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# Radiation Effect on Three Dimensional MHD Flow Past a Vertical Porous Plate

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**ABSTRACT**

The magnetohydrodynamic flow of viscous incompressible fluid past a vertical porous plate in the presence of radiation has been studied. Approximate solution for velocity and temperature fields have been obtained by using perturbation technique. It is found that main fluid velocity decreases with increase in magnetic parameter, radiation parameter as well as suction parameter for cooling of the plate and increases for heating of the plate. The temperature profile decreases with the increase of radiation parameter.

***Keywords:*** Raditation and magnetic field, periodic suction, porous plate.

## 1 Introduction

The problem of laminar flow control plays an important role in many engineering applications, particularly in the fields of aeronautical engineering to reduce drag and hence the vehicle power requirement by substantial amount. The transition from laminar to turbulent flow was first examined by O, Reynolds in a pipe flow. Later Prandtl shown experimentally that the boundary layer also can be both laminar or turbulent and that process of separation and thus the drag problems are controlled by this transition. The effects of different arrangements and configurations of the suction holes and slits on the drag has been studied extensively. An analysis of such flows find applications in ion propulsion, electromagnetic pumps, MHD power generators, controlled fusion etc. The method of "cooling of the wall" in controlling the laminar flow together with the application of suction has become important and has received the attention of scholars. Singh et al.[1] studied the effect on wall shear stress and heat transfer of the flow caused by the periodic suction when the difference between the wall temperature and free stream temperature gives rise to buoyancy force in the directions of free stream. Singh et al.[2] also studied the three dimensional fluctuating flow and heat transfer by applying the transverse sinusoidal suction velocity distribution fluctuating with time at the porous plate. Singh [3] studied the effects of magnetic field on the three dimensional flow of a viscous, incompressible fluid past a porous plate by applying transverse sinusoidal suction. Singh [4] analyzed the effect of magnetic field on the oscillatory flow past a porous plate by applying transverse sinusoidal suction. Also Singh [5] studied the flow of viscous incompressible fluid past a porous plate with transverse sinusoidal suction in the presence of viscous dissipative heat. Guria and Jana [6] considered the unsteady three dimensional flow of viscous incompressible fluid past a vertical porous plate. If the fluid temperature is rather high, radiation effects play an important role and this situation does exist in space technology. Nuclear power plants, gas turbines and the various propulsion devices for aircraft, missiles, satellites are examples of such engineering areas. In this cases, one has to take into account the effects of radiation and free convection. Also when the temperature of the plate is high, the radiation effects are not negligible. Seddeek [7] also studied the effect of radiation past a moving plate with variable viscosity. The effect of radiation on the flow past a vertical plate was discussed by Takhar et al. [8]. Rapits [9] also studied the effect of radiation and free convection on steady flow past a vertical porous plate through porous medium. Sharma et al. [10] studied the effect of radiation on temperature distribution in three-dimensional Coutte flow subjected to a periodic suction velocity distribution. Recently, Guria et al. [11] investigated the effect of radiation on three dimensional flow in a vertical channel subjected to a periodic suction. Guria et al. [12] also investigated the three dimensional flow past a vertical porous plate in the presence of transverse magnetic field. The aim of this paper is to study the effect of radiation and magnetic field on three dimensional flow past a vertical porous plate subject to the periodic suction velocity distribution.

## 2 Formulation of the Problem

Consider the flow of viscous, incompressible, electrically conducting fluid past along a semi infinite vertical porous plate. A uniform magnetic field $B_0$ is imposed perpendicular to the plane of the plate, that is in the $y^*$-direction. The $x^*$ axis is chosen along the vertical plate that is the direction of the flow, $y^*-$ axis is perpendicular to the plate and $z^*-$ axis is perpendicular to the $x^* y^*-$ plane (Fig.1.). The plate is subjected to a periodic suction velocity distribution of the form

