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Effects of Radiation and Magnetic field on Free Convection at a Vertical Plate Embedded in a Porous Medium with Variable Fluid Properties and Varying Plate Temperature

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Abstract— The similarity equations for free convection boundary layer flows over a vertically and varying plate temperature which is embedded in a porous medium with effects of magnetic field, radiation, variable viscosity and variable thermal conductivity are studied numerically. A similarity transformation is used to reduce partial differential equations governing the problem into ordinary differential equations and the equations are solved numerically subject to appropriate boundary conditions by the use of Runge-Kutta-Gill method together with shooting technique. The cases of hot and cold plate are considered and interesting features of solutions are presented in terms of table and graphs are presented and discussed.

Keywords— Free Convection, Magnetic field, Radiation, Varying wall, Darcy model.

I. INTRODUCTION

Free convection boundary-layer flows in porous media have important applications in fields such as geothermal energy extraction, oil reservoir modelling, analysis of insulating systems, food processing, casting and welding in manufacturing processes and the dispersion of chemical contaminants in different industrial processes in the environment. Books on Porous media by [8] and [12] stand evident to the fact that convective flows in porous media are of vital importance to these processes. Studies on the effect of magnetic field, variable physical properties and varying wall temperature embedded in a porous medium on free convection is discussed in [6] and reference [9] discussed the effects of variable fluid properties on free convection flows and heat transfer at an isothermal vertical plate embedded in a porous medium in the presence of magnetic field and radiation.

Studies of radiation effects on free convection flow are important in the context of space technology and also in processes involving high temperature. Investigations both theoretical and experimental have been conducted on flow and heat transfer through Porous media covering a broad range of fields. The effect of radiation on free convection flow of fluids with variable viscosity from a porous plate is discussed in [1]. The fluid considered in that paper is an optically dense viscous incompressible fluid of linearly varying temperature dependent viscosity. Reference [11] discussed radiative convective flow past a semi-infinite vertical plate. Reference [3] discussed radiation effect on mixed convection along a vertical plate with uniform surface temperature. Reference [10] discussed coupled heat and mass transfer in Darcy-Forchheimer Mixed convection from a vertical flat plate embedded in a fluid saturated porous medium under the effects of radiation and viscous dissipation. Mixed convection boundary layer flow on a vertical surface in a saturated porous medium is studied in [7]. In that paper the flow of a uniform stream past an impermeable vertical surface embedded in a saturated porous medium and which is supplying heat to the porous medium at a constant rate is considered.

The object of the present paper is to find the varying wall temperature, variable fluid properties and applied magnetic field, transfer of heat energy from the fluid due to radiation is also taken in to consideration. Rosseland approximation is used to describe radiative heat flux from the fluid and a numerical study is made of the effect of variable viscosity, variable thermal conductivity, varying wall temperature, radiation and magnetic field on convection flows at a vertical plate embedded in a porous medium.

Based on variations of viscosity (μ) and thermal conductivity (k_m) with temperature, fluids can be classified into four categories for which (i) both μ and k_m increase with increase in temperature- Type-I, (ii) both μ and k_m decrease with increase in temperature- Type-II, (iii) μ increases while k_m decreases with increase in temperature- Type-III and (iv) μ decreases while k_m increases with increase in temperature- Type-IV. Examples of fluids and appropriate ranges of temperature in which those fluids fall under the above categories are- Type-I: air (between 100^0 C and 800^0 C), steam (between 100^0 C and 1000^0 C) , Nitrogen (between 0^0 C and 1000^0 C); Type-II: saturated water (between 100^0 C and 200^0 C), unused engine oil (between 0^0 C and 160^0 C), Transformer oil (between -$50^0$$C$ and -40^0

C): Type-III: Methyl Chloride (between -50^0C and 50^0C); Type-IV: Dichloro- Difluro Methane (between -50^0C and 20^0C) is observed in [4] & [5]. As such this data helps in interpreting the results of analysis as applicable to certain fluids in specific ranges of temperatures. In the present work authors made their attention towards two categories Type-III and Type- IV as in [9].

II. FORMULATION AND SOLUTION

The physical model and coordinate system for free convection is presented in the Fig.1. Let a varying wall be embedded vertically in a saturated porous medium with viscous incompressible homogeneous quiescent fluid. The porous medium is assumed to be homogeneous and is in thermal equilibrium with the surrounding fluid. Let a magnetic field of uniform strength is assumed to be acting a direction normal to the plate. The fluid is assumed to be a gray medium that emits and absorbs but do not scatter thermal radiation. It is also assumed that radiation from the fluid is only taken into consideration which is present in the form of a unidirectional flux, transverse to the vertical plate. Let *X*-axis be taken along the plate and *Y*-axis perpendicular to it and $T_0 = T_\infty + Ax^\lambda$ is assumed as the temperature of the plate

