\frac{\partial\psi_0}{\partial y}+\left(\omega\mathrm{Pr}i-\pi^2-S\right)\psi_0=0,\tag{19}$$

$$\begin{aligned}&\frac{\partial^2\phi_1}{\partial y^2}+\mathrm{Re}\,\frac{\partial\phi_1}{\partial y}\\&\quad+\left[\omega i-\pi^2-\left(M^2+\frac{1}{K_P}\right)\right]\phi_1=-\mathrm{ReGr}\psi_1(y),\\&\frac{\partial^2\psi_1}{\partial y^2}+\mathrm{PrRe}\frac{\partial\psi_1}{\partial y}+\left(\omega\mathrm{Pr}i-\pi^2-S\right)\psi_1=-2\mathrm{Re}^2\mathrm{Pr}\frac{\partial u_{01}}{\partial y}\frac{\partial\phi_0}{\partial y}.\end{aligned}\tag{20}$$

The corresponding boundary conditions are:

$$\begin{aligned}&y=0;\quad\phi_0=0,\quad\phi_1=0,\quad\psi_0=1,\quad\psi_1=0,\\&y\longrightarrow\infty;\quad\phi_0=0,\quad\phi_1=0,\quad\psi_0=0,\quad\psi_1=0.\end{aligned}\tag{21}$$

The solutions of (18) under the boundary conditions (21) are

$$\begin{aligned}\phi_0(y)&=A_{11}\left(e^{-m_3y}-e^{-m_4y}\right),\\\psi_0(y)&=e^{-m_3y},\\\psi_1(y)&=A_{16}e^{-m_3y}+A_{12}e^{-(m_1+m_3)y}+A_{13}e^{-(m_1+m_3)y}\\&\quad+A_{14}e^{-(m_2+m_3)y}+A_{15}e^{-(m_1+m_3)y},\\\phi_1(y)&=A_{22}e^{-m_4y}+A_{17}e^{-m_3y}+A_{18}e^{-(m_1+m_3)y}\\&\quad+A_{19}e^{-(m_1+m_4)y}+A_{20}e^{-(m_2+m_3)y}+A_{21}e^{-(m_2+m_4)y}.\end{aligned}\tag{22}$$

The important flow characteristics of the problem are the plate shear stress and the rate of heat transfer at the plate. The expressions for shear stress (τ) and Nusselt number (Nu) are given by

$$\begin{aligned}\tau&=\frac{\tau^*l}{\mu V}=\mathrm{Real}\left.\frac{du}{dy}\right|_{y=0}\\&=A_1(m_2-m_1)-\mathrm{Re}\left(m_2A_{10}+m_1A_6+2m_1A_7\right.\\&\qquad\left.+2m_2A_8+(m_1+m_2)A_9\right)\\&\quad+\varepsilon|F|\,\mathrm{Cos}(\pi z-t+\alpha),\end{aligned}\tag{23}$$

where

$$\begin{aligned}F&=F_r+iF_i\\&=A_{11}(m_4-m_3)\\&\quad-\mathrm{Ec}\left(m_3A_{17}+m_4A_{22}+A_{18}(m_1+m_3)\right.\\&\qquad+A_{19}(m_1+m_4)+A_{20}(m_3+m_2)\\&\qquad\left.+A_{21}(m_4+m_2)\right),\end{aligned}\tag{24}$$

$$\begin{aligned}\mathrm{Nu}&=-\frac{q^*l}{k\left(T_0^*-T_\infty^*\right)}\\&=\mathrm{Real}\,\frac{dT}{dy}\quad\text{at } y=0\\&=m_1+\mathrm{Re}\left[m_1A_5+2m_1A_2+2m_2A_3+A_4(m_1+m_2)\right]\\&\quad-\varepsilon|G|\cos(\pi z-t+\beta),\end{aligned}\tag{25}$$

where

$$\begin{aligned}G&=\mathrm{Gr}+iG_i\\&=m_3+\mathrm{Ec}\left[m_3A_{16}+A_{12}(m_1+m_2)\right.\\&\qquad+A_{13}(m_1+m_4)+A_{14}(m_2+m_3)\\&\qquad\left.+A_{15}(m_2+m_4)\right].\end{aligned}\tag{26}$$

3. Results and Discussion

This section analyses the velocity, temperature, amplitude of shear stress, and rate of heat transfer. The present discussion brings the following cases to its fold.

(i) $M = 0$ and $S = 0$ represent the case of nonconducting fluid without magnetic field and heat source, respectively.

(ii) $K_P \to \infty$ represents without-porous medium.