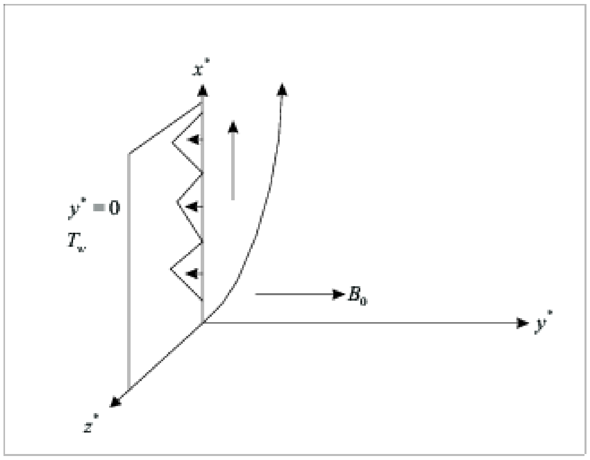


Fig.1: Geometry of the problem

$$v^* = -V_0\left[1+\varepsilon\cos\frac{u_\infty z^*}{\nu}\right], \tag{1}$$

where $\varepsilon(<<1)$ is the amplitude of the suction velocity.

Denoting velocity components $u^*, v^*, w^*$ in the directions $x^*-, y^*-$ and $z^*-$ axes respectively, the flow is governed by the following equations

$$\frac{\partial v^*}{\partial y^*}+\frac{\partial w^*}{\partial z^*}=0, \tag{2}$$

$$v^*\frac{\partial u^*}{\partial y^*}+w^*\frac{\partial u^*}{\partial z^*}=\nu\left(\frac{\partial^2 u^*}{\partial y^{*2}}+\frac{\partial^2 u^*}{\partial z^{*2}}\right)+g\beta(T-T_\infty)-\frac{\sigma B_0^2 u^*}{\rho}, \tag{3}$$

$$v^*\frac{\partial v^*}{\partial y^*}+w^*\frac{\partial v^*}{\partial z^*}=-\frac{1}{\rho}\frac{\partial p^*}{\partial y^*}+\nu\left(\frac{\partial^2 v^*}{\partial y^{*2}}+\frac{\partial^2 v^*}{\partial z^{*2}}\right), \tag{4}$$

$$v^*\frac{\partial w^*}{\partial y^*}+w^*\frac{\partial w^*}{\partial z^*}=-\frac{1}{\rho}\frac{\partial p^*}{\partial z^*}+\nu\left(\frac{\partial^2 w^*}{\partial y^{*2}}+\frac{\partial^2 w^*}{\partial z^{*2}}\right)-\frac{\sigma B_0^2 w^*}{\rho}, \tag{5}$$

$$v^*\frac{\partial T}{\partial y^*}+w^*\frac{\partial T}{\partial z^*}=\frac{K}{\rho C_p}\left(\frac{\partial^2 T}{\partial y^{*2}}+\frac{\partial^2 T}{\partial z^{*2}}\right)-\frac{1}{\rho C_p}\frac{\partial q_r^*}{\partial y^*}, \tag{6}$$

where $\rho$ is the density, $p^*$ is the fluid pressure, $g$ is the acceleration due to gravity, $\beta$ is the coefficient of thermal expansion, $K$ is the coefficient of heat conduction, $C_p$ is the specific heat at constant pressure, $\sigma$ is the electrical conductivity.