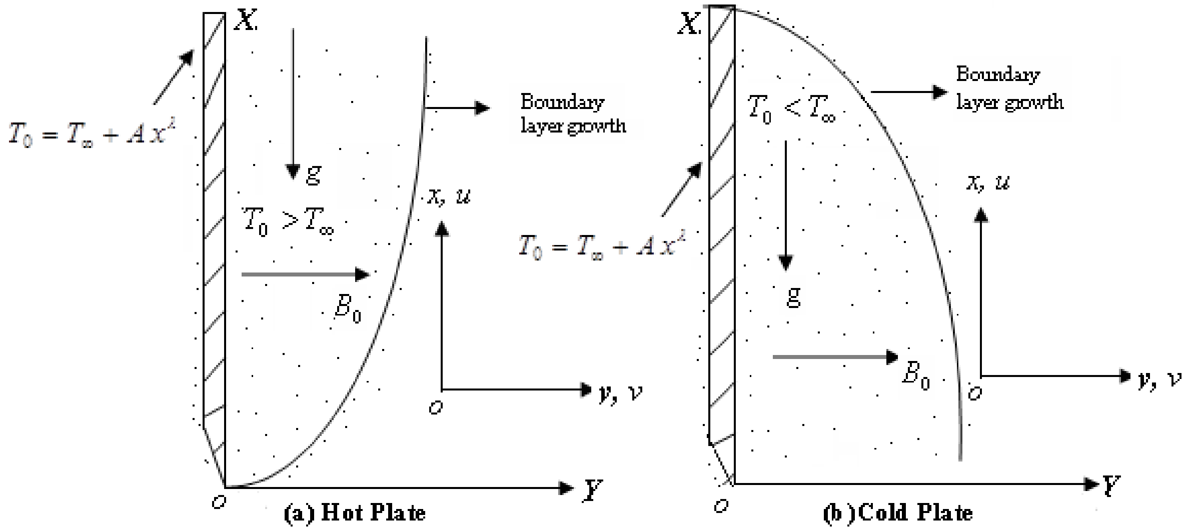

Fig .1 Physical model and coordinate system For Free convection

The equations governing free convection boundary- layer flow are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (1)$$

$$\frac{\partial p}{\partial x} + (\rho - \rho_\infty)g + \sigma B_0^2 u + \frac{\mu}{K}u = 0 \qquad (2)$$

$$\frac{\partial p}{\partial y} + \frac{\mu}{K}v = 0 \qquad (3)$$

$$\rho c_p \left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} \right) = \frac{\partial}{\partial y}\left(k_m \frac{\partial T}{\partial y} \right) - \frac{\partial q_r}{\partial y} \qquad (4)$$

where u, v are fluid velocity components, *T* is fluid temperature, K is Permeability, k_m is effective thermal conductivity of the porous medium, B_0 is the magnetic flux, σ is the electric conductivity, q_r is radiative heat flux. The Rosseland approximation is used in the energy equation to describe the thermal radiative heat transfer.

In fact the radiative heat flux q_r is given by $q_r = -\frac{4\sigma_s}{3k_e}\frac{\partial T^4}{\partial y}$, where σ_s the Stefan-Boltzmann is's constant and k_e is the mean absorption coefficient. Assuming temperature differences within the flow to be sufficiently small, the term $\frac{\partial q_r}{\partial y}$ of equation (4) is simplified by expanding T^4 into the Taylor series about T_∞, and neglecting higher order terms. It may be noted that because of the use of Rosseland approximation, the present analysis gets limited to optically thick fluids.

Taking $\rho = \rho_\infty[1-\beta(T-T_\infty)]$ in the body force term, introducing a stream function ψ and eliminating fluid pressure from equations (2) and (3), the governing equations are obtained as

$$\left(\mu + K\,\sigma\,B_0^2\right)\left(\frac{\partial^2\psi}{\partial y^2}\right)+\left(\frac{\partial\psi}{\partial y}\right)\left(\frac{\partial\mu}{\partial y}\right)=K\,g\,\rho_\infty\,\beta\left(\frac{\partial T}{\partial y}\right) \quad (5)$$

$$\frac{\partial\psi}{\partial y}\frac{\partial T}{\partial x}-\frac{\partial\psi}{\partial x}\frac{\partial T}{\partial y}=\frac{1}{\rho c_p}\left(k_m\frac{\partial^2 T}{\partial y^2}+\frac{\partial k_m}{\partial y}\frac{\partial T}{\partial y}\right)+\frac{16\sigma_s T_\infty^3}{3\rho c_p k_e}\frac{\partial^2 T}{\partial y^2} \quad (6)$$

The boundary conditions on T and ψ are

$$\left.\begin{array}{l} at\ \ y=0,\ T_0=T_\infty+Ax^\lambda,\ \dfrac{\partial\psi}{\partial x}=0, \\ as\ \ y\to\infty,\ T\to T_\infty,\ \dfrac{\partial\psi}{\partial y}\to 0 \end{array}\right\} \quad (7)$$

Introducing ***Rayleigh*** number (Ra_x), ***Hartman*** number (M^2), a magnetic interaction parameter ***C,*** Radiation parameter ***Rd*** and the non dimensional functions $f,\ \theta$ together with a similarity variable η through the relations

$$\left.\begin{array}{l} Ra_x=\dfrac{\rho_\infty K\,g\beta|T_0-T_\infty|\,x}{\alpha_m\mu_f} \\ M^2=\dfrac{B_0^2L^2\sigma}{\mu_f} \\ K^*=\dfrac{L^2}{K} \\ C=\dfrac{K^*}{K^*+M^2} \\ F=\dfrac{k_f\,k_c}{4\sigma_1 T_\infty^3} \\ T_0=T_\infty+Ax^\lambda \\ f(\eta)=\dfrac{\psi}{\alpha Ra_x^{\frac{1}{2}}} \\ \theta(\eta)=\dfrac{T-T_\infty}{T_0-T_\infty} \\ \eta=\dfrac{y}{x}Ra_x^{\frac{1}{2}} \end{array}\right\} \quad (8)$$

