Hydromagnetic convective couette flow in presence of time dependent suction and radiative heat source

S. S. Das, S. Panda, N. C. Bera

Abstract— **This paper concerns with the effect of radiative heat transfer on unsteady hydromagnetic free convective couette flow of a viscous incompressible electrically conducting fluid in presence of variable suction. Employing perturbation technique, the governing equations of the flow field are solved and the expressions for the velocity, temperature, skin friction and the heat flux i.e. the rate of heat transfer in terms of Nusselts number N_u are obtained. The effects of the important flow parameters such as radiation parameter F, magnetic parameter M, slip flow parameters h_1, h_2; suction parameters α_1, α_2, Prandtl number P_r etc. on the velocity and temperature of the flow field are analyzed and discussed graphically with the help of figures and tables.**

Index Terms- **Convective, Couette, Heat source, Hydromagnetic, Suction.**

I. INTRODUCTION

The phenomenon of hydromagnetic couette flow with heat transfer has been a subject of interest of many researchers because of its possible applications in many branches of science and technology. Flows through porous media have several engineering and geophysical applications such as, in the field of agricultural engineering to study the underground water resources; in petroleum industry to study the movement of natural gas, oil and water through oil channels and reservoirs; in the field of chemical engineering for filtration and purification processes. A series of investigations have been made by the researchers where the medium is either bounded by horizontal or vertical surfaces.
Several researchers have analyzed such similar types of flows under various physical situations. Soundalgekar and Wavre [1] discussed the unsteady free convection flow past an infinite vertical plate with constant suction and mass transfer. Bejan and Khair [2] analyzed the heat and mass transfer by natural convection in a porous medium. Takhar *et al*. [3] studied the radiation effects on MHD free convection flow of a gas past a semi-infinite vertical plate. Attia [4] presented the transient MHD flow and heat transfer between two parallel plates with temperature dependent viscosity. Chamkha and his team [5] discussed the radiation effects on free convection flow past a semi-infinite vertical plate with mass transfer. Das and his co-workers [6] analyzed the hydromagnetic flow and heat transfer between two stretched/squeezed horizontal porous plates. Singh [7] studied the MHD free convection and mass transfer flow with heat source and thermal diffusion.

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Nagraju *et al*. [8] discussed the simultaneous radiative and convective heat transfer in a variable porosity medium. Singh and Sharma [9] analyzed the MHD three dimensional Couette flow with transpiration cooling.
The influence of moving magnetic field on three dimensional Couette flow was discussed by Singh [10].Das and his team [11] analyzed the unsteady free convection MHD flow of a second order fluid between two heated vertical plates through a porous medium with mass transfer and internal heat generation. Makinde [12] showed the free convection flow with thermal radiation and mass transfer past a moving vertical porous plate. Singh *et al*. [13] described the MHD free convection transient flow through a porous medium in a vertical channel. Ogulu and Prakash [14] studied the heat transfer to unsteady magneto-hydrodynamic flow past an infinite vertical moving plate with variable suction. Das and his team [15] reported the unsteady free convective MHD flow and heat transfer of a second order fluid between two heated vertical plates through a porous medium. Das *et al*. [16] examined the effect of heat source and variable suction on unsteady viscous stratified flow past a vertical porous flat moving plate in the slip flow regime. Recently, Das and his co-workers [17] studied the unsteady transient MHD free convective mass transfer flow past an infinite vertical porous plate embedded in a porous medium in presence of suction and heat sink.
The present study estimates the effect of radiative heat transfer on unsteady hydromagnetic convective couette flow of a viscous incompressible electrically conducting fluid in presence of variable suction and heat source. The effects of the important flow parameters on the velocity and temperature of the flow field are analyzed and discussed graphically with the help of figures and tables.