The boundary conditions of the problem are

$$u^* = 0, v^* = -V_0\left[1+\varepsilon\cos\frac{u_\infty z^*}{\nu}\right], w^* = 0, T = T_w \quad \text{at} \quad y^* = 0,$$

$$u^* = 0, v^* = -V_0, w^* = 0, p^* = p_\infty, \; T = T_\infty \quad \text{at} \quad y^* \to \infty. \tag{7}$$

Introducing the non-dimensional variables

$$y = \frac{u_\infty y^*}{\nu}, z = \frac{u_\infty z^*}{\nu}, t = ct^*, p = \frac{p^*}{\rho u_\infty^2}, u = \frac{u^*}{u_\infty}, v = \frac{v^*}{u_\infty}, w = \frac{w^*}{u_\infty}, \theta = \frac{(T - T_\infty)}{T_w - T_\infty}, \tag{8}$$

equations (2.2)- (2.6) become

$$\frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \tag{9}$$

$$v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} + G_r\theta - Mu, \tag{10}$$

$$v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{\partial p}{\partial y} + \left(\frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right), \tag{11}$$

$$v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{\partial p}{\partial z} + \left(\frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) - Mw, \tag{12}$$

$$v\frac{\partial \theta}{\partial y} + w\frac{\partial \theta}{\partial z} = \frac{1}{Pr}\left(\frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2}\right) - F\theta, \tag{13}$$

where $Gr = \frac{g\beta(T_w - T_\infty)\nu}{u_\infty^3}$ is the Grashof number, $M = \frac{\sigma B_0^2 \nu}{\rho u_\infty^2}$ is the magnetic parameter and $Pr = \frac{\rho \nu C_p}{K}$ is the Prandtl number. $T_\infty$ and $p_\infty$ are the temperature and presure outside the boundary layer.

The corresponding boundary conditions (2.7) become

$$u = 0, v = -S[1+\varepsilon\cos(\pi z)], w = 0, \theta = 1 \quad \text{at } y = 0,$$

$$u = 0, v = -S, w = 0, \theta = 0 \quad \text{at} \quad y \to \infty, \tag{14}$$

where $S = V_0/u_\infty$, is the suction parameter.

## 3 Solution of the problem

To solve (2.9)-(2.13), we assume the solution of the following form:

$$u(y,z,t) = u_0(y) + \varepsilon u_1(y,z,t) + \varepsilon^2 u_2(y,z,t) + \cdots,$$

$$v(y,z,t) = v_0(y) + \varepsilon v_1(y,z,t) + \varepsilon^2 v_2(y,z,t) + \cdots,$$

$$w(y,z,t) = w_0(y) + \varepsilon w_1(y,z,t) + \varepsilon^2 w_2(y,z,t) + \cdots,$$

$$p(y,z,t) = p_0(y_0) + \varepsilon p_1(y,z,t) + \varepsilon^2 p_2(y,z,t) + \cdots, \tag{15}$$

$$\theta(y,z,t) = \theta_0(y) + \varepsilon\theta_1(y,z,t) + \varepsilon^2\theta_2(y,z,t) + \cdots.$$

Substituting (3.15) in (2.9)-(2.13), comparing the term free from $\varepsilon$ and the coefficient of $\varepsilon$ from both sides, and neglecting those of $\varepsilon^2$, the term free from $\varepsilon$ is

$$v_0' = 0, \tag{16}$$

$$u_0'' + Su_0' + Gr\theta_0 - Mu_0 = 0, \tag{17}$$

$$\theta_0'' + SPr\theta_0' - FP_r\theta_0 = 0, \tag{18}$$

where the primes denote differentiation with respect to $y$.

The boundary conditions are

$$u_0 = 0, v_0 = -S, \theta_0 = 1 \text{ at } y = 0 \text{ and } u_0 = 0, v_0 = -S, \theta_0 = 0 \text{ at } y \to \infty. \tag{19}$$

The solutions of (3.16)-(3.18) under the boundary conditions (3.19) are

$$v_0(y) = -S, \tag{20}$$

$$u_0(y) = \frac{G_r}{(\lambda_1^2 - S\lambda_1 - M)}\left[e^{-\lambda_2 y} - e^{-\lambda_1 y}\right] \tag{21}$$

$$\theta_0(y) = e^{-\lambda_1 y} \tag{22}$$

where $$\lambda_1 = \frac{SP_r + \sqrt{S^2 p_r^2 + 4FP_r}}{2}, \lambda_2 = \frac{S + \sqrt{S^2 + 4M}}{2}. \tag{23}$$