Equations (5), (6) are rewritten as

$$\left[1+C\gamma_\mu\left(\theta-\frac{1}{2}\right)\right]f''+C\gamma_\mu\,f'\theta'=C\theta' \quad (9)$$

$$\left[1+\gamma_k\left(\theta-\frac{1}{2}\right)+\frac{4(Rd)}{3}\right]\theta''-\lambda\,f'\theta+\frac{(\lambda+1)}{2}f\,\theta'+\gamma_k\theta'^2=0 \quad (10)$$

Here $C=\dfrac{K^*}{K^*+M^2}$ is the ***magnetic field parameter***, $M^2=\dfrac{B_0^2\,L^2\,\sigma}{\mu_f}$ & $K^*=\dfrac{L^2}{K}$, $Rd=\dfrac{4\sigma_s T_\infty^3}{k\,k_e}$ is the radiation parameter, $Ra_x=\dfrac{\rho_\infty K\,g\,\beta(T_0-T_\infty)x}{\mu_f\,\alpha}$ is the *Rayleigh* number,

$\mu=\mu_f\left[1+\gamma_\mu\left(\theta-\frac{1}{2}\right)\right]$ and $k_m=k_f\left[1+\gamma_k\left(\theta-\frac{1}{2}\right)\right]$(by [2]&[4]).

The boundary conditions (7) become

$$\left.\begin{array}{l} at \quad \eta = 0, \quad \theta = 1, \quad f = 0, \\ as \ \eta \to \infty, \ \theta \to 0, \ f' \to 0 \end{array}\right\} \tag{11}$$

Equation (9) can be integrated once using the condition on f' at infinity to get

$$f' = \frac{C\theta}{\left[C\gamma_{\mu}\left(\theta - \frac{1}{2}\right) + 1\right]} \tag{12}$$

Evaluating this expression at $\eta = 0$ which gives the slip velocity $f'(0)$ as

$$f'(0) = \frac{2C}{C\gamma_{\mu} + 2} \tag{13}$$

III. SOLUTION OF THE PROBLEM

A.**PARAMETERS OF THE PROBLEM-** In the free convection case, the flow and heat transfer depend on the parameters $C, \gamma_{\mu}, \gamma_k$, *Rd* and λ where *C* is magnetic field parameter, γ_{μ} is viscosity variation coefficient, γ_k is thermal conductivity variation coefficient , *Rd* is the radiation parameter and λ is power of index of the plate temperature and the constant *A* appearing in the expression for the temperature of the plate .

The parameter *C* takes smaller values (less than unity) when either the porous parameter takes smaller values or the Hartmann number takes larger values, that is, when porosity of the medium is high or the intensity of the medium is high or the intensity of magnetic field is high. When there is no applied magnetic field M^2 takes zero value as a result *C* takes value of unity. Solutions are found for the values 0.1, 0.5 and 1 of *C*. As the magnetic field lines obstruct the flow due to Lorentz force it can be expected for smaller values of *C* or increase intensity of the magnetic field.

The parameter γ_{μ} and γ_k takes positive as well as negative values, the limiting values being '-2' and '+2'. Zero value of γ_{μ} and γ_k corresponds to variation of constant viscosity and constant thermal conductivity. In this paper solutions are found for the values of -1, 0, 0.5 and 1 of both γ_{μ} and γ_k. In this paper, VFP is used as an abbreviation for variable fluid properties ($\gamma_{\mu} = \gamma_k = -1, 0.5 \,\&1$) and CFP as an abbreviation for constant fluid properties ($\gamma_{\mu} = \gamma_k = 0$).

In the present work the attention is made for $T_0 > T_{\infty}$ (Hot Plate), fluids like (Dichloro Fluro Methane) $\gamma_{\mu} < 0, \gamma_k > 0$ and for $T_0 < T_{\infty}$ (Cold Plate) fluids like (Methyl Chloride) $\gamma_{\mu} > 0, \gamma_k < 0$. (By [9]).

Zero value for the parameter *Rd* corresponds to the case when transfer of heat energy through radiation from the fluid is neglected. Positive numerical values of *Rd* correspond to intensity of thermal radiation from the fluid. Solutions are found for the values 0, 0.5, 1 of the parameter *Rd.* Thermal radiation causes thickening of the thermal boundary layer and hence increasing values of the parameter *Rd* can increase thermal boundary layer thickness.

To determine certain important values for λ, the total heat convected in the flow, $Q(x)$ at any downstream location *x* is considered.

$$Q(x) = \int_0^{\infty} \rho C_p \, \beta (T - T_{\infty}) u \, dy \propto x^{\frac{3\lambda+1}{2}} \qquad \text{(By [6])} \tag{14}$$

$Q(x)$ should vary linearly with *x* and so $\lambda = \frac{1}{3}$, for an adiabatic surface, $Q(x)$ should independent of *x* and so $\lambda = -\frac{1}{3}$. Zero value of λ corresponds to isothermal case. In the present study solutions are found for the values -0.3, 0 and 0.5 of λ. For positive values of constant *A*, an increase in the temperature of the plate in expansively, it can result an enhance flow.

