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## Free Convection Flows of a Dissipative Fluid Bounded By an Oscillating Plate with Heat Sink

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**ABSTRACT:**The mass, momentum and heat transfer in unsteady free convection flow past an infinite hot vertical oscillating plate, with heat absorbing sink, has been studied. The analytical solutions of resulting ordinary differential equations have been obtained in terms of repeated integrals of complementary error functions. The numerical values of surface heat transfer, surface shearing stress and surface species concentration transfer functions for various values of different parameters have been tabulated and discussed in detail. Also, the velocity, temperature and concentration profiles have been drawn and discussed.

**KEYWORDS:** Free convection; Boundary Layer flow; Porous medium; Mass transfer; Sink 2000 Mathematics Subject classification: 76R10, 76D10, 76S05

### I. INTRODUCTION

The study of free convective flow through a porous medium and heat absorbing. Sinks has become a principle interest in recent years because of its numerous scientific and engineering applications mainly in fields of astrophysics, geophysics, aeronautical engineering, space sciences and aerodynamics etc. Porous media is used widely to insulate heated body in order to maintain its temperature and to reduce boundary layer thickness. The study of convective heat transfer from surfaces embedded in porous media has applications in Thermal engineering such as geothermal systems, oil extraction, thermal insulation and ground water pollution. To make the heat insulation of the surface more effective, it is necessary to study the free convection flow through a porous medium and to estimate its effect on heat and mass transfer. Heat and mass transfer in MHD flow with pressure gradient suction and injection has been studied by Soundalgekar and Ramana Murty [1], Takhar and Soundalgekar [2] and Bansal [3]. The unsteady free convection flow past an impulsively started infinite plate in presence of transverse magnetic field fixed relative to fluid has been studied by Dave et al [4], Tak and Pathak [5] & [6]. The same problem is further studied by Tak and Sisodia[7] and Pathak et al [8], on considering the viscous heating effect. The unsteady two dimensional flow of viscous fluid through a porous medium bounded by infinite porous plate with constant suction and variable temperature was studied by Raptis [9]. Again, when the temperature of porous plate oscillates in time about a constant mean has been studied by Raptis and Perdikis [10]. Free convection and mass transfer in steady flow through porous medium with constant suction in presence of magnetic field is studied by Sharma [11] and Acharya et al [12]. The study of unsteady MHD flows through porous medium with oscillatory suction velocity has been studied by Singh et al [13] and Chand et al [14]. Mixed convection flow past an oscillating vertical plate have been studied by Soundalgekar [15] and Vighnesam et al [16]. Recently, MHD unsteady flow past an infinite vertical plate with constant suction and heat sink is studied by Sahoo et al [17].

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### II. MATHEMATICAL FORMULATION AND ANALYSIS

Consider an unsteady flow of an incompressible viscous fluid through a porous medium bounded by an infinite vertical oscillating plate with heat sink. At time  $t^* \leq 0$  the temperature and foreign species concentration at the plate and the fluid are assumed to be  $T_\infty^*$  and  $c_\infty^*$  respectively. For  $t^* > 0$ , the plate starts oscillating in its own plane and maintained at a constant velocity  $u_0^*$  with frequency  $\omega^*$  and the heat is supplied to the oscillating plate such that its plate temperature and species concentration at the plate are instantaneously raised to  $T_w^*$  and  $c_w^*$ . The transverse magnetic field is assumed to be fixed relative to the fluid. The  $x^*$  axis is taken along the plate in upward direction and  $y^*$  axis normal to it. Since the motion is two-dimensional and length of the plate is large, therefore, all the physical variables are independent of  $x^*$  only. For a small concentration level, the Soret-Dufour effects can be neglected in the energy equation. The electrical conductivity of the fluid is assumed to be small so that the induced magnetic field can be neglected in comparison of applied magnetic field. Then, under the usual Boussinesq's approximations, equations governing the flow in absence of frictional heating are (Gebhart [18]):

$$\frac{\partial v^*}{\partial y^*} = 0 \tag{1}$$

$$\frac{\partial u^*}{\partial t^*} + v^* \frac{\partial u^*}{\partial y^*} = \nu \frac{\partial^2 u^*}{\partial y^{*2}} + g\beta(T^* - T_\infty^*) + g\beta^*(c^* - c_\infty^*) - \frac{\nu u^*}{K^*} - \frac{\sigma B_0^2 u^*}{\rho} \tag{2}$$

$$\frac{\partial T^*}{\partial t^*} + v^* \frac{\partial T^*}{\partial y^*} = \frac{k}{\rho c_p} \frac{\partial^2 T^*}{\partial y^{*2}} + S^*(T^* - T_\infty^*) + \frac{\nu}{c_p} \left( \frac{\partial u^*}{\partial y^*} \right)^2 \tag{3}$$

$$\frac{\partial c^*}{\partial t^*} + v^* \frac{\partial c^*}{\partial y^*} = D \frac{\partial^2 c^*}{\partial y^{*2}} \tag{4}$$

where  $u^*$  and  $v^*$  are longitudinal and normal components of velocity respectively,  $\nu$  the kinematic viscosity,  $T^*$  the temperature,  $C^*$  the concentration,  $D$  the coefficient of mass diffusion,  $g$  the acceleration due to gravity,  $\beta$  the coefficient of thermal expansion,  $\beta^*$  the coefficient of species concentration expansion,  $k$  the thermal conductivity,  $c_p$  the specific heat at constant pressure,  $\sigma$  electrical conductivity,  $\rho$  the density,  $K^*$  the permeability of porous medium,  $S^*$  is rate of heat generation/absorption and  $B_0$  is uniform applied magnetic field strength.

