EFFECT OF RADIATION ON UNSTEADY FREE CONVECTION FLOW BOUNDED BY AN OSCILLATING PLATE WITH VARIABLE WALL TEMPERATURE

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The object of the paper is to study the radiation effects on an unsteady free convective flow through a porous medium bounded by an oscillating plate with a variable wall temperature. The momentum and energy boundary layer equations have been solved by taking series expansions of velocity and temperature function in powers of product of magnetic field and time. The analytical solution of resulting ordinary differential equations has been obtained in terms of repeated integrals of complementary error functions. Also, the velocity and temperature profiles, for different values of the parameters, have been drawn and discussed.

Key words: free convection; porous medium; boundary layer flow; radiation; skin friction coefficient; oscillating plate.

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1. Introduction

In recent years, free convection flow of viscous fluids through porous medium have attracted the attention of a number of authors in view of its application to geophysics, astrophysics, meteorology, aerodynamics, boundary layer control and so on. In addition, convective flow through a porous medium has application in the field of chemical engineering for filtration and purification processes. In petroleum technology, to study the movement of natural gas oil and water through oil channels/reservoirs and in the field of agriculture engineering to study the underground resources, the channel flows through porous medium have numerous engineering and geophysical applications. Effects of free convection currents on the flow were studied. However, these studies are confined to normal temperatures of the surrounding medium. If the temperature of the surrounding fluid is rather high, radiation effects play an important role and this situation does exist in space technology. In such cases, one has to take into account the effects of radiation and free convection.

The unsteady free convection flow past an impulsively started infinite plate in the presence of transverse magnetic field fixed relative to the fluid has been studied by Dave *et al*. (1990) and Tak and Pathak (2002). The unsteady two-dimensional flow of a viscous fluid through a porous medium bounded by an infinite porous plate with constant suction and variable temperature was studied by Raptis (1983). The same problem is already studied by Raptis and Perdikis (1985) when the temperature of the porous plate oscillates in time about a constant mean. Sharma (1992) and Acharya *et al*. (2000) have analysed free convection and mass transfer in a steady flow through a porous medium with constant suction in the presence of magnetic field. A mixed convection flow past an oscillating vertical plate has been studied by Soundalgekar (1977) and Vighnesam *et al*. (2001). When the temperature of the plate is high, the radiation

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effects are not negligible. Takhar *et al*. (1996) considered the effect of radiation on the free convective flow along a semi infinite vertical plate in the presence of transverse magnetic field. Recently, taking an impulsively started infinite vertical plate, Tak and Maharshi (2001) and Ganesan *et al*. (2001) have studied radiation effects in the free convection flow.

The purpose of this paper is to study the effects of radiation on the free convective flow through a porous medium bounded by an oscillating plate with a variable wall temperature. The solutions of governing equations have been obtained in terms of *repeated integrals of complementary error functions.*

2. Mathematical formulation and analysis

Consider the free convective flow of an incompressible viscous radiating fluid, through a porous medium bounded by an infinite vertical plate with a variable wall temperature. At time $t^* \le 0$, the temperature at the plate and the fluid is assumed to be T_∞^*. For $t^* > 0$, the plate starts oscillating in its own plane at a constant velocity u_0^* with frequency ω^* and the heat is supplied to the oscillating plate such that its temperature is increasing linearly with time. The transverse magnetic field is fixed relative to the fluid. The x^* axis is taken along the vertical plate in upward direction and the y^* axis normal to it. Then, under the usual Bousinesq's approximations, the flow of a radiative fluid can be governed by the following system of equations

$$\frac{\partial v^*}{\partial y^*} = 0 \qquad \Rightarrow \qquad v^* = v_w^*\left(t^*\right), \tag{2.1}$$

$$\frac{\partial u^*}{\partial t^*} + v^* \frac{\partial u^*}{\partial y^*} = \upsilon \frac{\partial^2 u^*}{\partial y^{*2}} + g\beta\left(T^* - T_\infty^*\right) - \frac{\upsilon}{K^*}u^* - \frac{\sigma B_0^2}{\rho}u^*, \tag{2.2}$$

and

$$\frac{\partial T^*}{\partial t^*} + v^* \frac{\partial T^*}{\partial y^*} = \frac{\kappa}{\rho c_P}\frac{\partial^2 T^*}{\partial y^{*2}} - \frac{1}{\rho c_P}\frac{\partial q_r^*}{\partial y^*}. \tag{2.3}$$

Where u^* and v^* are components of velocity along the x^* and y^* directions, g is the acceleration due to gravity, β is the coefficient of volume expansion, T^* – the temperature, υ is the kinematic viscosity, ρ – the density, k– the thermal conductivity, c_p – the specific heat at constant pressure, σ – the electrical conductivity, B_0 is the magnetic field, K^* and q_r^* are permeability and heat flux respectively.