NUMERICAL SOLUTION- The equations for *f* and θ are integrated numerically subject to appropriate boundary conditions by **Runge-Kutta-Gill** method with a **Shooting technique** using **FORTRAN code**. The accuracy of the method is tested by comparing appropriate results of the present analysis with available results. Results of present work for *C* =*1*, *Rd* = 0, $\gamma_\mu = 0$ $\gamma_k = 0$ (i.e., no magnetic field, no radiation, constant viscosity, constant thermal conductivity) are in very good agreement with those in [3]. Results of the present authors work for *C* = 0.5, 0.1, *Rd* = 0, $\gamma_\mu = 0,-1,1$, $\gamma_k = 0,-1,1$ and $\lambda = 0$ (i.e., magnetic field, no radiation, constant viscosity, constant thermal conductivity and isothermal plate) agreed very well with those of [3]. Also the results of present work for *C*=1, 0.5, 0.1, *Rd* = 0, 0.5 & 10, $\gamma_\mu = 0,-1,1$, $\gamma_k = 0,-1,1$ & $\lambda = 0$ (i.e., with and without magnetic effect, with and without radiation effect, CFP and VFP, isothermal plate) well agreed with [9].

IV. DISCUSSION OF THE RESULTS

. Variations in skin friction with different parameters are presented in figures-2 to 5. From these figures, skin friction $f''(0)$ can be observed to take negative values, for all values of the parameter under consideration indicating that the drag coefficient is negative for all values of the parameters. From figure-2 it can be observed that for *C*=1 (no magnetic effect), $\gamma_\mu = 0$ (no variation of viscosity) absolute values of $f''(0)$ can be observed to be larger for negative values of γ_k than for positive values of γ_k. As λ increases from -0.3 to 0.5 an absolute value of $f''(0)$ increases. It can also be observed that absolute value of $f''(0)$ decreases as the radiation parameter increases from 0 to 0.5. Absolute value of the skin friction can be observed to be more in the varying wall temperature case and in the absence of radiation.

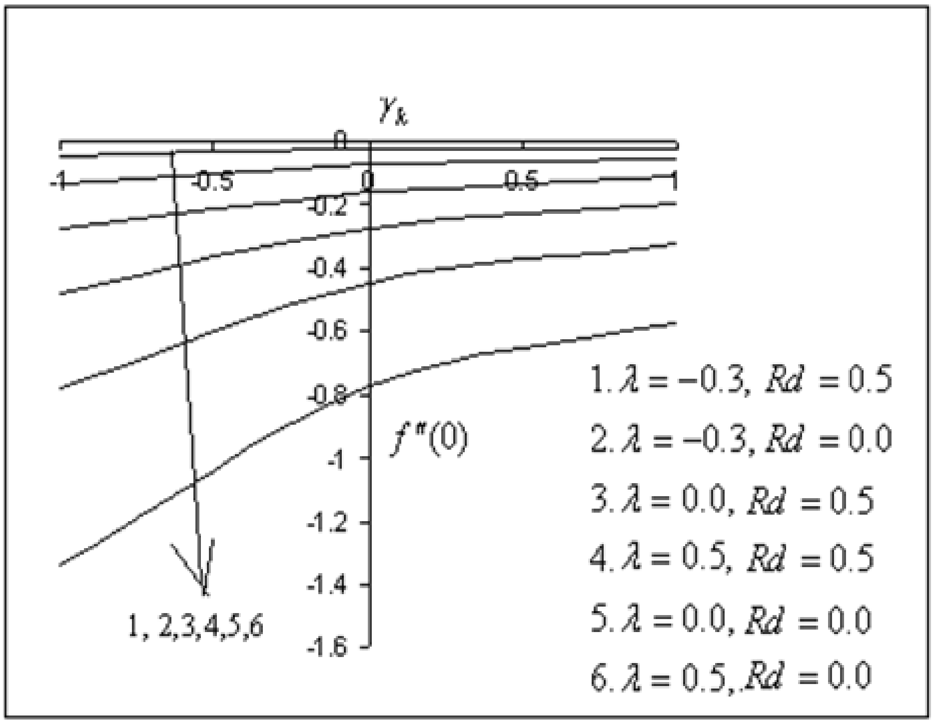

Fig. 2 Variations of $f''(0)$ with γ_k for $\gamma_\mu = 0$ & $C = 1.0$

From figure-3, it may be noted that with increasing values of the parameter λ, absolute value of skin friction increases. Similar is the behaviour when *C* changes from 0.5 to 1 or *Rd* changes from 0.5 to 0. It means that the absolute values are larger in the absence of magnetic field than in its presence. Also, the absolute values are larger in the absence of radiation than in its presence. By comparing figures- 3and 4, we may observe that variations in skin friction for fluids like Dichloro Difluro methane are similar to those of fluids like methyl chloride except that in the former case, certain numerical values are relatively larger than those in the latter case.