The initial and boundary conditions are:

$$\left. \begin{aligned} t^* \leq 0: u^* = 0, T^* = T_\infty^*, c^* = c_\infty^* \quad \forall y^* \\ t^* > 0: u^* = u_0^* \cos \omega^* t^*, T^* = T_w^*, c^* = c_w^* \quad \text{at } y^* = 0 \\ u^* = 0, T^* \rightarrow T_\infty^*, c^* \rightarrow c_\infty^* \quad \text{as } y^* \rightarrow \infty \end{aligned} \right\} \tag{5}$$

Introducing the following non-dimensional quantities:

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$$y = \frac{y^* u_0^*}{\nu}, \quad t = \frac{t^* u_0^{*2}}{\nu}, \quad u = \frac{u^*}{u_0^*}, \quad v = \frac{v^*}{u_0^*}, \quad \theta = \frac{T^* - T_\infty^*}{T_w^* - T_\infty^*}, \quad c = \frac{c^* - c_\infty^*}{c_w^* - c_\infty^*}$$

the equations (1) to (5) transform to

$$\frac{\partial v}{\partial y} = 0 \tag{6}$$

$$\frac{\partial u}{\partial t} + v \frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + Gr \cdot \theta + Gc \cdot c - \left( M + \frac{1}{K_0} \right) u \tag{7}$$

$$\frac{\partial \theta}{\partial t} + v \frac{\partial \theta}{\partial y} = \frac{1}{Pr} \frac{\partial^2 \theta}{\partial y^2} + S \cdot \theta + Er \left( \frac{\partial u}{\partial y} \right)^2 \tag{8}$$

$$\frac{\partial c}{\partial t} + v \frac{\partial c}{\partial y} = \frac{1}{Sc} \frac{\partial^2 c}{\partial y^2} \tag{9}$$

with initial and boundary conditions:

$$\left. \begin{aligned} t \leq 0 : u = 0, \quad \theta = 0, \quad C = 0 \quad \forall y \\ t > 0 : u = \cos \omega t, \quad \theta = 1, \quad C = 1 \quad \text{at } y = 0 \\ u = 0, \quad \theta = 0, \quad C = 0 \quad \text{as } y \rightarrow \infty \end{aligned} \right\} \tag{10}$$

where

$$\begin{aligned} Gr &= \frac{\nu g \beta (T_w^* - T_\infty^*)}{u_0^{*3}} \text{ (Grashof number)}, \quad M = \frac{\sigma B_0^2 \nu}{\rho u_0^{*2}} \text{ (magnetic field parameter)}, \\ Gc &= \frac{\nu g \beta^* (C_w^* - C_\infty^*)}{u_0^{*3}} \text{ (modified Grashof number)}, \quad Pr = \frac{\mu c_p}{\kappa} \text{ (Prandtl number)}, \\ Sc &= \frac{\nu}{D} \text{ (Schmidt number)}, \quad S = \frac{S^* \nu}{u_0^{*2}} \text{ (sink strength)}, \quad Er = \frac{u_0^{*2}}{C_p (T_w^* - T_\infty^*)} \text{ (Eckert number)}, \\ K_0 &= \frac{K^* u_0^{*2}}{\nu^2} \text{ (permeability parameter)} \quad \text{and} \quad \omega = \frac{\omega^* \nu}{u_0^{*2}}. \end{aligned}$$

Integrating equation (4.B.6), we obtain

$$v = -\frac{a}{\sqrt{t}} \tag{11}$$

where  $a$  is suction/injection parameter. It may be noted that for suction  $a > 0$ , for injection  $a < 0$  and for impermeable plate  $a = 0$ . We observe that the concentration equation (9) is not depends upon the magnetic field parameter and, therefore the solution is obtained by assuming the following similarity transformation:

$$C(y, t) = C(\eta), \quad \eta = \frac{y}{2\sqrt{t}} \tag{12}$$

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For solution of momentum equation (7) and energy equation (8), the similar solution is not feasible and therefore we see a series solution by expanding  $u$  and  $\theta$  in terms of power series ( $Mt$ ), called magnetic interaction parameter, which is considered to be small i.e.  $Mt \ll 1$  (Dave et al[4]):

$$\left. \begin{aligned} u(y,t) &= \sum_{i=0}^{\infty} (Mt)^i f_i(\eta) \\ \theta(y,t) &= \sum_{i=0}^{\infty} (Mt)^i \theta_i(\eta) \end{aligned} \right\} \quad (13)$$

then equating the like powers of ( $Mt$ ) equations (6) to (10) are reduced to the following set of ordinary differential equations up to second order terms, are obtained