II. FORMULATION OF THE PROBLEM

Consider a two dimensional unsteady free convective magnetohydrodynamic flow of a viscous incompressible electrically conducting fluid between two vertical parallel porous plates placed at a distance h apart in the slip flow regime in presence of variable suction and radiative heat source. Let a time dependent suction

$$v'(t') = -v'_0\left(1 + \varepsilon A e^{-\omega' t'}\right) \tag{1}$$

be applied at the plate y=0 and the same injection velocity be applied at the plate y=1. We choose x-axis along the plate and y-axis normal to it. Under the above conditions the equations governing the flow are:
Momentum equation:

$$\frac{\partial u'}{\partial t'} - v'_0\left(1 + \varepsilon A e^{-\omega' t'}\right)\frac{\partial u'}{\partial y'} = g\beta\left(T' - T'_h\right) + \nu\frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_0^2}{\rho}u', \tag{2}$$

Energy equation:

$$\frac{\partial T'}{\partial t'}-v_0'\left(1+\varepsilon A e^{-\omega' t'}\right)\frac{\partial T'}{\partial y'}=\frac{k}{\rho C_p}\frac{\partial^2 T'}{\partial y'^2}-\frac{1}{\rho C_p}\frac{\partial q_r}{\partial y'}. \quad (3)$$

The boundary conditions of the problem are:

$$u'-U_1=L_1\frac{\partial u'}{\partial y'},\frac{\partial T'}{\partial y'}=-\frac{q}{k} \text{ at } y'=0,$$

$$u'-U_2=L_2\frac{\partial u'}{\partial y'},T'=T_h', \quad at\ y'=h, \quad (4)$$

where $L_1=\frac{(2-\mu_1)}{\mu_1}L$, L being the mean free path and μ_1, the Maxwell's reflection coefficient.

The radiative heat flux q_r is given by

$$\frac{\partial q_r}{\partial y'}=4(T'-T_h')I \ , \quad (5)$$

where $I=\int k_{\lambda w}\frac{\partial e_{b\lambda}}{\partial T}d\lambda$, $k_{\lambda w}$ is the absorption coefficient at the wall, $e_{b\lambda}$ is Planck's function and λ is the frequency, u' is the velocity, T' is the temperature, B_0 is the uniform transverse magnetic field, β is the volumetric coefficient of expansion for heat transfer, β* is the volumetric coefficient of expansion for mass transfer, k is the thermal conductivity, ν is the kinematic viscosity, C_p is the specific heat at constant pressure, σ is the electrical conductivity, g is the acceleration due to gravity, A is a real positive constant, t is the time and ε is a small positive number such that εA<<1. Introducing the following non-dimensional variables and parameters,

$$y=\frac{y'v_0'}{\nu},t=\frac{t'v_0'^2}{\nu},\omega=\frac{\nu\omega'}{v_0'^2},u=\frac{u'}{v_0'},\nu=\frac{\eta_0}{\rho},M=\left(\frac{\sigma B_0^2}{\rho}\right)\frac{\nu}{v_0'^2}, \text{by}$$

$$\theta=\frac{kv_0'(T'-T_h')}{\nu q'},P_r=\frac{\rho\nu C_p}{k},G_r=\frac{\nu^2 g\beta q}{kv_0'^4},F=\frac{4\nu I}{\rho C_p v_0'^2},$$

$$\alpha_1=\frac{U_1}{v_0},\ \alpha_2=\frac{U_2}{v_0},\ R=\frac{v_0'h}{\nu},\ h_1=\frac{L_1 v_0'}{\nu},\ h_2=\frac{L_2 v_0'}{\nu}. \quad (6)$$

in Equations (2)-(3), we get the following non-dimensional equations

$$\frac{\partial u}{\partial t}-\left(1+\varepsilon A e^{-\omega t}\right)\frac{\partial u}{\partial y}=G_r\theta+\frac{\partial^2 u}{\partial y^2}-Mu\ , \quad (7)$$

$$\frac{\partial\theta}{\partial t}-\left(1+\varepsilon A e^{-\omega t}\right)\frac{\partial\theta}{\partial y}=\frac{1}{P_r}\frac{\partial^2\theta}{\partial y}-F\theta\ , \quad (8)$$

where M is the magnetic parameter, G_r is the Grashof number for heat transfer, F is the radiation parameter, P_r is the Prandtl number, α_1 and α_2 are the suction parameters and h_1 and h_2 are the slip flow parameters.