The radiative heat flux q_r^* is given by Cogley *et al.* (1968)

$$\frac{\partial q_r^*}{\partial y^*} = 4\left(T^* - T_\infty^*\right)I^* \tag{2.4}$$

where $I^* = \int_0^\infty K_{\lambda w} \cdot \frac{\partial e_{b\lambda}}{\partial T^*} d\lambda$, $K_{\lambda w}$ is the absorption coefficient at the wall and $e_{b\lambda}$ is the plank function.

The boundary conditions are

$$\left.\begin{array}{lll} t^* \le 0 : u^* = 0, & T^* = T^*_\infty, & \forall y^* \\ t^* > 0 : u^* = u^*_0 \cos\omega t^*, & T^* = T^*_\infty + T^*_w t^* & \text{at} \quad y^* = 0 \\ u^* = 0, \quad T^* = T^*_\infty & \text{as} & y^* \to \infty \end{array}\right\} \tag{2.5}$$

Introducing the following non-dimensional quantities

$$y = \frac{y^* u^*_0}{\upsilon}, \quad t = \frac{t^* u^{*2}_0}{\upsilon}, \quad u = \frac{u^*}{u^*_0}, \quad v = \frac{v^*}{u^*_0}, \quad v_w = \frac{v^*_w}{u^*_0}, \quad \theta = \frac{\upsilon g \beta \left(T^* - T^*_\infty\right)}{u^{*3}_0},$$

$$\text{Gr} = \frac{\upsilon^2 g \beta T^*_w}{u^{*5}_0} \ (\text{Grashof number}), \quad m = \frac{\sigma B^2_0 \upsilon}{\rho u^{*2}_0} \ (\text{magnetic parameter}),$$

$$\text{Pr} = \frac{\mu c_p}{\kappa} \ (\text{Prandtl number}), \quad K_0 = \frac{u^{*2}_0 K^*}{\upsilon^2} \ (\text{permeability parameter}),$$

$$F = \frac{4 \upsilon I^*}{\rho c_P u^{*2}_0} \ (\text{radiation parameter}), \quad \omega = \frac{\omega^* \upsilon}{u^{*2}_0}$$

and then applying the following transformations

$$\left.\begin{array}{ll} u(y,t) = \sum\limits_{i=0}^{\infty} (mt)^i f_i(\eta), & \eta = \dfrac{y}{2\sqrt{t}}, \\ \theta(y,t) = \sum\limits_{i=0}^{\infty} (mt)^i \theta_i(\eta), & v_w(t) = -\dfrac{a}{\sqrt{t}} \end{array}\right\} \tag{2.6}$$

Equations (2.2) and (2.3) in view of Eqs (2.4) and (2.5), reduce to the following set of ordinary differential equations

$$f''_0 + 2(a+\eta) f'_0 = 0, \tag{2.7}$$

$$\text{Pr}^{-1} \theta''_0 + 2(a+\eta)\theta'_0 = 0, \tag{2.8}$$

$$f''_1 + 2(a+\eta) f'_1 - 4 f_1 + \frac{4}{m}\theta_0 - 4\left(1 + \frac{1}{mK_0}\right) f_0 = 0, \tag{2.9}$$

$$\text{Pr}^{-1} \theta''_1 + 2(a+\eta)\theta'_1 - 4\theta_1 - \frac{4F}{m}\theta_0 = 0, \tag{2.10}$$

$$f_i'' + 2(a+\eta) f_i' - 4if_i + \frac{4}{m}\theta_{i-1} - 4\left(1+\frac{1}{mK_0}\right)f_{i-1} = 0\,, \qquad i \ge 2\,, \tag{2.11}$$

$$\mathrm{Pr}^{-1}\theta_i'' + 2(a+\eta)\theta_i' - 4i\theta_i - \frac{4F}{m}\theta_{i-1} = 0\,, \qquad i \ge 2\,, \tag{2.12}$$

with initial condition

$$\left.\begin{array}{llll} \eta = 0 : \theta_0 = \mathrm{Gr}\,t, & f_0 = \cos\omega t, & f_i = 0, & \theta_i = 0 \forall i \ge 1, \\ \eta \to \infty : \theta_i = 0, & f_i = 0, & \forall i \ge 0 & \end{array}\right\} \tag{2.13}$$

where a is the suction/injection parameter. It may be noted that for suction $a > 0$, for injection $a < 0$ and for impermeable plate $a = 0$.