The term depending on $\varepsilon$ is

$$\frac{\partial v_1}{\partial y} + \frac{\partial w_1}{\partial z} = 0, \tag{24}$$

$$v_1 \frac{\partial u_0}{\partial y} - S\frac{\partial u_1}{\partial y} = \frac{\partial^2 u_1}{\partial y^2} + \frac{\partial^2 u_1}{\partial z^2} + Gr\theta_1 - Mu_1, \tag{25}$$

$$-S\frac{\partial v_1}{\partial y} = -\frac{\partial p_1}{\partial y} + \left(\frac{\partial^2 v_1}{\partial y^2} + \frac{\partial^2 v_1}{\partial z^2}\right), \tag{26}$$

$$-S\frac{\partial w_1}{\partial y} = -\frac{\partial p_1}{\partial z} + \left(\frac{\partial^2 w_1}{\partial y^2} + \frac{\partial^2 w_1}{\partial z^2}\right) - Mw_1, \tag{27}$$

$$v_1 \frac{\partial \theta_0}{\partial y} - S\frac{\partial \theta_1}{\partial y} = \frac{1}{Pr}\left(\frac{\partial^2 \theta_1}{\partial y^2} + \frac{\partial^2 \theta_1}{\partial z^2}\right) - F\theta_1. \tag{28}$$

The boundary conditions are

$$u_1 = 0, v_1 = -S\cos(\pi z), w_1 = 0, \theta_1 = 0 \quad \text{at} \quad y = 0,$$

$$u_1 = 0, v_1 = 0, w_1 = 0, \theta_1 = 0 \quad \text{at} \quad y \to \infty. \tag{29}$$

Equations (3.24)-(3.28) are the linear partial differential equations describing the three dimensional flow. Now we assume velocity components, pressure, and temperature in the following form

$$u_1(y,z) = u_{11}(y)\cos(\pi z), \;\; v_1(y,z) = v_{11}(y)\cos(\pi z),$$

$$w_1(y,z) = -\frac{1}{\pi} v_{11}'(y)\sin(\pi z), \quad p_1(y,z) = p_{11}(y)\cos(\pi z), \tag{30}$$
$$\theta_1(y,z) = \theta_{11}(y)\cos(\pi z),$$

Substituting (3.30)in (3.24)-(3.28), we obtain the following set of differential equations

$$v_{11}'' + Sv_{11}' - \pi^2 v_{11} = p_{11}', \tag{31}$$
$$v_{11}''' + Sv_{11}'' - (\pi^2 + M)v_{11}' = \pi^2 p_{11}, \tag{32}$$
$$\theta_{11}'' + SPr\theta_{11}' - (\pi^2 + FPr)\theta_{11} = -Pr\lambda_1 v_{11} e^{-\lambda_1 y}, \tag{33}$$
$$u_{11}'' + Su_{11}' - (\pi^2 + M)u_{11} = v_{11}u_0' - Gr\theta_{11}. \tag{34}$$

Using (3.30), boundary conditions (3.29) become

$$u_{11} = 0, v_{11} = -S, w_{11} = 0, \theta_{11} = 0 \quad \text{at} \quad y = 0,$$
$$u_{11} = 0, v_{11} = 0, w_{11} = 0, \theta_{11} = 0 \quad \text{at} \quad y \to \infty. \tag{35}$$