The corresponding boundary conditions are:

$$u=\alpha_1+h_1\frac{\partial u}{\partial y},\ \frac{\partial\theta}{\partial y}=-1 \quad at\ \ y=0\ ,$$

$$u=\alpha_2+\frac{\partial u}{\partial y},\ \ \theta=0 \quad at\ \ y=h\ . \quad (9)$$

III. METHOD OF SOLUTION

We now seek the solutions for Equations (7)-(8) under boundary condition (9) for a particular case R=1, which is valid for an incompressible fluid. In order to solve Equations (7)-(8), we assume

$$u\ (y,\ t)=u_0\ (y)+\varepsilon u_1\ (y)\ e^{-\omega t}+\ldots\ldots \quad (10)$$

$$\theta(y,\ t)=\theta_0\ (y)+\varepsilon\theta_1\ (y)\ e^{-\omega t}+\ldots\ldots \quad (11)$$

Using Equations (10)-(11) in Equations (7)-(8), we get the following zeroth order and first order equations:

Zeroth order:

$$-\frac{\partial u_0}{\partial y}=G_r\theta_0+\frac{\partial^2 u_0}{\partial y^2}-Mu_0\ , \quad (12)$$

$$-\frac{\partial\theta_0}{\partial y}=\frac{1}{P_r}\frac{\partial^2\theta_0}{\partial y}-F\theta_0\ , \quad (13)$$

First order:

$$-\omega u_1-A\frac{\partial u_0}{\partial y}-\frac{\partial u_1}{\partial y}=G_r\theta_1+\frac{\partial^2 u_1}{\partial y^2}-Mu_1\ , \quad (14)$$

$$-\omega\theta_1-A\frac{\partial\theta_0}{\partial y}-\frac{\partial\theta_1}{\partial y}=\frac{1}{P_r}\frac{\partial^2\theta_1}{\partial y}-F\theta_1\ , \quad (15)$$

The corresponding boundary conditions are

$$u_0=\alpha_1+h_1\frac{\partial u_0}{\partial y},u_1=h_1\frac{\partial u_1}{\partial y},\ \frac{\partial\theta_0}{\partial y}=-1,\ \frac{\partial\theta_1}{\partial y}=0\ \ at\ \ y=0$$

$$u_0=\alpha_2+h_2\frac{\partial u_0}{\partial y},u_1=h_2\frac{\partial u_1}{\partial y},\ \ \theta_0=0,\ \theta_1=0\ \ at\ \ y=1 \quad (16)$$

The solutions of Equations (12)-(15) under boundary condition (16) are given by

$$u(y,t)=\left(A_5e^{m_5y}+A_6e^{m_6y}-A_{11}e^{m_1y}-A_{12}e^{m_2y}\right)+\varepsilon e^{-\omega t}\left(A_7e^{m_7y}+A_8e^{m_8y}\right.$$
$$\left.+B_1e^{m_1y}+B_2e^{m_2y}-B_3e^{m_3y}-B_4e^{m_4y}-B_5e^{m_5y}-B_6e^{m_6y}\right) \quad (17)$$

$$\theta(y,t)=\left(A_1e^{m_1y}+A_2e^{m_2y}\right)+\varepsilon e^{-\omega t}\left(A_3e^{m_3y}+A_4e^{m_4y}-A_9e^{m_1y}-A_{10}e^{m_2y}\right) \quad (18)$$

The wall shear stress i.e. the skin friction at the wall is given

$$\tau=\left(\frac{\partial u}{\partial y}\right)_{y=0}=\left(\frac{\partial u_0}{\partial y}\right)_{y=0}+\varepsilon e^{-\omega t}\left(\frac{\partial u_1}{\partial y}\right)_{y=0}. \quad (19)$$

Using Equation (17) in Equation (19), it is given by

$$\tau=\left(m_5A_5+m_6A_6-m_1A_{11}-m_2A_{12}\right)+\varepsilon e^{-\omega t}\left(m_7A_7+m_8A_8\right.$$
$$\left.+m_1B_1+m_2B_2-m_3B_3-m_4B_4-m_5B_5-m_6B_6\right). \quad (20)$$

The rate of heat transfer i.e. the heat flux at the wall is given by

$$N_u=\left(\frac{\partial\theta}{\partial y}\right)_{y=0}=\left(\frac{\partial\theta_0}{\partial y}\right)_{y=0}+\varepsilon e^{-\omega t}\left(\frac{\partial\theta_1}{\partial y}\right)_{y=0}. \quad (21)$$