The most important part of the discussion is due to the presence of sinusoidal variation of surface temperature with space and time and the forcing forces such as Lorentz force (electromagnetic force), porosity of the medium, thermal buoyancy. The cross-flow due to permeable surface has a significant effect on modifying the velocity also.

From (5) the following results follow.

In the absence of cross-flow, $V = 0 \Rightarrow \mathrm{Re}(= Vl/\upsilon) = 0$, the u component of velocity remains unaffected by convective acceleration and thermal buoyancy force and (5) reduces to

$$u_t = \frac{1}{\omega}\left[\left(u_{yy} + u_{zz}\right) - \left(M^2 + \frac{1}{K_P}\right)u\right]. \tag{27}$$

Moreover, the viscosity contributes significantly to a combined retarding effect caused by magnetic force and resistance due to porous medium with an inverse multiplicity of the frequency of the temperature function. Further, $M = 0$ and $K_P \to \infty$ reduce the problem to a simple unsteady motion given by $u_t = (1/\omega)(u_{yy} + u_{zz})$.

Thus, in the absence of cross-flow, that is, in case of a nonpermeable surface, frequency of the fluctuating temperature parameter $\omega = (\omega^* l^2/\upsilon)$ acts as a scaling factor. In case of impermeable surface, that is, in absence of cross-flow, (6) reduces to $T_t = (1/\omega \mathrm{Pr})(T_{yy} + T_{zz} - ST)$.

This shows that the unsteady temperature gradient is reduced by high Prandtl number fluid as well as increasing frequency of the fluctuating temperature and viscous dissipation fails to affect the temperature distribution.

From Figure 2 it is observed that maximum velocity occurs in case of cooling the plate ($\mathrm{Gr} > 0$) without magnetic field and heat source (curve I) and reverse effect is observed exclusively due to heating the plate ($\mathrm{Gr} < 0$) with a back flow (curve XIII). Thermal buoyancy effect has a significant contribution over the flow field.

From curves VIII and IX, it is seen that the Lorentz force has a retarding effect which is in conformity with the earlier reported result [14]. Source decelerates the velocity profile at all points in both absence and presence of porous medium.

Moreover, it is interesting to note that increase in Pr leads to significant decrease of the velocity (curve III (air) and VII (water)) throughout the flow field, but an increase in cross-flow Reynolds number increases the velocity in the vicinity of the plate. Afterwards, it decreases rapidly. The effects of these pertinent parameters have the same effect in both presence and absence of porous medium.

It is interesting to note that, from curves III and IX, there is no significant change in velocity due to increase in viscous dissipation. These observations are clearly indicated by the additive and subtractive terms in the equation discussed earlier.

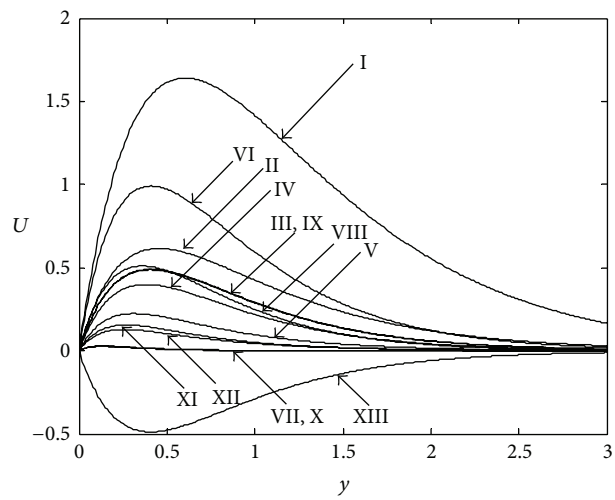

Figure 2: Velocity profile with $\omega t = \pi/2$ and $\varepsilon = 0.002$.

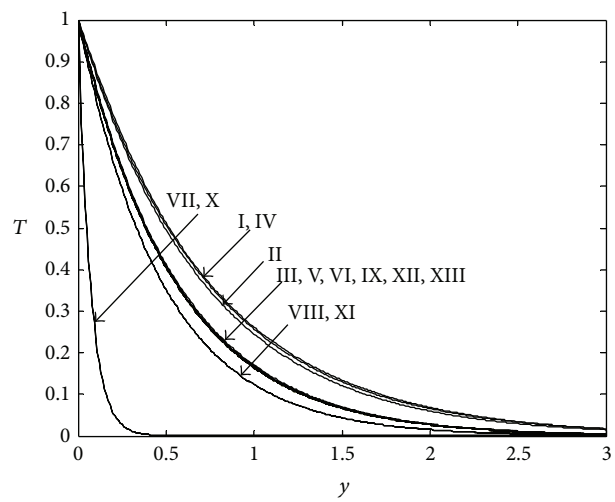

Figure 3: Temperature profile with $\omega t = \pi/2$ and $\varepsilon = 0.002$.