Variation of skin friction for, $C = 0.5, \lambda = 0.5$ and $\gamma_k = 0$ with various values of γ_μ is shown in figure-5. It may be observed that variations with γ_μ are similar to variations with γ_k (compare figures-2 and figure-5). Also, even in the presence of magnetic field, varying wall temperature and constant thermal conductivity, variations with the parameter *C* and *Rd* are similar to those observed earlier Variation of skin friction with γ_μ for $C = 0.5, \lambda = 0.5$ and $\gamma_k = 0$ γ_μ are shown in figure-5. It may be observed that variations with γ_μ are similar to those observed earlier. The absolute value of skin friction increases as λ increases.

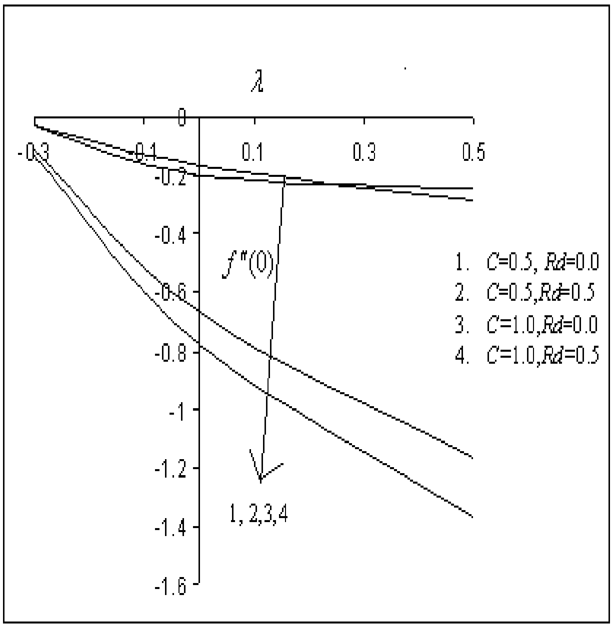

Fig. 3 Variations of $f''(0)$ with λ for $\gamma_\mu = -1, \gamma_k = 1$

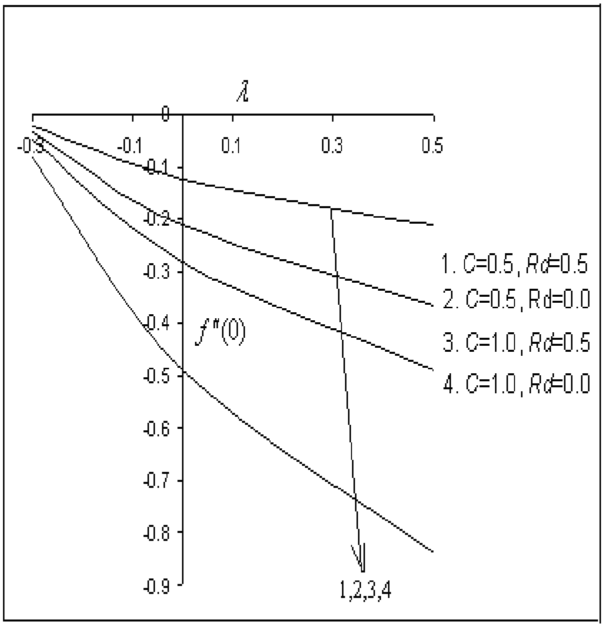

Fig.4 Variations of $f''(0)$ with λ for $\gamma_\mu = 1, \gamma_k = -1$

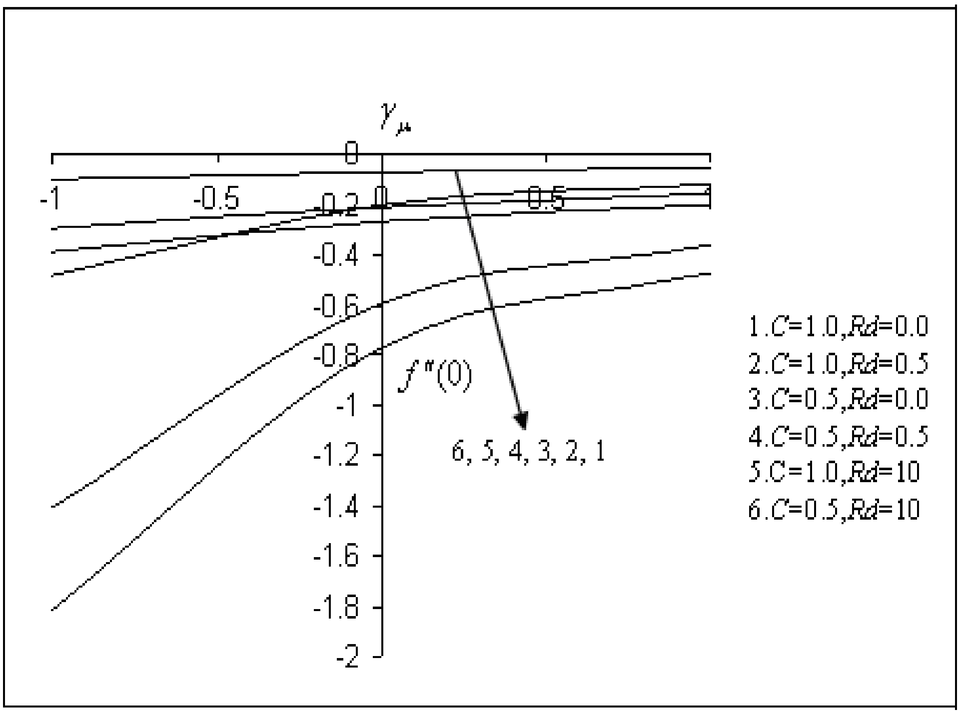

Fig. 5 Variations of $f''(0)$ with γ_μ for $\gamma_k = 0, C = 0.5 \& \lambda = 0.5$