Using Equation (18) in Equation (21), it is given by

$$N_u=\left(m_1A_1+m_2A_2\right)+\varepsilon e^{-\omega t}\left(m_3A_3+m_4A_4-m_1A_9-m_2A_{10}\right), \quad (22)$$

where

$$m_1=-\frac{P_r}{2}+\frac{1}{2}\sqrt{P_r^2+4P_rF}\quad,\quad m_2=-\frac{P_r}{2}-\frac{1}{2}\sqrt{P_r^2+4P_rF}\quad,$$

$$m_3=-\frac{P_r}{2}+\frac{1}{2}\sqrt{P_r^2-4P_r(\omega-F)}\ ,\ m_4=-\frac{P_r}{2}-\frac{1}{2}\sqrt{P_r^2-4P_r(\omega-F)}\ ,$$

$$m_5=-\frac{1}{2}+\frac{1}{2}\sqrt{1+4M}\ ,\ m_6=-\frac{1}{2}-\frac{1}{2}\sqrt{1+4M}\ ,$$

$$m_7=-\frac{1}{2}+\frac{1}{2}\sqrt{1+4(M-\omega)}\quad,\quad m_8=-\frac{1}{2}-\frac{1}{2}\sqrt{1+4(M-\omega)}\quad,$$

$$A_1=\frac{e^{m_2}}{\left(m_2e^{m_1}-m_1e^{m_2}\right)}\quad,\quad A_2=-\frac{A_1e^{m_1}}{e^{m_2}}\quad,$$

$$A_3 = \frac{e^{m_4}\left(A_9 m_1 + A_{10} m_2\right) - m_4\left(A_9 e^{m_1} + A_{10} e^{m_2}\right)}{\left(m_3 e^{m_4} - m_4 e^{m_3}\right)} ,$$

$$A_4 = \frac{A_9 m_1 + A_{10} m_2 - A_3 m_3}{m_4} , \quad A_5 = \frac{C_3 C_5 - C_2 C_6}{C_1 C_5 - C_2 C_4} ,$$

$$A_6 = \frac{C_3 - A_5 C_1}{C_2} , \quad A_7 = \frac{C_9 C_{11} - C_8 C_{12}}{C_7 C_{11} - C_8 C_{10}} ,$$

$$A_8 = \frac{C_9 - A_7 C_7}{C_8} , \quad A_9 = \frac{A P_r A_1 m_1}{m_1^2 + m_1 P_r + P_r(\omega - F)} ,$$

$$A_{10} = \frac{A P_r A_2 m_2}{m_2^2 + m_2 P_r + P_r(\omega - F)} , \quad A_{11} = \frac{G_r A_1}{m_1^2 + m_1 - M} ,$$

$$A_{12} = \frac{G_r A_2}{m_2^2 + m_2 - M} , \quad B_1 = \frac{G_r A_9 + A A_{10} m_1}{m_1^2 + m_1 - (M - \omega)} ,$$

$$B_2 = \frac{G_r A_{10} + A A_{12} m_4}{m_2^2 + m_2 - (M - \omega)} , \quad B_3 = \frac{G_r A_3}{m_3^2 + m_3 - (M - \omega)} ,$$

$$B_4 = \frac{G_r A_4}{m_4^2 + m_4 - (M - \omega)} , \quad B_5 = \frac{A A_5 m_5}{m_5^2 + m_5 - (M - \omega)} ,$$

$$B_6 = \frac{A A_6 m_6}{m_6^2 + m_6 - (M - \omega)} , C_1 = 1 - h_1 m_5 , C_2 = 1 - h_1 m_6 ,$$

$$C_3 = \alpha_1 + A_{11}(1 - h_1 m_1) + A_{12}(1 - h_1 m_2) ,$$

$$C_4 = e^{m_5}(1 - h_2 m_5) , \quad C_5 = e^{m_6}(1 - h_2 m_6) ,$$

$$C_6 = \alpha_2 + A_{11} e^{m_3}(1 - h_2 m_1) + A_{12} e^{m_4}(1 - h_2 m_4) ,$$

$$C_7 = 1 - h_1 m_7 , C_8 = 1 - h_1 m_8 ,$$

$$C_9 = -B_1(1 - h_1 m_1) - B_2(1 - h_1 m_2) + B_3(1 - h_1 m_3) + B_4(1 - h_1 m_4) + B_5(1 - h_1 m_5) + B_6(1 - h_1 m_6) ,$$

$$C_{10} = e^{m_7}(1 - h_2 m_7), C_{11} = e^{m_8}(1 - h_2 m_8),$$

$$C_{12} = -B_1 e^{m_1}(1 - h_2 m_1) - B_2 e^{m_2}(1 - h_2 m_2) + B_3 e^{m_3}(1 - h_2 m_3) + B_4 e^{m_4}(1 - h_2 m_4) + B_5 e^{m_5}(1 - h_2 m_5) + B_6 e^{m_6}(1 - h_2 m_6) . \quad (23)$$