Solving (3.31)-(3.34), under the boundary conditions (3.35) and on using (3.30) we get

$$v_1(y,z) = \frac{S}{(\alpha-\beta)}\left[\beta e^{-\alpha y} - \alpha e^{-\beta y}\right]\cos\pi z, \tag{36}$$
$$w_1(y,z) = \frac{\alpha\beta S}{\pi(\alpha-\beta)}\left[e^{-\alpha y} - e^{-\beta y}\right]\sin\pi z, \tag{37}$$
$$p_1(y,z) = \frac{\alpha\beta S}{\pi^2(\alpha-\beta)}\left[\left\{\beta^2 - S\beta - \left(M+\pi^2\right)\right\}e^{-\beta y}\right.$$
$$\left. - \left\{\alpha^2 - S\alpha - \left(M+\pi^2\right)e^{-\alpha y}\right\}\right]\cos\pi z, \tag{38}$$
$$\theta_1(y,z) = \left[A_1\left(e^{-\lambda_4 y} - e^{-(\lambda_1+\alpha)y}\right) + A_2\left(e^{-\lambda_4 y} - e^{-(\lambda_1+\beta)y}\right)\right]\cos\pi z \tag{39}$$
$$u_1(y,z) = \left[A_{10}e^{-\lambda_5 y} + K\left(A_3 e^{-(\lambda_2+\alpha)y} + A_4 e^{-(\lambda_2+\beta)y} + A_5 e^{-(\lambda_1+\alpha)y}\right.\right.$$
$$\left.\left. + A_6 e^{-(\lambda_1+\beta)y}\right) - Gr\left(A_7 e^{-\lambda_4 y} + A_8 e^{-(\lambda_1+\alpha)y} + A_9 e^{-(\lambda_1+\beta)y}\right)\right]\cos\pi z \tag{40}$$

where

$$\lambda_3 = \frac{1}{2}\left[S - \sqrt{S^2 + 4M}\right], \qquad \lambda_4 = \frac{1}{2}\left[SPr + \sqrt{S^2Pr^2 + 4(\pi^2 + FPr)}\right],$$
$$\lambda_5 = \frac{1}{2}\left[S + \sqrt{S^2 + 4(\pi^2 + M)}\right], \qquad \alpha = \frac{1}{2}\left[\lambda_2 + \sqrt{\lambda_2^2 + 4\pi^2}\right],$$
$$\beta = \frac{1}{2}\left[\lambda_3 + \sqrt{\lambda_3^2 + 4\pi^2}\right], \qquad A_1 = \frac{SPr\lambda_1\beta}{\alpha(\alpha-\beta)(2\lambda_1 + \lambda_2 - SPr)},$$
$$A_2 = \frac{-SPr\lambda_1\alpha}{\beta(\alpha-\beta)(2\lambda_1 + \lambda_3 - SPr)}, \quad A_3 = \frac{-\lambda_2\beta}{\alpha(3\lambda_2 - S)},$$
$$A_4 = \frac{\lambda_2\alpha}{\beta(2\lambda_2 + \lambda_3 - S)}, \quad A_5 = \frac{\lambda_1\beta}{(\lambda_1+\alpha)^2 - S(\lambda_1+\alpha) - (\pi^2 + M)},$$

$$A_6 = \frac{-\lambda_1\alpha}{(\lambda_1+\beta)^2 - S(\lambda_1+\beta)-(\pi^2+M)}, A_7 = \frac{(A_1+A_2)}{\lambda_4^2 - S\lambda_4 - (\pi^2+M)},$$

$$A_8 = \frac{-A_1}{(\lambda_1+\alpha)^2 - S(\lambda_1+\alpha)-(\pi^2+M)}, A_9 = \frac{-A_2}{(\lambda_1+\beta)^2 - S(\lambda_1+\beta)-(\pi^2+M)},$$

$$A_{10} = -K[A_3+A_4+A_5+A_6]+Gr[A_7+A_8+A_9],\ K = \frac{SGr}{(\alpha-\beta)(\lambda_1^2 - S\lambda_1 - M)}. \quad (41)$$

**4 Results and discussion**

We have computed the numerical value of the velocity, temperature, shear stresses, and rate of heat transfer for different values of the non dimensional parameters and plotted in the diagram. The value of dimensionless parameter $Gr$ is taken positive and negative values. The positive value corresponds to an extremely cooled plate by the free convection currents and the negative value corresponds to the hotted plate. The value of Prandtl number is taken equal to $0.71$ and this value corresponds to the air. The values of Grashof numbers ($Gr$) are taken to be large from the physical point of view. The large Grashof number values correspond to free convection problem.The effect of magnetic parameter, radiation parameter and suction parameter on main flow velocity is shown in Figs.2-4.