The homogenous parts of the above system of differential equations admit solutions in terms of repeated integrals of complementary error functions (See Abramowitz and Stegun, 1972). For non-homogenous part of Eqs (2.9) and (2.10), the particular integrals have been obtained by the method of undetermined coefficients. The complete solutions of Eqs (2.7) to (2.10), satisfying the boundary conditions (2.13) are as follows

$$f_0(\xi) = \cos\omega t\,\frac{i^0\mathrm{erf_c}(\xi)}{i^0\mathrm{erf_c}(a)}, \tag{2.14}$$

$$\theta_0 = \frac{\mathrm{Gr}\cdot t\cdot \mathrm{erf_c}\left(\sqrt{\mathrm{Pr}}\,\xi\right)}{i^0\mathrm{erf_c}\left(\sqrt{\mathrm{Pr}}\,a\right)}, \tag{2.15}$$

$$f_1 = Ai^2\mathrm{erf_c}(\xi) - \cos\omega t\left(1+\frac{1}{mK_0}\right)\frac{i^0\mathrm{erf_c}(\xi)}{i^0\mathrm{erf_c}(a)} - \frac{4i^2\mathrm{erf_c}\left(\sqrt{\mathrm{Pr}}\,\xi\right)}{m(\mathrm{Pr}-1)i^0\mathrm{erf_c}\left(\sqrt{\mathrm{Pr}}\,a\right)}, \tag{2.16}$$

$$A = \frac{4i^2\mathrm{erf_c}\left(\sqrt{\mathrm{Pr}}\,a\right)}{m(\mathrm{Pr}-1)i^0\mathrm{erf_c}\left(\sqrt{\mathrm{Pr}}\,a\right)i^2\mathrm{erf_c}(a)} + \left(1+\frac{1}{mK_0}\right)\frac{\cos\omega t}{i^2\mathrm{erf_c}(a)}\,. \tag{2.17}$$

It may be noted that the solution of Eq.(2.16) is valid when $\mathrm{Pr} \ne 1$. In case of $\mathrm{Pr} = 1$, on taking the limiting values we get

$$f_1 = \left[\cos\omega t\left(1+\frac{1}{mK_0}\right) - \frac{1}{m}\right]\frac{i^2\mathrm{erf_c}(\xi)}{i^2\mathrm{erf_c}(a)} + \frac{1}{m}\frac{i^0\mathrm{erf_c}(\xi)}{i^0\mathrm{erf_c}(a)} - \cos\omega t\left(1+\frac{1}{mK_0}\right)\frac{i^0\mathrm{erf_c}(\xi)}{i^0\mathrm{erf_c}(a)}, \tag{2.18}$$

$$\theta_1 = \frac{F}{m}\left(\frac{i^2\mathrm{erf_c}(\xi)}{i^2\mathrm{erf_c}(a)} - \frac{i^0\mathrm{erf_c}(\xi)}{i^0\mathrm{erf_c}(a)}\right), \tag{2.19}$$

$$\theta_2 = \frac{F^2}{2m^2}\frac{i^4\mathrm{erf}_c(\xi)}{i^4\mathrm{erf}_c(a)} - \frac{F^2}{m^2}\frac{i^2\mathrm{erf}_c(\xi)}{i^2\mathrm{erf}_c(a)} + \frac{F^2}{2m^2}\frac{i^0\mathrm{erf}_c(\xi)}{i^0\mathrm{erf}_c(a)}, \tag{2.20}$$

and the function $i^n\mathrm{erf}_c(\xi)$ is the repeated integral of the complementary error function defined as

$$i^n\mathrm{erf}_c(\xi) = \frac{2}{\sqrt{\pi}}\int_\xi^\infty \frac{(t-\xi)^n}{n!}e^{-t^2}dt\,, \qquad n = 0,1,2...... \tag{2.21}$$

or

$$i^n\mathrm{erf}_c(\xi) = \sum_{K=0}^{\infty}\frac{(-1)^K \xi^K}{2^{n-K}K!\,\Gamma\left(1+\frac{n-K}{2}\right)}, \tag{2.22}$$

$$i^{-1}\mathrm{erf}_c(\xi) = \frac{2}{\sqrt{\pi}}e^{-\xi^2}\,, \qquad i^n\mathrm{erf}_c(\xi) = \mathrm{erf}_c(\xi), \tag{2.23}$$

$$\frac{\partial}{\partial\xi}i^n\mathrm{erf}_c(\xi) = -i^{n-1}\mathrm{erf}_c(\xi), \tag{2.24}$$

and the recurrence relation is

$$i^{n-2}\mathrm{erf}_c(\xi) - 2\xi\, i^{n-1}\mathrm{erf}_c(\xi) - 2ni^n\mathrm{erf}_c(\xi) = 0 \tag{2.25}$$

It is remarked here that the analytical solutions up to the first order approximation have been obtained in a similar manner. As the numerical values of functions like $\mathrm{erf}_c\left(\sqrt{\mathrm{Pr}}\,a\right)$ for arbitrary values of Pr and parameter a are not readily available, the differential Eqs (2.7) to (2.12), up to second order with boundary conditions (2.13) have also been solved numerically. For the numerical solution of Eq.(2.7) to (2.12), the unknown initial values have been computed by the method suggested by Jain and Menon (1971) for linear boundary value problems. For this purpose, the Runge-Kutta-Gill integration scheme, with a step size of *0.01* has been adopted. To ensure the accuracy of the numerical results so obtained, we have compared these results with the results obtained by exact solutions in some simple cases $(a = 0)$ in which the numerical values of $i^n\mathrm{erf}_c(0)$ are readily available in Abramowitz and Stegun (1972) and found that the numerical results obtained by both the methods are in good agreement (upto fourth decimal places). The results are presented for comparison in Tab.1 and unknown initial values are reported in Tabs 2 and 3.