Variations in heat transfer coefficient $(-\theta'(0))$ are presented figures-6 to 8. From figure-6 and figure-7, the heat transfer coefficient can be seen to increase as λ changes from -0.3 to 0.5. The heat transfer coefficient can be seen to assume relatively larger values when *C*=1 and *Rd*=0 (i.e., in the absence of magnetic field and absence of radiation) as compared to those when *C*=0.5and *Rd*=0.5. (i.e., presence of magnetic field as well as the presence of radiation). By comparison of the figures it can be observed that '$-\theta'(0)$' assumes relatively larger values for fluids like Methyl chloride than for fluids like Dichloro Difluro methane. From figure-8, when $\gamma_k = 0,$ the heat transfer coefficient can be seen to take larger values when $\gamma_\mu = -1$ and diminish as γ_μ changes from -1 to +1.

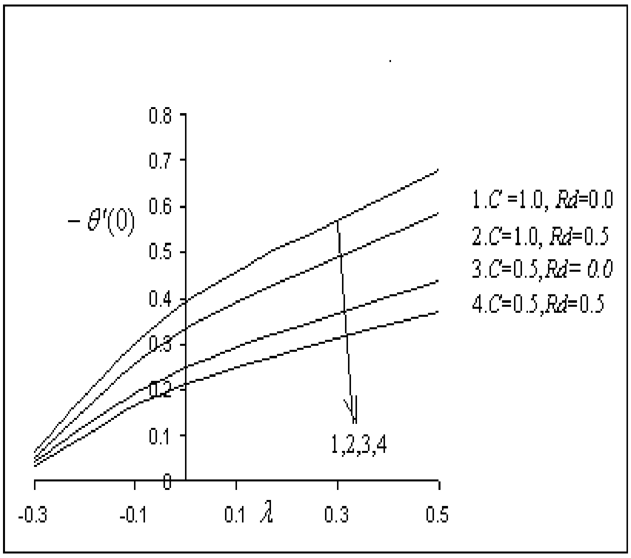

Fig. 6 Variations of '$-\theta'(0)$' **with** λ **for** $\gamma_\mu = -1$ & $\gamma_k = 1$

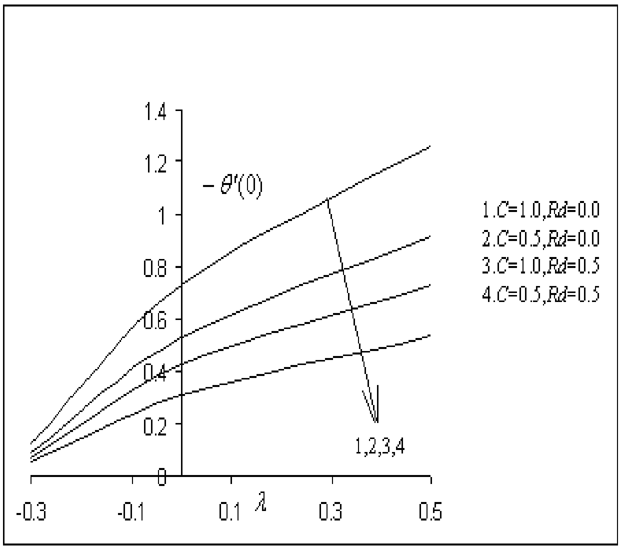

Fig. 7 Variations of '$-\theta'(0)$' **with** λ **for** $\gamma_\mu = 1, \gamma_k = -1$

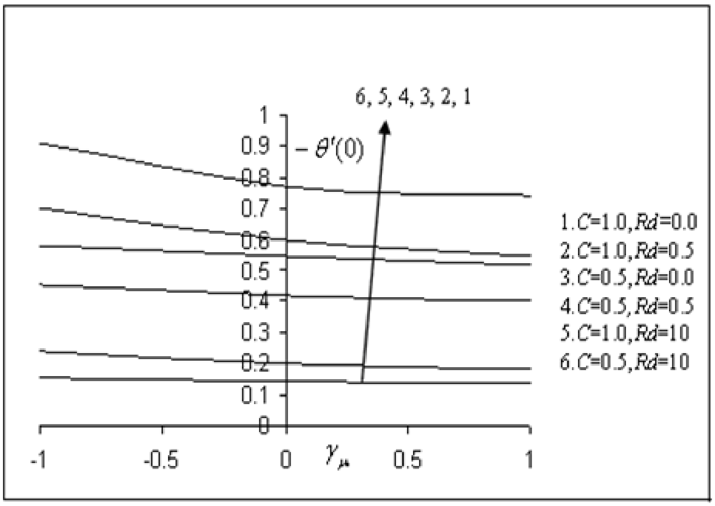

Fig. 8 Variations of '$-\theta'(0)$' **with** γ_μ **for** $\gamma_k = 0$ & $\lambda = 0.5$

Variations in shear stress with different parameters are shown in figure-9. Shear stress is observed to be negative for all values of the parameters. Shear stress assumes a non-zero value at the plate, increase or decrease up to some distance near the plate and later approach the zero value far away from the plate.