$$Sc^{-1} C'' + 2(a + \eta) C' = 0 \quad (14)$$

$$f_0'' + 2(a + \eta) f_0' = 0 \quad (15)$$

$$Pr^{-1} \theta_0'' + 2(a + \eta) \theta_0' + Er f_0'^2 = 0 \quad (16)$$

$$f_1'' + 2(a + \eta) f_1' - 4f_1 - 4 \left( 1 + \frac{1}{Mk_0} \right) f_0 + \frac{4Gr\theta_0}{M} + \frac{4Gc.C}{M} = 0, \quad (17)$$

$$Pr^{-1} \theta_1'' + 2(a + \eta) \theta_1' - 4\theta_1 + \frac{4.S}{M} \theta_0 + 2Er f_0' f_1' = 0 \quad (18)$$

$$f_2'' + 2(a + \eta) f_2' - 8f_2 - 4 \left( 1 + \frac{1}{Mk_0} \right) f_1 + \frac{4Gr\theta_1}{M} = 0 \quad (19)$$

$$Pr^{-1} \theta_2'' + 2(a + \eta) \theta_2' - 8\theta_2 + \frac{4.S}{M} \theta_1 + Er(f_1'^2 + 2f_0' f_2') = 0 \quad (20)$$

with initial and boundary conditions:

$$\left. \begin{aligned} \eta = 0: & \theta_0 = 1, C = 1, f_0 = \cos \omega t, f_i = 0, \theta_i = 0 \quad \forall i \geq 1 \\ \eta \rightarrow \infty: & \theta_i = 0, C = 0, f_i = 0, i \geq 0 \end{aligned} \right\} \quad (21)$$

The homogenous parts of the above system of differential equation admit solutions in terms of repeated integrals of complementary error functions (See Abramowitz and Stegun [19]). For non-homogenous part of equation (16) to (20), the particular integrals have been obtained by the method of undetermined coefficients. On taking the limiting value  $Pr = 1.0$  and  $\omega t = 0$ , the complete solutions of some equation (14) to (17), satisfying boundary conditions (21) are as follows:

$$C = \frac{i^0 \operatorname{erfc}(\sqrt{Sc} \xi)}{i^0 \operatorname{erfc}(\sqrt{Sc} a)}, \quad \xi = a + \eta \quad (22)$$

$$f_0(\xi) = \frac{i^0 \operatorname{erfc}(\xi)}{i^0 \operatorname{erfc}(a)} \quad (23)$$

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$$\theta_0 = \left( 1 + \frac{Er}{2} \right) \frac{i^0 erf_c(\xi)}{i^0 erf_c(a)} - \frac{Er}{2} \left( \frac{i^0 erf_c(\xi)}{i^0 erf_c(a)} \right)^2 \quad (24)$$

$$f_1(\xi) = A i^2 erf_c(\xi) + \frac{i^0 erf_c(\xi)}{i^0 erf_c(a)} \left\{ \frac{Gc}{M} + \frac{Gr}{M} \left( 1 + \frac{Er}{2} \right) - \left( 1 + \frac{1}{MK_0} \right) \right\} - Er \left\{ \frac{i^1 erf_c(\xi)}{i^0 erf_c(a)} \right\}^2 \quad (25)$$

where,

$$A = - \frac{i^0 erf_c(\xi)}{i^0 erf_c(a) i^2 erf_c(a)} \left\{ \frac{Gc}{M} + \frac{Gr}{M} \left( 1 + \frac{Er}{2} \right) - \left( 1 + \frac{1}{MK_0} \right) \right\} - Er \left\{ \frac{i^1 erf_c(\xi)}{i^0 erf_c(a)} \right\}^2$$

and the function  $i^n erf_c(\xi)$  is the repeated integral of complementary error function defined as:

$$i^n erf_c(\xi) = \frac{2}{\sqrt{\pi}} \int_{\xi}^{\infty} \frac{(t-\xi)^{n-1}}{n!} e^{-t^2} dt, n=0,1,2,\dots \quad (26)$$

$$= \sum_{K=0}^{\infty} \frac{(-1)^K \xi^K}{2^{n-K} K! \Gamma\left(1 + \frac{n-K}{2}\right)} \quad (27)$$

$$i^{-1} erf_c(\xi) = \frac{2}{\sqrt{\pi}} e^{-\xi^2}, i^n erf_c(\xi) = erf_c(\xi), \quad (28)$$

$$\frac{\partial}{\partial \xi} i^n erf_c(\xi) = -i^{n-1} erf_c(\xi) \quad (29)$$

and the recurrence relation is

$$i^{n-2} erf_c(\xi) - 2\xi i^{n-1} erf_c(\xi) - 2n i^n erf_c(\xi) = 0 \quad (30)$$

It is remarked here that the analytical solutions up to first order approximation have been obtained in a similar manner. As the numerical values of functions like  $erf_c(\sqrt{Pr} \cdot a)$  for arbitrary values of  $Pr$ ,  $Sc$  and parameter  $a$  are not readily available, the differential equations (14) to (20), up to second order with boundary conditions (21) have also been solved numerically on computer. For the numerical solution of equation (14) to (20), the unknown initial values have been computed by the method suggested by Jain and Menon [20] for linear boundary value problems. For this purpose, the Runge-Kutta-Nystrom 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  $i^n erf_c(0)$  are readily available in Abramowitz and Stegun [19] and found that the numerical results obtained by both the methods are in good agreement (upto fourth decimal places). The unknown initial values are reported in Table 1 and Table 2.