IV. RESULTS AND DISCUSSIONS

The present study considers the hydromagnetic convective couette flow with heat transfer in the slip flow regime in presence of variable suction and radiative heat source. The governing equations of the flow field are solved for velocity, temperature, skin friction and heat flux and the effects of the flow parameter such as radiation parameter F, magnetic parameter M, slip flow parameters h_1 and h_2 , suction parameters α_1 and α_2 and the Prandtl number P_r on the velocity, temperature and skin friction are analyzed with the aid of velocity profiles shown in Figures 1-6, temperature profiles shown in Figures 7-8 and Tables 1-2 respectively.

4.1. Velocity field

There is a drastic change in the magnitude of velocity of the flow field with the variation of radiation parameter F, magnetic parameter M, slip flow parameters h_1, h_2 and suction parameters α_1 and α_2 in the flow field. Figures 1-6 clearly show the variations in the velocity field due to the change in the above parameters.

Figure 1 elucidates the effect of radiation parameter F on the velocity of the flow field. An increase in radiation parameter is reported to enhance the velocity of the flow field at all points. The magnetic parameter affects the velocity of the flow field to an appreciable extent. Figure 2 depicts the effect of magnetic parameter M on the velocity of the flow field. The magnetic parameter is reported to decelerate the velocity of the flow field at all points due to the magnetic pull of the Lorentz force acting on the flow field. Figures 3 and 4 estimate the effect of slip flow parameters on the velocity of the flow field. Comparing the curves of both the figures, it is observed that the effect of growing slip flow parameters h_1 and h_2 is to enhance the velocity of the flow field at all points. Figures 5 and 6 point out the effects of suction parameters α_1 and α_2 on the velocity field. Both the parameters α_1 and α_2 lead to accelerate the velocity of the flow field at all points.

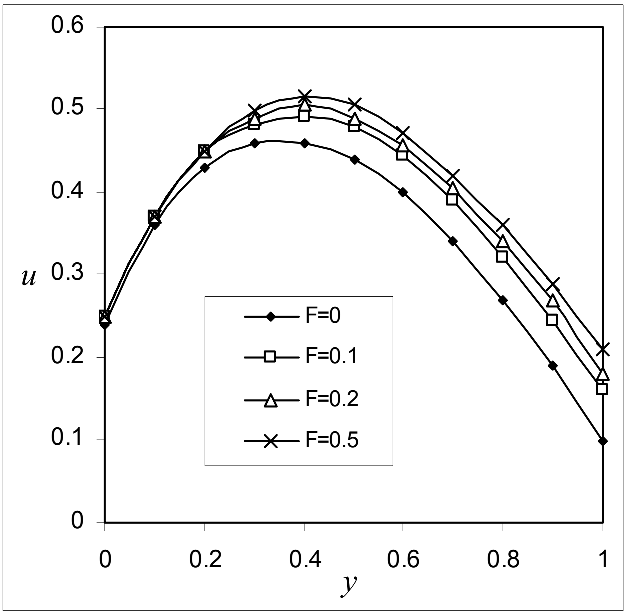

Figure 1. Velocity profiles against y for different values of F with M=1, G_r=1, h_1=0.1, h_2=0.1, α_1=0.1, α_2=0.2, P_r=0.71, A=0.5, ω=0.1, t=0.1 and ε=0.01