The effect of magnetic parameter $M$ on the main flow velocity is shown in Fig.2. for cooling and heating plate. This figure shows that velocity decreases with the increase of the magnetic parameter for cooling of the plate and increases for heating of the plate.

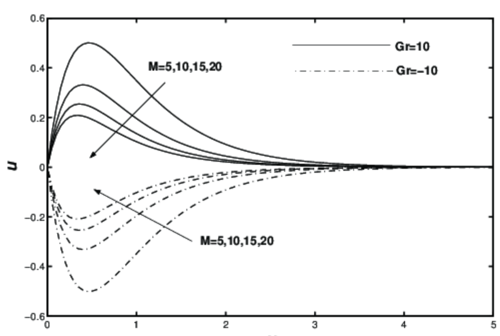


Fig.2: Variation of main flow velocity for $Pr = 0.71, F = 2.0, S = 1.0 \varepsilon = 0.05, z = 0.0.$

Fig.3. shows the effect of radiation parameter $F$ on the main flow velocity profile for both cooling and heating of the plate. From Fig.3 we see that for cooling of the plate velocity profile decreases whereas these profile increases with the increase of $F$ for heating of the plate.

Fig.4 shows the effects of suction parameter $S$ on the main flow velocity for cooling and heating of the plate. For a cooling plate fluid velocity decreases whereas for a heating plate it increases with increase in $S$.

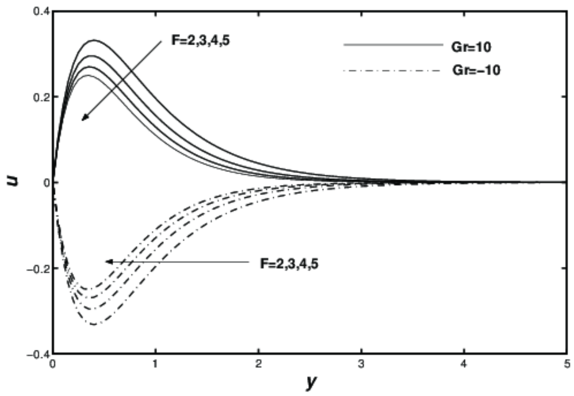


Fig.3:Variation of main flow velocity for $Pr = 0.71, M = 5.0, S = 1.0, \varepsilon = 0.05, z = 0.0.0.$

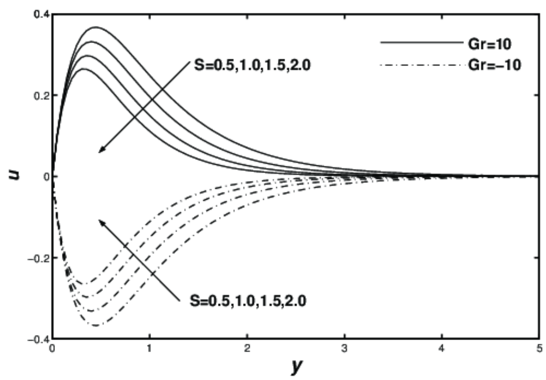


Fig.4:Variation of main flow velocity for $Pr = 0.71, F = 2.0, M = 5.0, \varepsilon = 0.05, z = 0.0.$

Fig.5 shows the effects of $F$ on the temperature profile. It is clear that temperature decreases more rapidly with the increase of $F$ . Therefore using radiation we can control the flow characteristic as well as temperature distribution. The cross flow velocity is same as Guria et al. [12]. This is due to fact that cross flow velocity is independent of radiation effect.