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## Skin Friction Coefficient and Surface Heat Transfer

The main physical quantities of interest are skin-friction coefficient  $C_f$  and local Nusselt number  $Nu$  which are defined as

$$C_f = \frac{\mu \left( \frac{\partial u^*}{\partial y^*} \right)_{y^*=0}}{\rho u_0^{*2} / 2} \quad \text{and} \quad Nu = - \frac{L}{(T_w^* - T_\infty^*)} \left( \frac{\partial T^*}{\partial y^*} \right)_{y^*=0} \quad (31)$$

which, in present case, can be expressed in the following forms:

$$C_f = \frac{1}{\sqrt{t}} \sum_{i=0}^{\infty} (Mt)^i f_i'(0) \quad \text{and} \quad \frac{2Nu}{Re} = - \frac{1}{\sqrt{t}} \sum_{i=0}^{\infty} (Mt)^i \theta_i'(0), \quad Re = \frac{u^* L}{\nu} \quad (32)$$

where  $L$  is the length of 'infinite plate'. Numerical values of functions  $f_i'(0)$ ,  $\theta_i'(0)$  and  $c'(0)$  for  $i = 0$  to 2 obtained by numerical solution for  $M = 0.5$ ;  $Pr = 0.71, 1.0$ ;  $a = 0, 0.5$ ;  $Gr = 5.0, 10.0$ ;  $Gc = 2.0$ ;  $Er = 0.01, 0.1, 0.4$ ,  $Sc = 0.30, 0.60, 2.62$  and different values of  $\omega t$  are presented in Table 1 and Table 2.

## III. RESULTS AND DISCUSSION

To study the viscous heating effect on free convection flow, the value of Schmidt number  $Sc$  are chosen to be 0.30, 0.60 and 2.62 which represent the diffusing chemical species of most common interest in air, namely- He, H<sub>2</sub>O and propyl benzene respectively. Also, the value of Prandtl number  $Pr$  are chosen to be 0.025, 0.72 and 1.0 which correspond to mercury, air and electrolyte solution.

Fig. 1 and Fig. 2 shows that the curve of skin friction coefficient increase with time and become asymptotic as  $t$  approaches 0.6. It is observed that  $C_f$  decreases as Prandtl number  $Pr$ , Schmidt number  $Sc$  and suction/ injection parameter  $a$  increases whereas it increases as Permeability  $K_0$ , Eckert number  $Er$  and sink strength  $S$  increases.

Fig. 3 and Fig. 4 shows that the function  $2Nu/Re$  decreases with time and become asymptotic for  $t \geq 0.6$ . It may also be observed that the rate of heat transfer decreases in as  $Pr$ ,  $K_0$  and  $a$  decreases. whereas the rate of heat transfer increase with decrease in sink strength  $S$  and Eckert number  $Er$  for both mercury and electrolyte solution.

In Fig. 5, the temperature profiles are plotted against  $\eta$ . It is observed that temperature increases as Eckert number increases and it decreases as suction/ injection parameter  $a$  or Prandtl number  $Pr$  or sink strength  $S$  increases for both mercury and electrolyte solution.

In Fig. 6, the concentration profiles are plotted against variable  $\eta$ . It is observed that concentration decreases as  $Sc$  or  $a$  increases for a fixed  $\eta$ .

In both figures Fig. 7 and Fig. 8, the velocity function  $u$  is plotted against  $\eta$ . It is observed from the figures that the velocity decreases as suction/ injection parameter  $a$ , Schmidt number  $Sc$  and sink strength  $S$  increases whereas velocity increases as permeability  $K_0$ , Eckert number  $Er$  or Prandtl number  $Pr$  increases. Thus the presence of foreign species decreases the velocity boundary layer thickness.

In Fig. 9, the velocity function  $u$  is plotted against  $\eta$  for different values of  $\omega t$  taking other parameters fixed. It is observed that velocity decreases as  $\omega t$  increases.

Table 1 represents Numerical values of wall shear stress functions  $f_i'$ ,  $i = 0, 1, 2$ , wall temperature function  $\theta_i'(0)$ ,  $i = 0, 1, 2$  and concentration function  $c'(0)$  for  $M = 0.5$ ,  $a = 0.5$ ,  $Gc = 2.0$ ,  $Gr = 5.0$ ,  $Pr = 1.0$ ,  $Sc = 1.0$  and  $\omega t = 0$ . The numerical solution is obtained with the help of a computer by Runge-Kutta-Gill integration scheme and the exact solution is obtained by repeated integrals of complementary error function. It may be noted that the numerical result obtained by both the methods are in a good arrangement.