Table 1. Comparison of results obtained by numerical solutions and exact solutions for $m = 0.5$, $\mathrm{Gr} = 5.0$, $\omega t = 0$, $F = 2.0$ and $K_0 = 0.2$.

Pr	a	$f_0'(0)$		$f_1'(0)$		$\theta_0'(0)$		$\theta_1'(0)$	
		Numerical Solution	Exact Solution	Numerical Solution	Exact Solution	Numerical Solution	Exact Solution	Numerical Solution	Exact Solution
0.72	*0.0*	*–1.12837*	*–1.12838*	*–9.97048*	*–9.97049*	*–0.95746*	*–0.95746*	*–3.82984*	*–3.82984*
1.0	*0.0*	*–1.12837*	*–1.12838*	*–4.51351*	*–4.51352*	*–1.12837*	*–1.12838*	*–4.51351*	*–4.51352*
1.0	*0.5*	*–1.83270*	*–1.83271*	*–4.08298*	*–4.08298*	*–1.83270*	*–1.83271*	*–4.08291*	*–4.08292*

Table 2. Numerical values of wall shear stress function $f_i'(0)$ and surface heat transfer function $\theta_i'(0)$ $i = 0, 1, 2$ for $m = 0.5$, $a = 0.5$, $\mathrm{Gr} = 5.0$ and $\omega t = \pi/3$.

Pr	K_0	F	$f_0'(0)$	$f_1'(0)$	$\theta_0'(0)$	$\theta_1'(0)$
0.72	0.2	2.0	–0.916354	–3.29679	–1.45803	–3.52508
0.72	0.4	0.0	–0.916354	–0.74492	–1.45803	0.0
0.72	2.0	2.0	–0.916354	1.29657	–1.45803	–3.52508
0.72	0.4	10.0	–0.916354	–0.74492	–1.45803	–17.6254
1.0	0.4	2.0	–0.916354	–1.02075	–1.83271	–4.08298
3.0	0.4	2.0	–0.916354	–1.85987	–4.18359	–6.46152

Table 3. Numerical values of wall shear stress function $f_i'(0)$ and surface heat transfer function $\theta_i'(0)$ $i = 0, 1, 2$ for $m = 0.5$, $a = 0.5$, $\mathrm{Pr} = 0.72$, $\mathrm{Gr} = 5.0$, $F = 2.0$ and $K_0 = 0.2$.

ωt	$\cos \omega t$	f_0'	f_1'	f_2'	θ_0'	θ_1'	θ_2'
0	1	–1.83271	–8.91089	12.5729	–1.45803	–3.52508	–1.67880
$\pi/6$	0.866	–1.57613	–7.33389	10.0463	–1.45803	–3.52508	–1.67880
$\pi/4$	0.707	–1.28289	–5.54250	7.15919	–1.45803	–3.52508	–1.67880
$\pi/3$	0.5	–0.91635	–3.29679	3.54940	–1.45803	–3.52508	–1.67880
$\pi/2$	0	0.0	2.31732	–5.47415	–1.45803	–3.52508	–1.67880

3. Skin friction coefficient

The main physical quantity of interest is the skin-friction coefficient C_f, which is defined as

$$C_f = \frac{\mu\left(\frac{\partial u^*}{\partial y^*}\right)_{y^*=0}}{\rho u_0^{*2}/2}, \tag{3.1}$$

which, in the present case, can be expressed in the following form

$$C_f = \frac{1}{\sqrt{t}} \sum_{i=0}^{\infty} (mt)^i \ f_i'(0). \tag{3.2}$$

4. Results and discussion

To discuss the physical importance of the problem like velocity, temperature and the skin-friction coefficient we have chosen different values of the parameter. Two cases of general interest for Grashof number $\mathrm{Gr} > 0$ corresponding to cooling of the plate and Grashof number $\mathrm{Gr} < 0$ corresponding to heating of the plate are considered. The value of magnetic field parameter m is chosen to be 0.5 in all cases.

In Fig.1, the skin-friction coefficient C_f is plotted against time t for different values of suction/injection parameter a, the Grashof number Gr for extremely cooled/hot plate and taking other parameters fixed. It is observed that C_f increases with Gr in both cases, whereas the same decreases as parameter a increases. It may be noted that the curve of the function C_f increases with time and that becomes asymptotic as t approaches 0.7.