Figure 3 exhibits the effect of pertinent parameters on temperature field. The variation is asymptotic in nature. Sharp fall of temperature is noticed in case of water ($\mathrm{Pr} = 7.0$) for both absence and presence of porosity. Absence of source contributes to the increase in the thickness of thermal boundary layer. Higher Prandtl number fluid causes lower thermal diffusivity and hence reduces the temperature at all points. It is interesting to note that the effect of source is to lower down the temperature.

Moreover, Reynolds number (Re) leads to a decrease in the temperature profile at all points in both presence and absence of porosity. Lorentz force and thermal buoyancy force (Gr) have no significant role in temperature distribution. It is interesting to remark that the cooling and heating of the plate (curves III and XIII) make no difference in temperature distribution which is compensated for due to increase in dissipative energy loss.

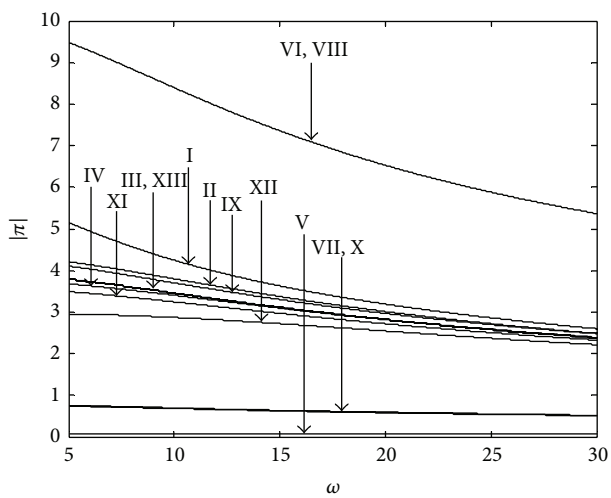

Figure 4: The amplitude of shear stress.

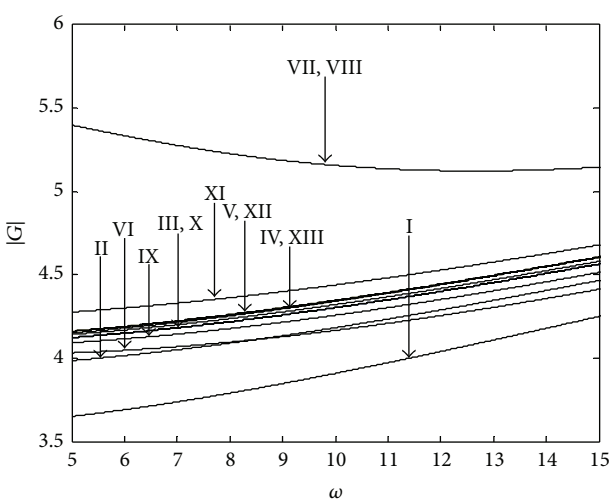

Figure 5: The amplitude $|G|$ of rate of heat transfer.

Figure 4 shows the variation of amplitude of shear stress in both the cases, that is, presence and absence of porous medium. Shear stress is almost linear for all values of frequency of fluctuation. For high Reynolds number as well as greater buoyancy force shearing stress increases.

Figure 5 exhibits the variation of amplitude $|G|$ in case of heat transfer. Further, $|G|$ exhibits three layer characters due to high, medium, and low value of Pr.

4. Conclusion

We conclude the following.

(1) Heating of the plate leads to back flow.

(2) Lorentz force has retarding effects in the velocity profile but there is no significant change marked in the temperature distribution.

(3) Presence of porous medium has no significant contribution.

(4) Viscous dissipation generates a cooling current which accelerates the velocity.

(5) There are three layer variations in amplitude of heat transfer.