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Table 2 represents Numerical values of wall shear stress function  $f_i'(0)$ , wall temperature function  $\theta_i'(0)$ ,  $i = 0,1,2$  and concentration function  $c'(0)$  for  $M = 0.5, a = 0.5, Gc = 2.0, Gr = 5.0, Pr = 0.72, Sc = 1.0, S = -0.10, Er = 0.1$  and  $K_0 = 0.2$ .

**Table 1** Numerical values of wall shear stress functions  $f_i'$ ,  $i = 0, 1, 2$ , wall temperature function  $\theta_i'(0)$ ,  $i = 0,1,2$  and concentration function  $c'(0)$  for  $M = 0.5, a = 0.5, Gc = 2.0, Gr = 5.0, Pr = 1.0, Sc = 1.0$  and  $\omega t = 0$

$Er$	$S$	$K_0$	$c'(0)$	$\theta_0'(0)$	$\theta_1'(0)$	$f_0'(0)$	$f_1'(0)$	$f_2'(0)$
0.1	-0.10	0.4	-1.83271	-1.74107	-0.49224	-1.83271	8.33833	-7.77005
0.1	-0.15	0.4	-1.83271	-1.74107	-0.59604	-1.83271	8.33833	-7.92320
0.1	-0.05	0.4	-1.83271	-1.74107	-0.38844	-1.83271	8.33833	-7.61688
0.4	-0.10	0.4	-1.83271	-1.46616	-1.46385	-1.83271	8.85530	-8.76058
0.01	-0.10	0.4	-1.83271	-1.82354	-0.23215	-1.83271	8.18326	-7.48848
0.1	-0.10	2.0	-1.83271	-1.74107	-0.63009	-1.83271	12.4213	-4.05979

**Table 2** Numerical values of wall shear stress function  $f_i'(0)$ , wall temperature function  $\theta_i'(0)$ ,  $i = 0,1,2$  and concentration function  $c'(0)$  for  $M = 0.5, a = 0.5, Gc = 2.0, Gr = 5.0, Pr = 0.72, Sc = 1.0, S = -0.10, Er = 0.1$  and  $K_0 = 0.2$

$\omega t$	$\text{Cos}\omega t$	$c_0'$	$f_0'$	$f_1'$	$f_2'$	$\theta_0'$	$\theta_1'$	$\theta_2'$
0	1	-1.83271	-1.83271	4.58629	-10.2055	-1.39087	-0.32271	0.42140
$\pi/6$	0.866	-1.83271	-1.58712	6.05459	-12.5188	-1.40766	-0.33343	0.44490
$\pi/4$	0.707	-1.83271	-1.29572	7.80362	-15.2804	-1.42446	-0.33416	0.44638
$\pi/3$	0.5	-1.83271	-0.91635	10.0917	-18.9028	-1.44124	-0.31539	0.40473
$\pi/2$	0	-1.83271	0.0	15.6696	-27.7758	-1.45803	-0.17625	0.09593

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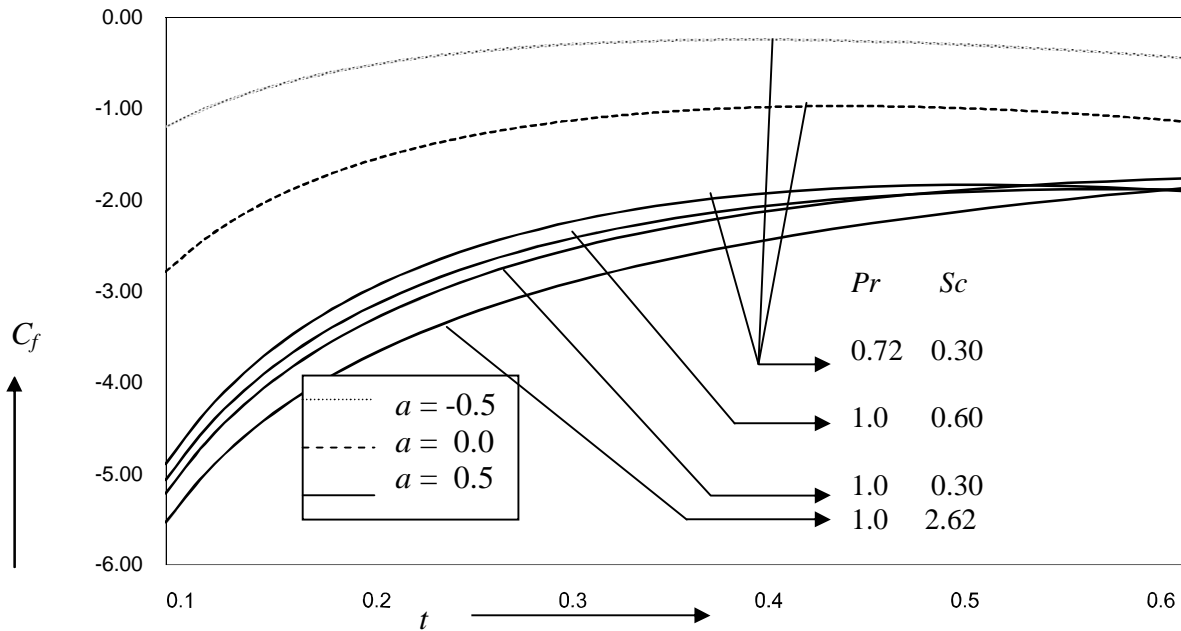