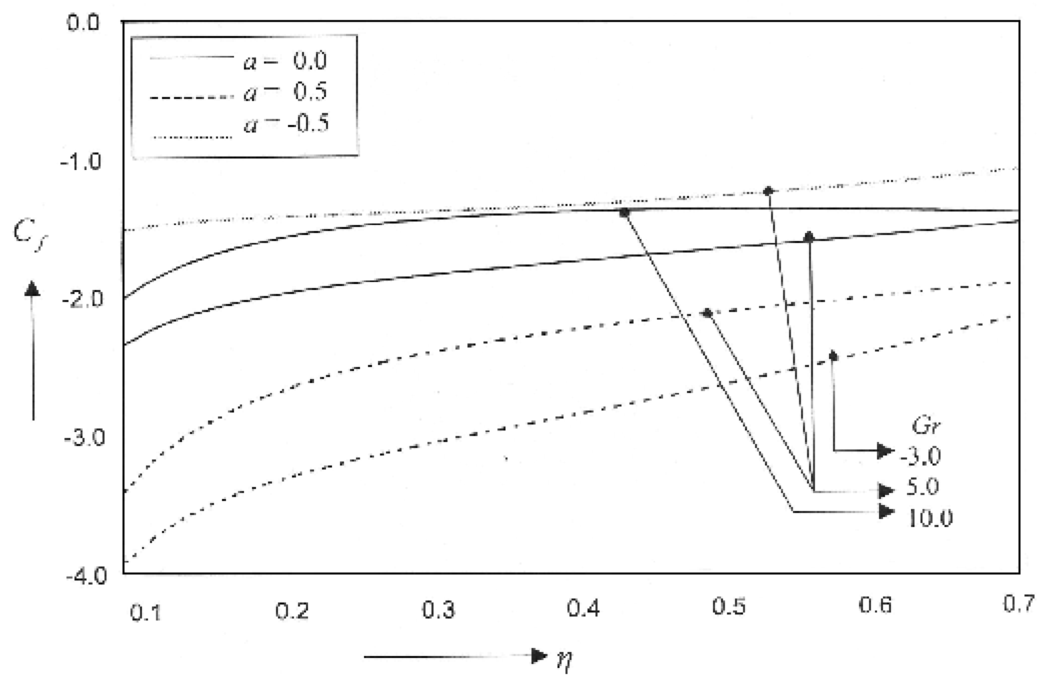

Fig.1. Variation of the skin-friction coefficient with time at fixed values of $\mathrm{Pr} = 0.72$, $K_0 = 0.2$ and $F = 2.0$.

In Fig.2, the skin-friction coefficient C_f is plotted against time t for different values of the Prandtl number Pr, permeability parameter K_0 and radition parameter F. It is observed that C_f increases with K_0 and decreases with an increase in the radiation parameter F or the Prandtl number Pr.

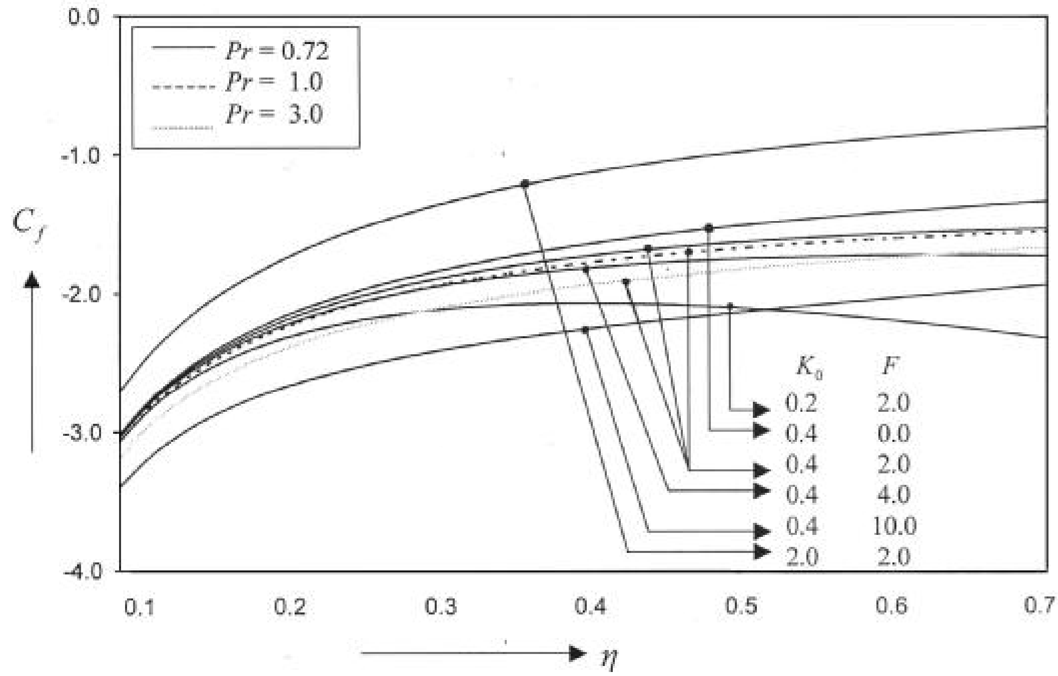

Fig.2. Variation of the skin-friction coefficient with time at fixed values of $\mathrm{Gr} = 5.0$ and $a = 0.5$.