Appendix

Consider the following:

$$m_1 = \frac{\mathrm{PrRe} + \sqrt{\mathrm{Pr}^2\mathrm{Re}^2 + 4S}}{2},$$

$$m_2 = \frac{\mathrm{Re} + \sqrt{\mathrm{Re}^2 + 4\left(M^2 + 1/K_p\right)}}{2},$$

$$m_3 = \frac{\mathrm{PrRe} + \sqrt{\mathrm{Pr}^2\mathrm{Re}^2 - 4\left(\mathrm{Pr}i\omega - \pi^2 - S\right)}}{2},$$

$$m_4 = \frac{\mathrm{Re} + \sqrt{\mathrm{Re}^2 - 4\left(i\omega - \pi^2 - \left(M^2 + 1/K_P\right)\right)}}{2},$$

$$A_1 = \frac{-\mathrm{ReGr}}{m_1^2 - m_1\,\mathrm{Re} - \left(M^2 + 1/K_P\right)},$$

$$A_2 = -\frac{\mathrm{PrRe}^2 A_1^2 m_1^2}{4m_1^2 - 2m_1\mathrm{PrRe} - S},$$

$$A_3 = -\frac{\mathrm{PrRe}^2 A_1^2 m_2^2}{4m_2^2 - 2m_2\mathrm{PrRe} - S},$$

$$A_4 = \frac{2\mathrm{PrRe}^2 A_1^2 m_1 m_2}{\left(m_1 + m_2\right)^2 - \mathrm{PrRe}\left(m_1 + m_2\right) - S},$$

$$A_5 = -\sum_{i=2}^{4} A_i,$$

$$A_6 = \frac{-\mathrm{ReGr}A_5}{m_1^2 - m_1\,\mathrm{Re} - \left(M^2 + 1/K_P\right)},$$

$$A_7 = \frac{-\mathrm{ReGr}A_2}{4m_1^2 - 2m_1\,\mathrm{Re} - \left(M^2 + 1/K_P\right)},$$

$$A_8 = \frac{-\mathrm{ReGr}A_3}{4m_2^2 - 2m_2\,\mathrm{Re} - \left(M^2 + 1/K_P\right)},$$

$$A_9 = \frac{-\mathrm{ReGr}A_4}{\left(m_1 + m_2\right)^2 - \mathrm{Re}\left(m_1 + m_2\right) - \left(M^2 + 1/K_P\right)},$$

$$A_{10} = -\sum_{i=6}^{9} A_i,$$

$$A_{11} = \frac{-\mathrm{ReGr}}{m_3^2 + m_3\,\mathrm{Re} - (\omega - \pi^2 - (M^2 + 1/K_P))},$$

$$A_{12} = \frac{-2\mathrm{Re}^2\mathrm{Pr}A_1A_{11}m_1m_3}{(m_1+m_3)^2 - \mathrm{RePr}\,(m_1+m_3) - (\omega\mathrm{Pr}i - \pi^2 - S)},$$

$$A_{13} = \frac{2\mathrm{Re}^2\mathrm{Pr}A_1A_{11}m_1m_4}{(m_1+m_4)^2 - \mathrm{RePr}\,(m_1+m_4) - (\omega\mathrm{Pr}i - \pi^2 - S)},$$

$$A_{14} = \frac{2\mathrm{Re}^2\mathrm{Pr}A_1A_{11}m_2m_3}{(m_2+m_3)^2 - \mathrm{RePr}\,(m_2+m_3) + (\omega\mathrm{Pr}i - \pi^2 - S)},$$

$$A_{15} = \frac{2\mathrm{Re}^2\mathrm{Pr}A_1A_{11}m_2m_4}{(m_2+m_4)^2 - \mathrm{RePr}\,(m_2+m_4) + (\omega\mathrm{Pr}i - \pi^2 - S)},$$

$$A_{16} = -\sum_{i=12}^{15} A_i,$$

$$A_{17} = \frac{-\mathrm{ReGr}A_{16}}{m_3^2 + m_3\,\mathrm{Re} - (\omega\mathrm{Pr}i - \pi^2 - (M^2 + 1/K_P))},$$

$$A_{18} = \frac{-\mathrm{ReGr}A_{12}}{(m_1+m_3)^2 - \mathrm{Re}\,(m_1+m_3) + (\omega\mathrm{Pr}i - \pi^2 - (M^2 + 1/K_P))},$$

$$A_{19} = \frac{-\mathrm{ReGr}A_{13}}{(m_1+m_4)^2 - \mathrm{Re}\,(m_1+m_4) + (\omega\mathrm{Pr}i - \pi^2 - (M^2 + 1/K_P))},$$

$$A_{20} = \frac{-\mathrm{ReGr}A_{14}}{(m_2+m_3)^2 - \mathrm{Re}\,(m_2+m_3) + (\omega\mathrm{Pr}i - \pi^2 - (M^2 + 1/K_P))},$$

$$A_{21} = \frac{-\mathrm{ReGr}A_{15}}{(m_2+m_4)^2 - \mathrm{Re}\,(m_2+m_4) + (\omega\mathrm{Pr}i - \pi^2 - (M^2 + 1/K_P))},$$