Fig. 1 Variation of skin friction coefficient with time at fixed values of  $M = 0.5$ ,  $Gr = 5.0$ ,  $Gc = 2.0$ ,  $S = -0.10$ ,  $Er = 0.1$ ,  $K_0 = 0.2$  and  $\omega t = 0$

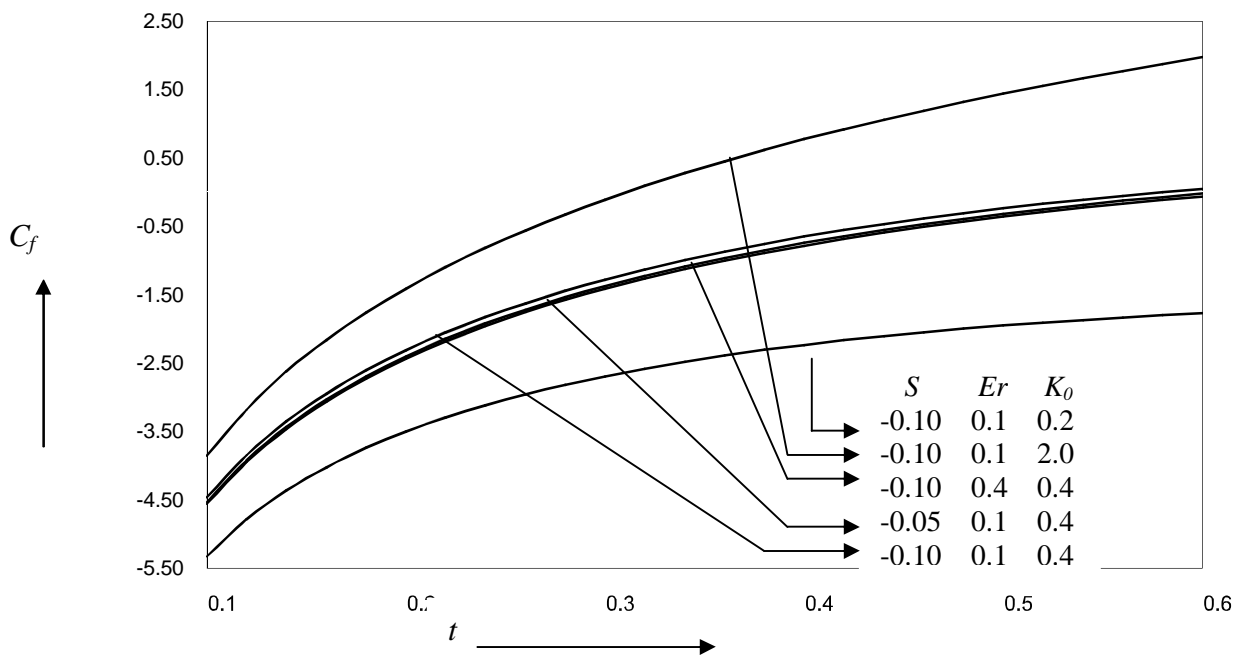


Fig. 2 Variation of skin friction coefficient with time at fixed values of  $M = 0.5$ ,  $Gr = 5.0$ ,  $Gc = 2.0$ ,  $Pr = 1.0$ ,  $Sc = 1.0$ ,  $a = 0.5$  and  $\omega t = 0$



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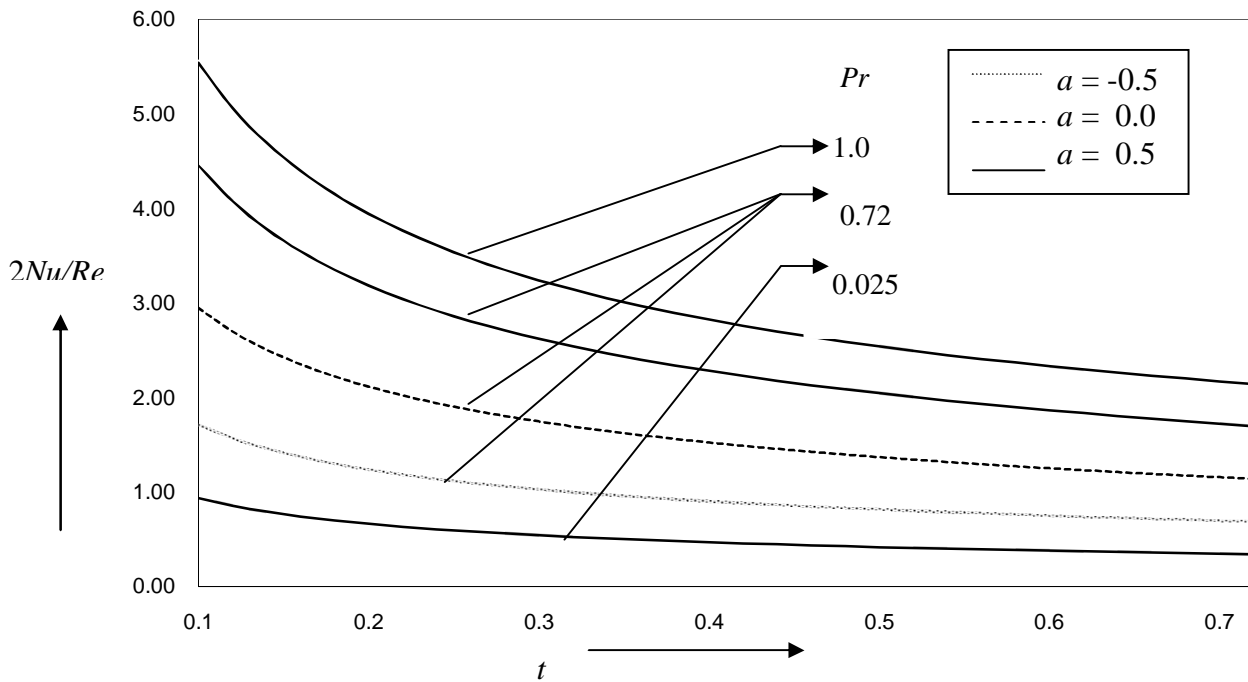