In Fig.3, the temperature function θ is plotted against the variable η for different values of the Grashof number Gr and suction/injection parameter ***a***, taking other parameter fixed. It may be noted that the temperature increases as Gr increases and decreases as ***a*** increases.

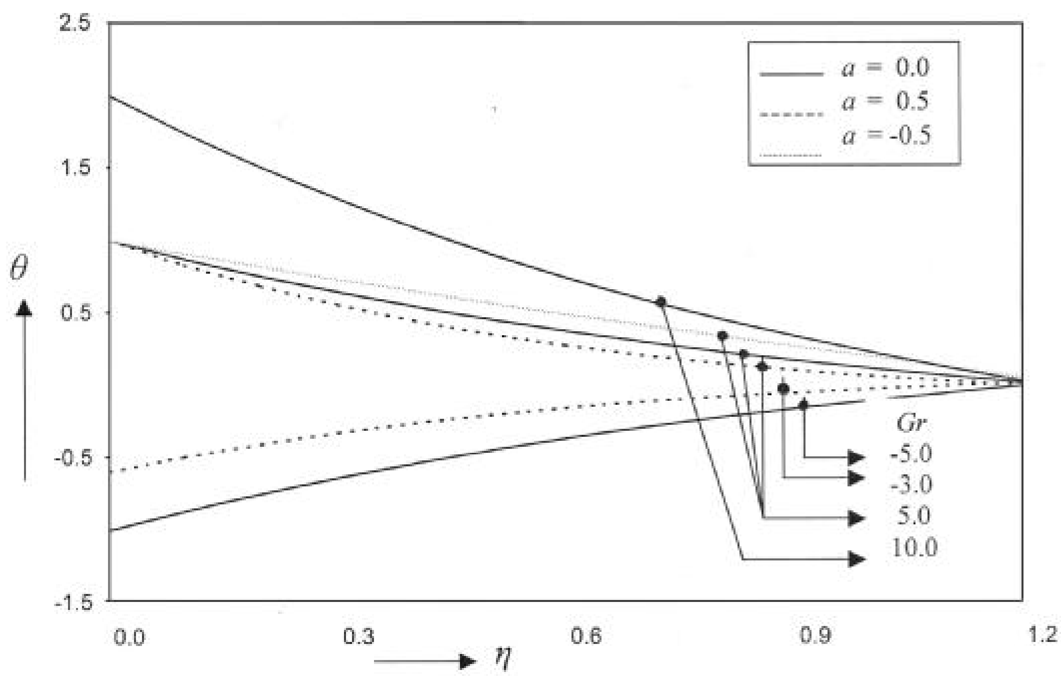

Fig.3. Temperature profiles at fixed values of $\mathrm{Pr} = 0.72$, $K_0 = 0.2$ and $F = 2.0$.

In Fig.4, the effect of the Prandtl number Pr and radiation parameter F on the temperature function θ has been shown. It is observed that θ decreases as Pr or F increases.

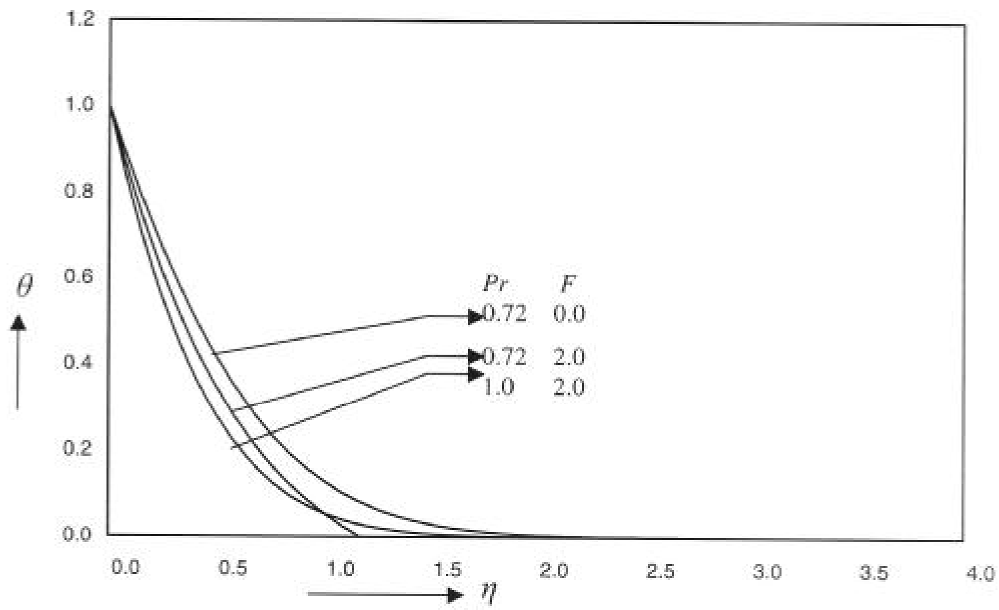

Fig.4. Temperature profiles at fixed values of $\mathrm{Gr} = 5.0$ and $a = 0.5$.