$$A_{22} = -\sum_{i=17}^{21} A_i. \tag{A.1}$$

Nomenclature

(x^*, y^*, z^*):	Cartesian coordinate system
V:	Suction velocity
l:	Wave length
ε:	Amplitude of the spanwise cosinusoidal temperature
υ:	Kinematics coefficient of viscosity
μ:	Coefficient of viscosity
$\left.\begin{matrix} y=y^*/l \\ z=z^*/l \end{matrix}\right\}$:	Dimensionless space variable
θ:	Dimensionless temperature
β:	Coefficient of volumetric expansion
B_0:	Uniform magnetic field strength
g:	Acceleration due to gravity
T_0^*:	Temperature of the plate
T_∞^*:	Ambient temperature
C_P:	Specific heat at constant pressure
K:	Thermal conductivity
ω:	Frequency of temperature fluctuation
Re:	Reynolds number
Pr:	Prandtl number
Gr:	Grashof number
Ec:	Eckert number
M:	Hartmann number
τ:	Dimensionless skin friction
Nu:	Nusselt number
K_P:	Permeability of the medium
ρ:	Density.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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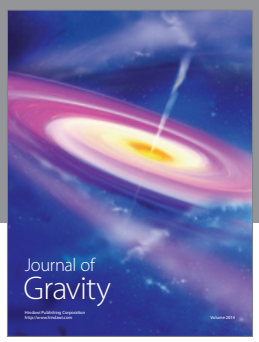

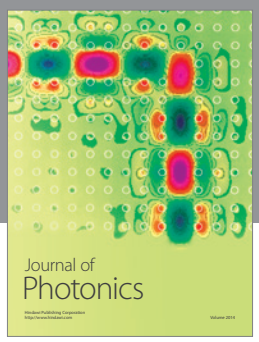

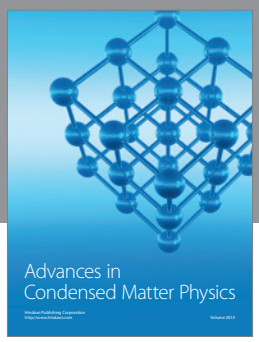

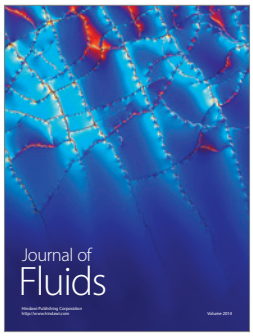

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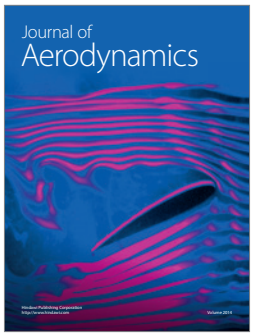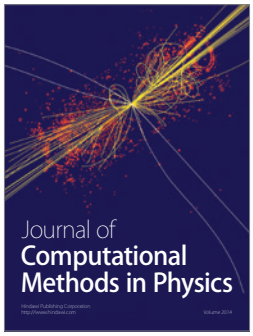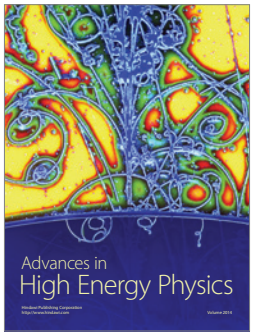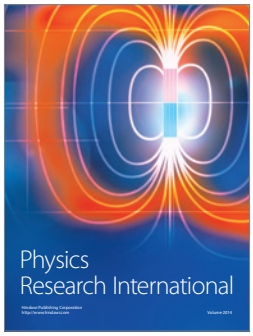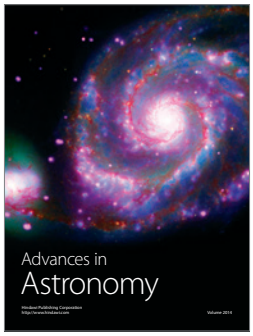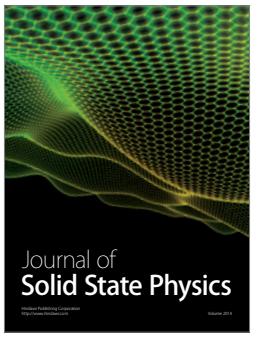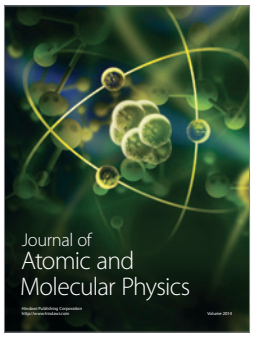
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