Fig. 3 Variation of surface heat transfer function with time at fixed value of  $M = 0.5$ ,  $Gr = 5.0$ ,  $Gc = 2.0$ ,  $Sc = 0.30$ ,  $S = -0.10$ ,  $Er = 0.1$ ,  $K_0 = 0.2$  and  $\omega t = 0$

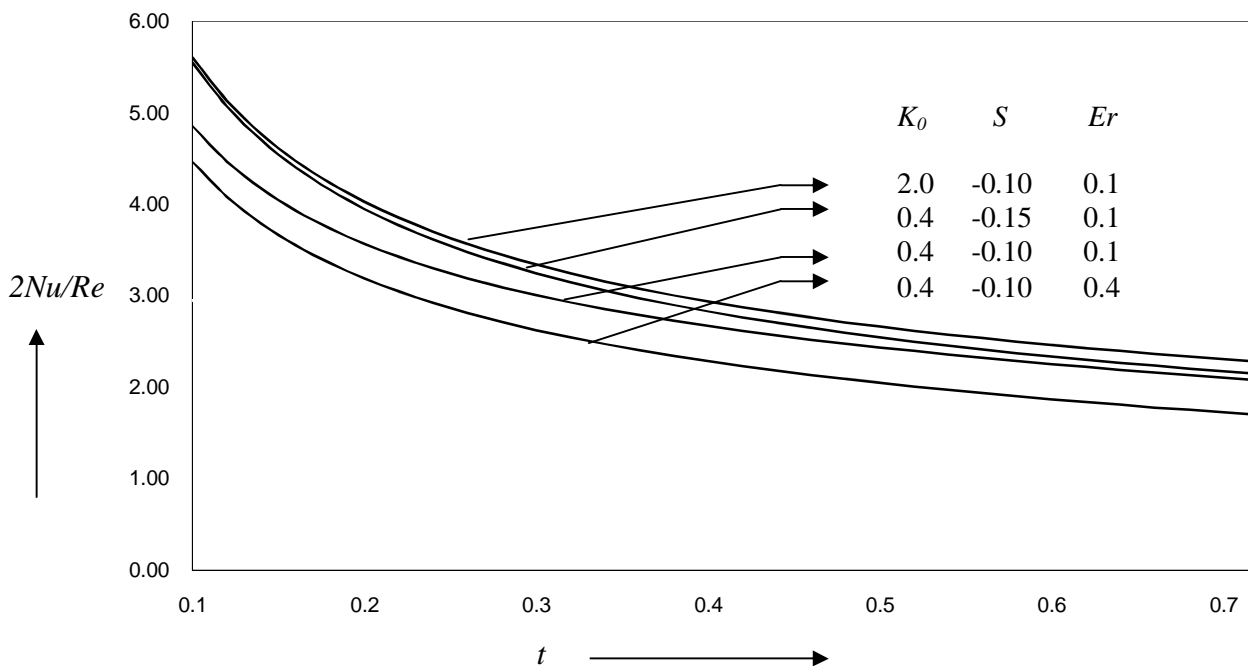


Fig. 4 Variation of surface heat transfer function with time at fixed value of  $M = 0.5$ ,  $Gr = 5.0$ ,  $Gc = 2.0$ ,  $Sc = 1.0$ ,  $Pr = 1.0$ ,  $a = 0.5$  and  $\omega t = 0$