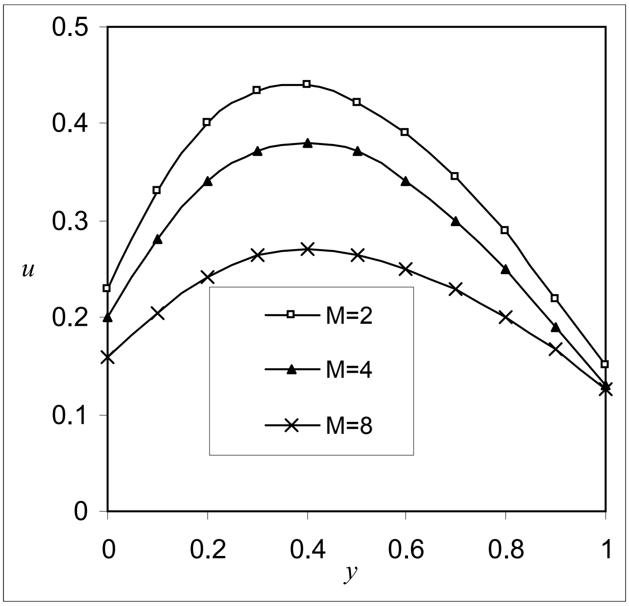

Figure 2. Velocity profiles against y for different values of M with G_r=1, F=0.1, h_1=0.1, h_2=0.1, α_1=0.1, α_2=0.2, P_r=0.71, A=0.5, ω=0.1, t=0.1and ε=0.01

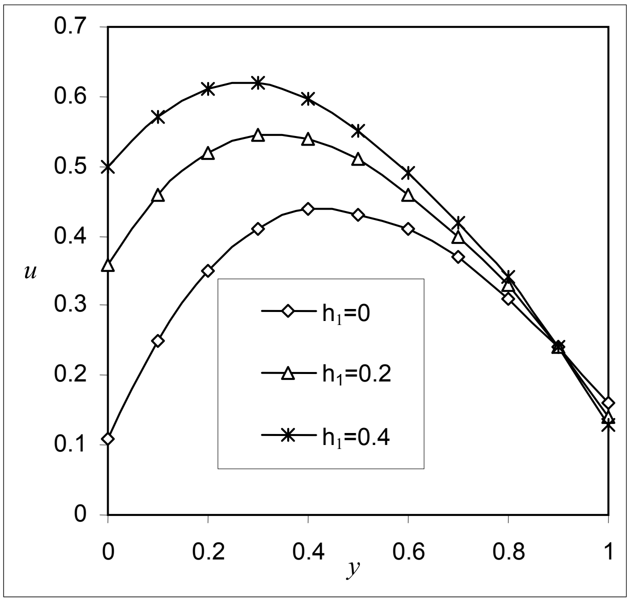

Figure 3. Velocity profiles against y for different values of h_1 with M=1, G_r=1, F=0.1, h_2=0.1, α_1 =0.1, α_2=0.2, P_r=0.71, A=0.5, ω=0.1, t=0.1and ε=0.01

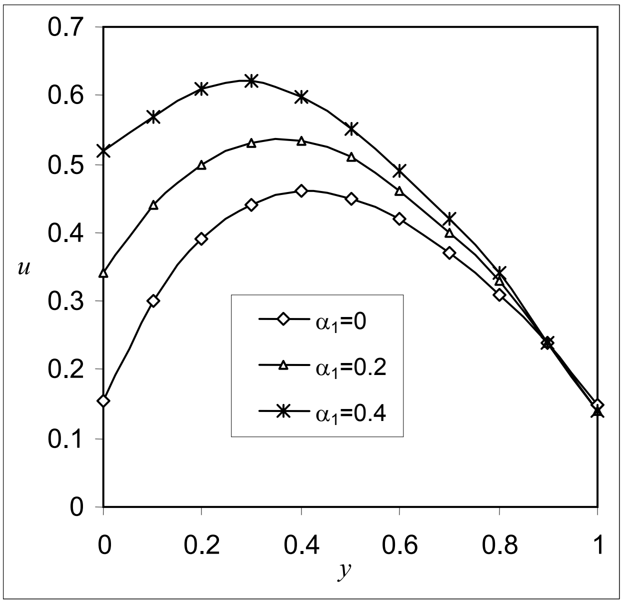

Figure 5. Velocity profiles against y for different values of α_1 with M=1, G_r=1, F=0.1, h_1=0.1, h_2=0.1, α_2=0.2, P_r=0.71, A=0.5, ω=0.1, t=0.1and ε=0.01