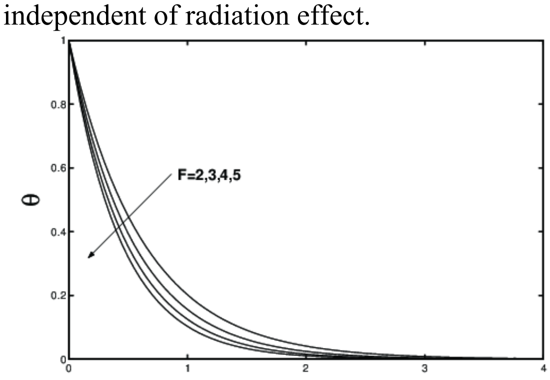


Fig.5: Variation of temperature profile for $Pr = 0.71, M = 5.0, S = 1.0, \varepsilon = 0.05, z = 0.0.$

The shear stress component due to main flow direction can be calculated as

$$\tau_x = u_0'(0) + \varepsilon u_1'(0),$$
$$= \frac{Gr(\lambda_1 - \lambda_2)}{(\lambda_1^2 - S\lambda_1 - M)} + \varepsilon[-A_{10}\lambda_5 - K[A_3(\lambda_2 + \alpha)$$
$$+ A_4(\lambda_2 + \beta)) + A_5(\lambda_1 + \alpha)) + A_6(\lambda_1 + \beta)]$$
$$+ Gr[A_7\lambda_4 + A_8(\lambda_1 + \alpha) + A_9(\lambda_1 + \beta)]]\cos \pi z. \quad (42)$$

**Table.1**

Shear stress component due to main flow for $Gr = 5.0$, $Pr = 0.71$, $S = 1.0$, $z = 0.2$.

| | $\tau_x$ | | | |
|---|---|---|---|---|
| $M$ | $F = 2.0$ | $F = 3.0$ | $F = 4.0$ | $F = 5.0$ |
| 5 | 1.49690068 | 1.38944519 | 1.30936277 | 1.24573088 |
| 10 | 1.17681360 | 1.10913873 | 1.05735397 | 1.01535368 |
| 15 | 1.00972211 | 0.95939857 | 0.92034388 | 0.88831282 |
| 20 | 0.90144366 | 0.86107111 | 0.82944739 | 0.80331767 |

The shear stress due to main flow are shown in Table.1. It is clear from Table.1 that the shear stress due to main flow decreases with increase in either radiation parameter or magnetic parameter.

The rate of heat transfer from the plate in terms of Nusselt number to the fluid can be calculated as

$$Nu = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} = \theta_0'(0) + \varepsilon\theta_1'(0),$$
$$= -\lambda_1 + \varepsilon\left[A_1(\lambda_1 + \alpha - \lambda_4) + A_2(\lambda_1 + \beta - \lambda_4)\right]\cos \pi z \quad (43)$$

**Table.2**

The rate of heat transfer due to main flow for $Gr = 5.0$, $S = 1.0$, $F = 2.0$, $\varepsilon = 0.2$, $z = 0.2$.

| | $Nu$ | | |
|---|---|---|---|
| $M$ | $Pr = 0.025$ | $Pr = 0.71$ | $Pr = 7.0$ |
| 5 | −0.23667052 | −1.63123524 | −9.45414162 |
| 10 | −0.23667265 | −1.63144767 | −9.45532703 |
| 15 | −0.23667456 | −1.63163674 | −9.45638561 |
| 20 | −0.23667628 | −1.63180685 | −9.45734119 |

The heat transfer coefficient in terms of Nusselt number is shown in Table.2 for several values of Prandtl number and magnetic parameter. The effect of magnetic parameter on Nusselt number is very small. It is seen that the heat transfer increases with increase in Prandtl number Pr. This is due to the fact that a fluid having larger Prandtl number possesses a larger heat capacity and hence enhances the heat transfer. Thus, the fluid with larger Prandtl numbers will perform more efficiently the cooling of the heated plate.

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