In Fig.5, the velocity function u is plotted against η for different values of K_0, Gr and a, taking other parameters fixed. It is observed that velocity increases as permeability K_0 or the Grashof number Gr increases, whereas it decreases as a increases.

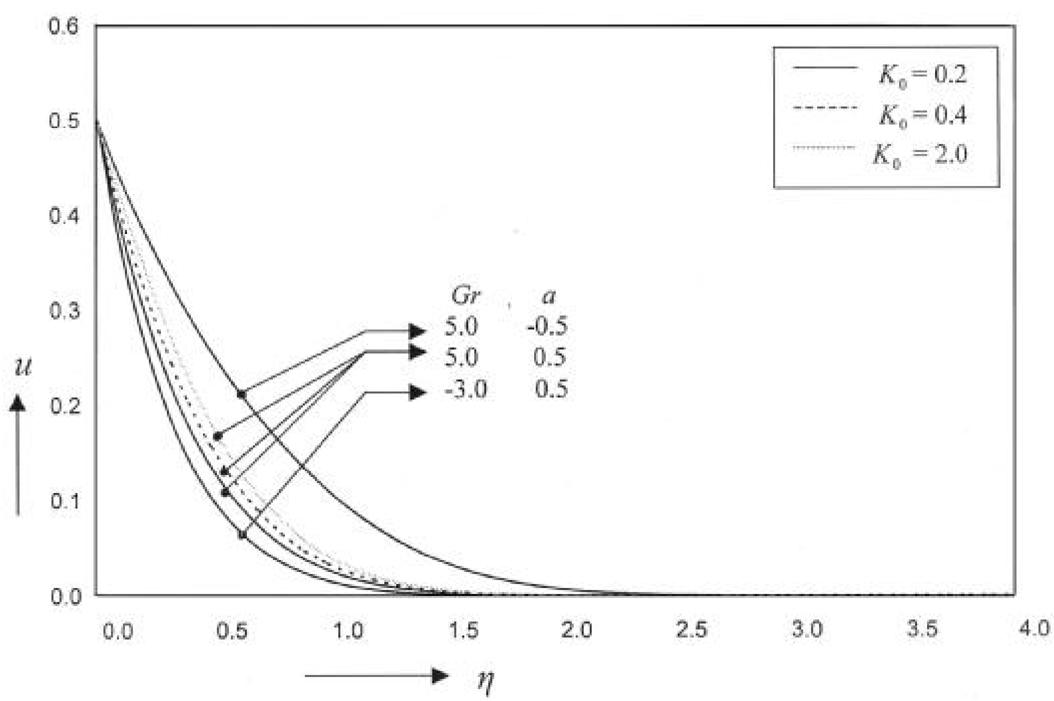

Fig.5. Velocity profiles at fixed values of $\mathrm{Pr} = 0.72$, $F = 2.0$ and $\omega t = \pi/3$.

In Fig.6, the velocity function u is plotted against η for different values of the Prandtl number Pr and radiation parameter F taking other parameters fixed. It is observed that velocity decreases as Pr or F increases.