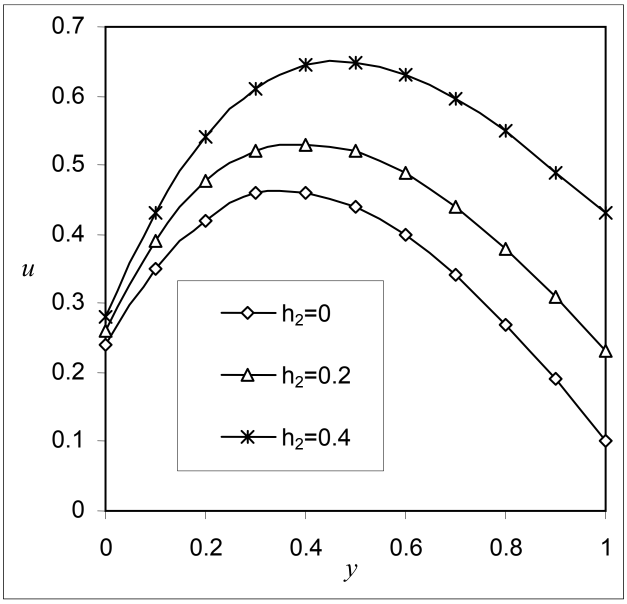

Figure 4. Velocity profiles against y for different values of h_2 with M=1, G_r=1, F=0.1, h_1=0.1, α_1=0.1, α_2=0.2, P_r=0.71, A=0.5, ω=0.1, t=0.1and ε=0.01

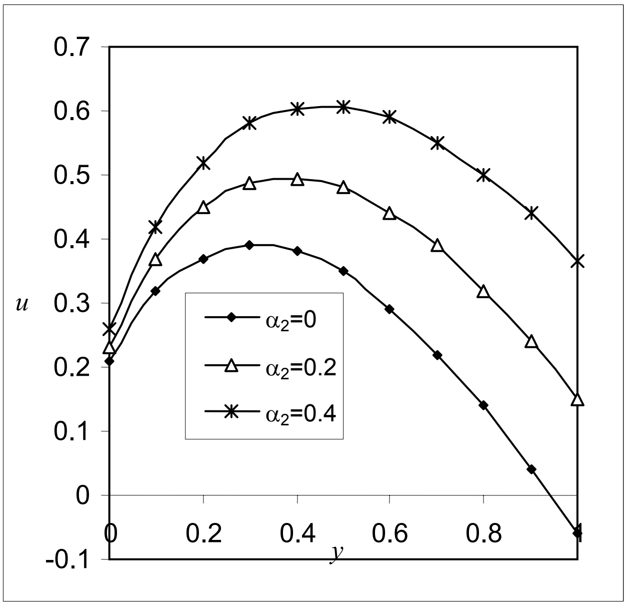

Figure 6. Velocity profiles against y for different values of α_2 with M=1, G_r=1, F=0.1, h_1=0.1, h_2=0.1, α_1=0.1, P_r=0.71, A=0.5, ω=0.1, t=0.1and ε=0.01

4.2. Temperature field

The major changes in the temperature profiles of the flow field are due to the variations in the radiation parameter and Prandtl number in the flow field. These changes in the temperature field are analyzed in Figures 6 and 7 respectively. A close observation of the curves of both the figures shows that a growing Prandtl number or radiation parameter decreases the temperature of the flow field at all points. But with growing values of Prandtl number and the radiation parameter, the decrease in temperature is more significant in case of Prandtl number.

4.3. Skin friction

Tables 1 and 2 elucidate the variations in the values of skin friction at the wall against magnetic parameter M with the variation of α_1 and α_2 respectively. A close observation of the values of Tables 1 and 2 depicts that a growing suction parameter α_1 decreases the skin friction at the wall for a given value of magnetic parameter M, while in case of the other suction parameter α_2 the effect reverses. It is further observed that a growing magnetic parameter decreases the skin friction at the wall at all points of the flow field for a given value of α_1 or α_2.

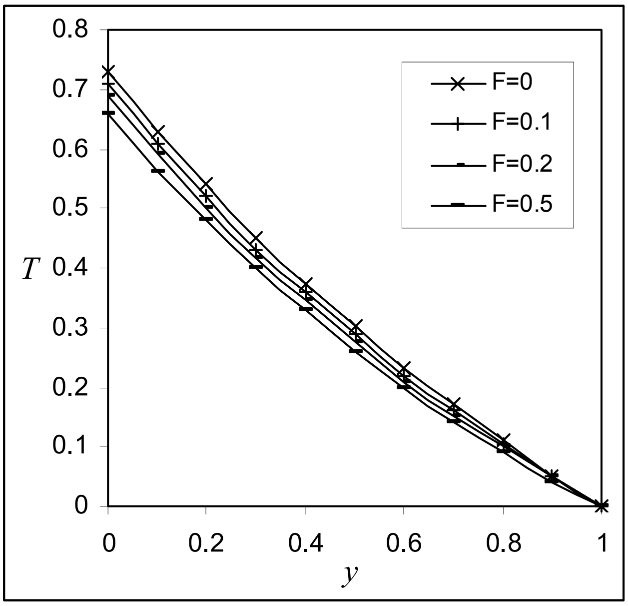

Figure 7. Temperature profiles against y for different values of F with M=1, G_r=1, h_1=0.1, h_2=0.1, α_1=0.1, α_2=0.2, P_r=0.71, A=0.5, ω=0.1, t=0.1 and ε=0.01