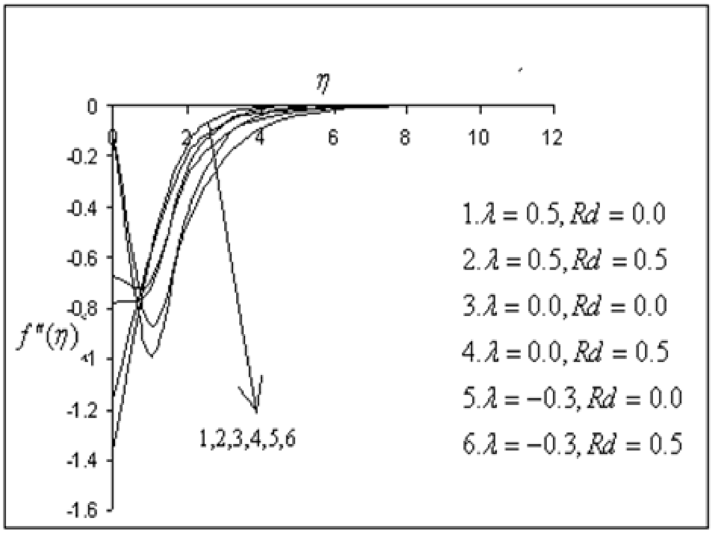

Fig. 9 Variations of $f''(\eta)$ **with** η **for** $C = 1.0, \gamma_\mu = -1$ & $\gamma_k = 1$

Some typical fluid velocity profiles (plots of $f'(\eta)$) are presented in figure-10 and some selected temperature profiles are presented in the figures-11. Fluid velocity starts with a non-zero value at the plate, diminish and approach zero far away from the plate. The velocity decreases with an increase of magnetic effect i.e., *C* changes from 1 to 0.5. From numerical results hydrodynamic boundary layer thickness is observed to be more in the presence of magnetic field and in the presence of radiation. Boundary layer thickness is considerably less in the absence of magnetic field (*C*=1), in the absence of radiation (*Rd*=0) and also for small values of *Rd*. From the temperature profile figure-11 thermal boundary layer thickness can be observed to be more for large radiative flux (*Rd*=10) in the presence of magnetic field (*C*=0.5). Like the hydrodynamic boundary layer thickness, thermal boundary layer thickness is also less in the absence of magnetic field (*C*=1) or in the absence of radiation (*Rd*=0) or for small values of *Rd*.

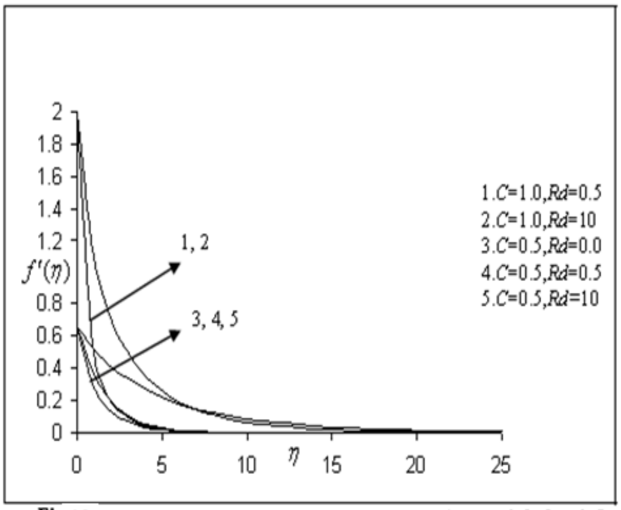

Fig.10 Variations of $f'(\eta)$ **with** η **for** $\gamma_\mu = -1, \gamma_k = 0 \,\&\, \lambda = 0.5$

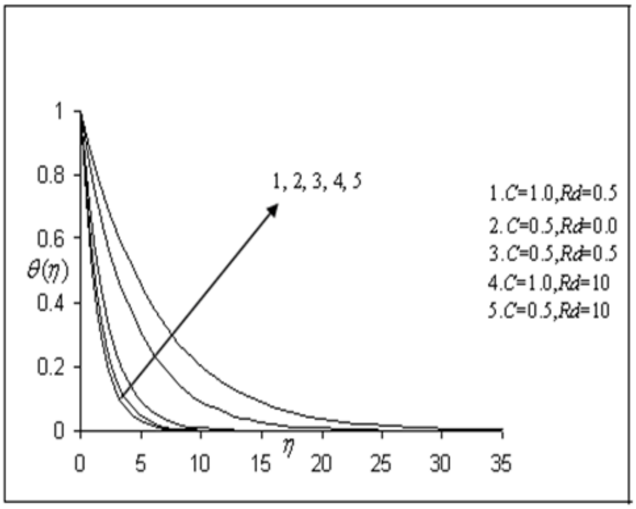

Fig.11 Variations of $\theta(\eta)$ **with** η **for** $\gamma_\mu = -1, \gamma_k = 0 \,\&\, \lambda = 0.5$

Plots of stream function are presented figure-12. Stream function can be observed to assume larger numerical values for enhanced radiative flux (*Rd*=10) in the absence of magnetic field (*C*=1). Stream function takes relatively smaller values in the presence of magnetic field (*C*=0.5) and also for diminishing effect of radiation (*Rd*=0 or *Rd*=0.5).