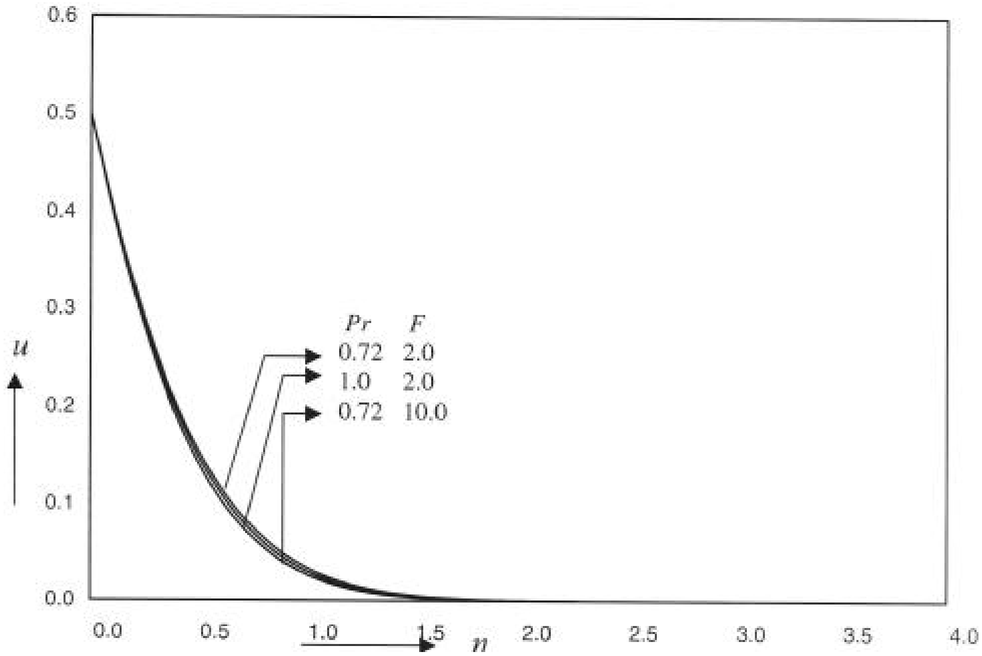

Fig.6. Velocity profiles at fixed values of $\mathrm{Gr} = 5.0$, $a = 0.5$, $K_0 = 0.4$ and $\omega t = \pi/3$.

In Fig.7, the velocity function u is plotted against η for different values of ωt taking other parameters fixed. It is observed that velocity decreases as ωt increases.

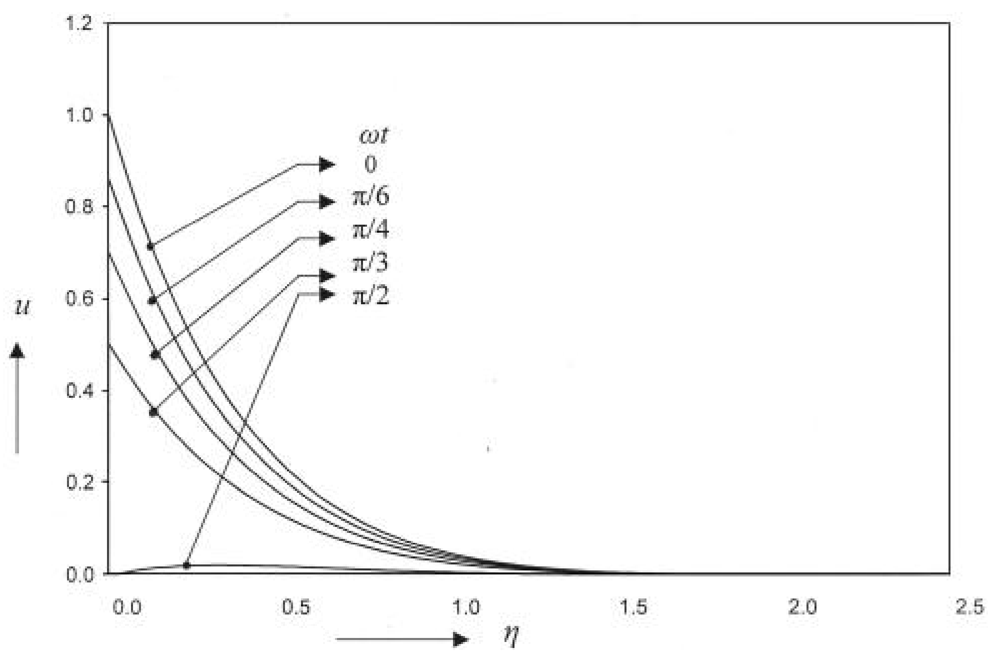

Fig.7. Velocity profile at fixed values of $\mathrm{Pr} = 0.72$, $\mathrm{Gr} = 5.0$, $F = 2.0$, $a = 0.5$ and $K_0 = 0.2$.

5. Conclusion

1. Greater cooling $\mathrm{Gr} > 0$ results in an increase in velocity and thermal boundary layer thickness. While greater heating $\mathrm{Gr} < 0$ causes a reduction in fluid velocity.
2. Since the graph of C_f becomes asymptotic for $t \geq 0.7$ in all the cases, it may be concluded that the flow is reduced to steadiness after time $t = 0.7$.
3. The effect of radiation F is to decrease the velocity and temperature in the free convective boundary layer.
4. But, with the increase in permeability parameter K_0 , the velocity increases in the boundary layer.

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Nomenclature

a – suction/injection parameter
c_p – specific heat at constant pressure
c_f – skin friction coefficient
$e_{b\lambda}$ – Plank function
erfc – complementary error function
Gr – Grashof number
G – acceleration due to gravity
K^* – permeability parameter
$K_{\lambda w}$ – absorption coefficient at the wall
Pr – Prandtl number
q_r^* – the radiative heat flux in the y^* direction
T^* – temperature of the fluid near the plate
T_∞^* – temperature of the fluid at infinity
T_w^* – temperature of the plate
t^* – time
t – dimensionless time
u^* – velocity of fluid along x^* direction
u_0^* – velocity of the plate
v^* – velocity of fluid along y^* direction
x^*, y^* – coordinates along and normal to the plate
σ – electrical conductivity
β – coefficient of thermal expansion
ω^0 – frequency
η – similarity variable
υ – kinematic viscosity
κ – thermal conductivity
ρ – density

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