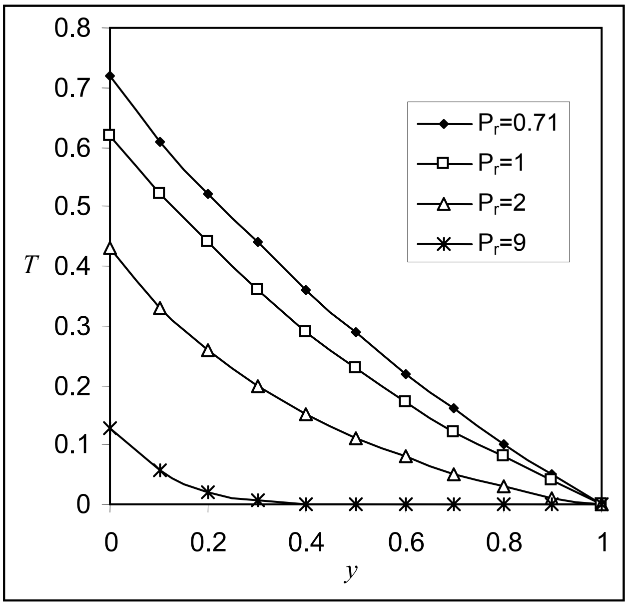

Figure 8. Temperature profiles against y for different values of P_r with M=1, G_r=1, F=0.1, h_1=0.1, h_2=0.1, α_1=0.1, α_2=0.2, A=0.5, ω=0.1, t=0.1 and ε=0.01

Table 1. Values of skin friction τ at the wall against M for different values of α_1 with G_r=1, F=0.1, A=0.5, α_2=0.2, h_1=0.1, h_2=0.1, P_r=0.71, ω=0.1, t=0.1 and ε=0.01

τ				
M	α_1=0	α_1=0.1	α_1=0.3	α_1=0.5
0	0.31603	0.04471	-0.49790	-1.04052
0.5	0.30734	0.03208	-0.51843	-1.06895
1	0.29913	0.02004	-0.53814	-1.09632
3	0.27030	-0.02304	-0.60974	-1.19644
5	0.24667	-0.05949	-0.67181	-1.28413

Table 2. Values of skin friction τ at the wall against M for different values of α_2 with G_r=1, F=0.1, A=0.5, α_1=0.1, h_1=0.1, h_2 =0.1, P_r=0.71, ω=0.1, t=0.1 and ε=0.01

τ				
M	α_2=0	α_2=0.1	α_2=0.3	α_2=0.5
0	-0.04887	-0.00208	0.09151	0.18510
0.5	-0.05701	-0.01246	0.07663	0.16572
1	-0.06484	-0.0224	0.06248	0.14735
3	-0.09347	-0.05825	0.01217	0.08259
5	-0.11852	-0.08912	-0.02996	0.02906

V. CONCLUSIONS

We report the following results of physical interest on the velocity, temperature and skin friction at the wall of the flow field from the present study.

1. An increase in magnetic parameter M decreases the velocity and also the skin friction at all points of the flow field.
2. A growing radiation parameter F enhances the velocity of the flow field at all points.
3. The effect of growing slip flow parameters h_1 and h_2 is to enhance the velocity of the flow field at all points.
4. The suction parameters α_1 and α_2 have an accelerating effect on the velocity of the flow field at all points.
5. The effect of increasing Prandtl number P_r or radiation parameter F is to decrease the temperature of the flow field at all points.
6. A growing suction parameter α_1 decreases the skin friction at the wall for a given value of magnetic parameter M, while in case of the other suction parameter α_2 the effect reverses. Further an increase in magnetic parameter decreases the skin friction at the wall at all points of the flow field for a given value of α_1 or α_2.

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