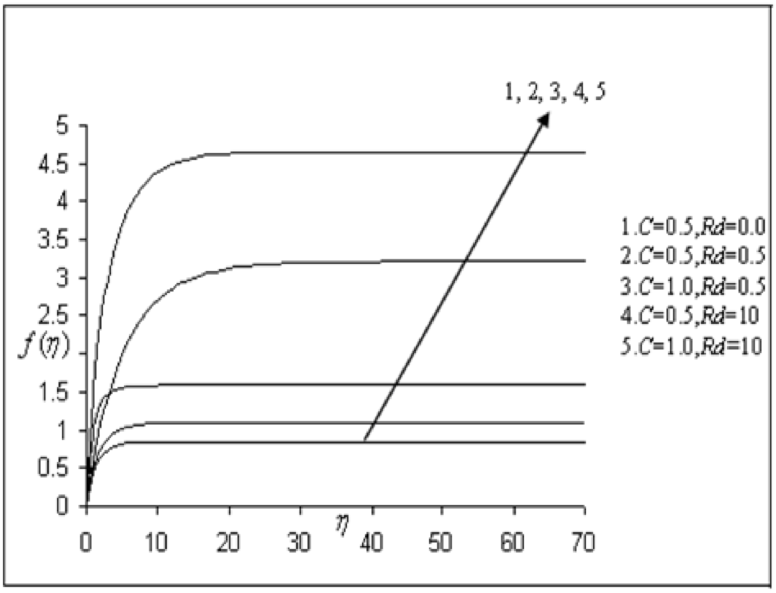

Fig.12 Variations of $f(\eta)$ **with** η **for** $\gamma_\mu = -1, \gamma_k = 0 \,\&\, \lambda = 0.5$

From Table1 it can be seen that thermal boundary layer thickness (δ_t) and hydrodynamic boundary layer thickness (δ_v) are presented for different effects. It can be seen that both the thicknesses are same. Boundary layer thickness for cold plate ($\gamma_\mu > 0, \gamma_k < 0$) is more than for the hot plate ($\gamma_\mu < 0, \gamma_k > 0$). As radiation and magnetic effect increases boundary thickness also increases and also it can be seen as λ value increases from -0.3 to 0.5 boundary layer thickness decreases.

Table.1

Variations of Thermal boundary layer thickness (δ_t) & Hydrodynamic boundary layer thickness (δ_v)

C	λ	Rd	γ_μ	γ_k	δ_t	δ_v
1	0.5	0.5	-1	1	17	17
1	0.5	0.5	0	0	25	25
1	0.5	0.5	1	-1	28	28
1	-0.3	0.5	-1	1	20	20
1	0.5	0	-1	1	10	10
0.5	-0.3	0	-1	1	18	18
0.5	0	0.5	-1	1	29	29
0.5	0.5	0.5	-1	1	25	25
0.5	0.5	0.5	1	-1	40	40
0.5	-0.3	0.5	-1	1	30	30
0.5	-0.3	0.5	1	-1	48	48
0.1	0	10	-1	1	242	242
0.1	0	100	-1	1	693	693

V. CONCLUSIONS

The conclusions of the above study are as follows:

1. The heat transfer coefficient $(-\theta'(0))$ increases as λ increases from -0.3 to 0.5. An increase in temperature of the plate it can be seen an enhanced flow.
2. Heat transfer coefficient $(-\theta'(0))$ takes larger values with diminishing values of *C* (intensity of the magnetic field increases) and also the radiation parameter (***Rd*** **)** takes diminishing values (the intensity of the radiation decreases). (Also seen in [9]).
3. The velocity $(f'(\eta))$ decreases with an increasing the magnetic intensity
4. Heat transfer coefficient is relatively larger values for fluid like Methyl Chloride (for $\gamma_\mu > 0,\ \gamma_k < 0$) (cold plate) than for fluid like Dichloro Fluro Methane (for $\gamma_\mu < 0,\ \gamma_k > 0$) (hot plate). (Also seen in [9]).
5. Hydrodynamic boundary layer as well as thermal boundary layer increases with increasing intensity of radiation (***Rd)*** as well as the increasing intensity of the magnetic field (*C*), boundary layer thickness increases.
6. Thermal boundary layer thickness is also seen increase for fluid like Methyl Chloride (for $\gamma_\mu > 0,\ \gamma_k < 0$) (cold plate) than for fluid like Dichloro Fluro Methane (for $\gamma_\mu < 0,\ \gamma_k > 0$) (hot plate). (Also seen in [9]).
7. The Absolute value of the skin friction increases as λ increases.
8. The absolute value of the skin friction $(f''(0))$ increases with diminishing intensity of the magnetic field and with diminishing effect of radiation.
9. The absolute value of the skin friction $(f''(0))$larger for fluid like Dichloro Fluro Methane (for $\gamma_\mu < 0,\ \gamma_k > 0$) (hot plate) than for fluid like Methyl Chloride (for $\gamma_\mu > 0,\ \gamma_k < 0$) (cold plate).
10. Stream function $f(\eta)$ can be observed larger numerical values for enhanced radiative flux and absence of magnetic field

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