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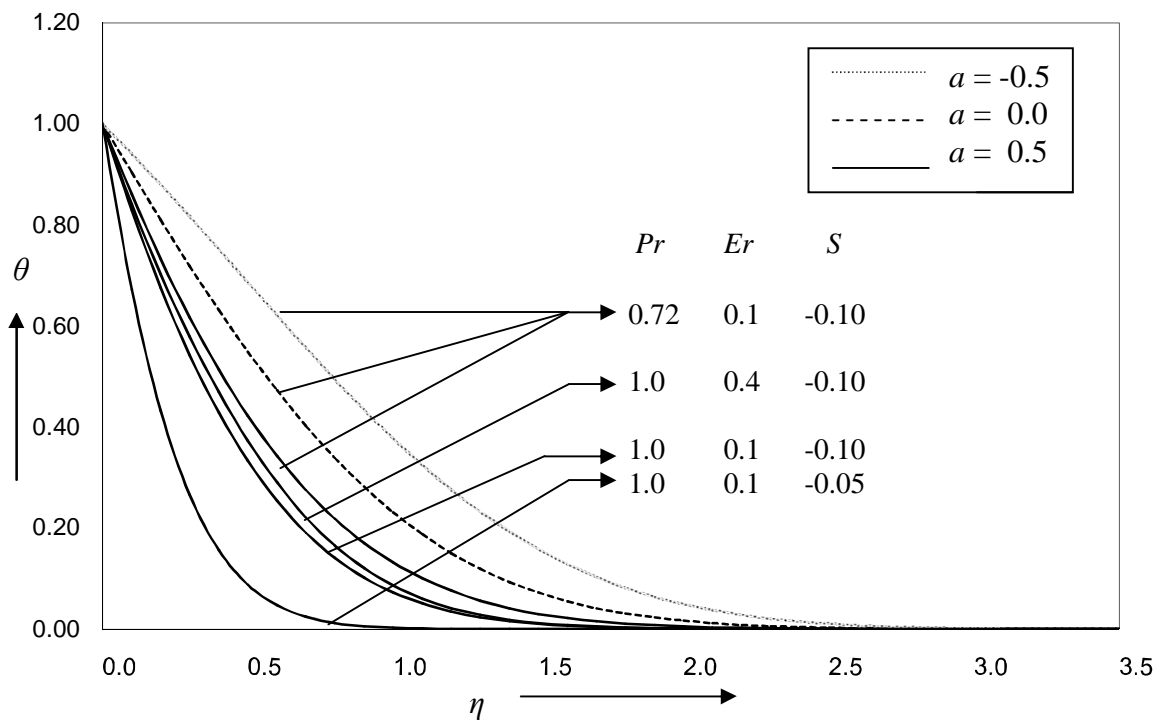


Fig. 5 Temperature profiles at fixed values of  $M = 0.5$ ,  $Gr = 5.0$ ,  $Gc = 2.0$ ,  $Sc = 0.30$ ,  $K_0 = 0.2$  and  $\omega t = 0$

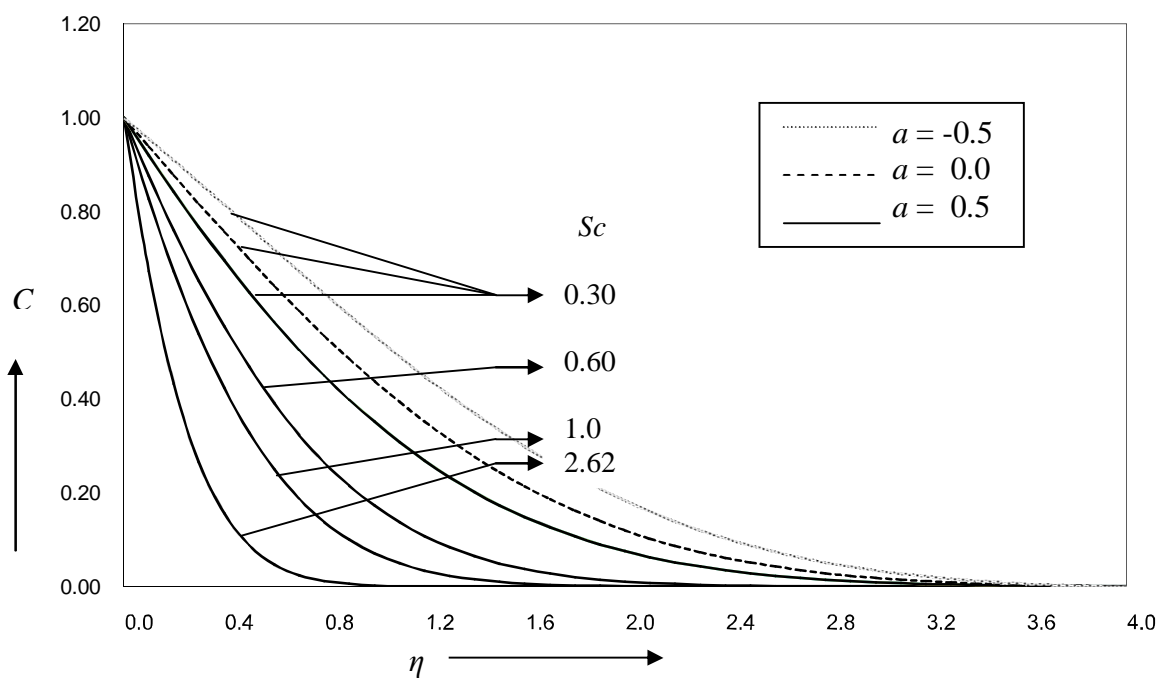


Fig. 6 Concentration profiles at fixed values of  $M = 0.5$ ,  $Gr = 5.0$ ,  $Gc = 2.0$ ,  $Pr = 1.0$ ,  $S = -0.10$ ,  $Er = 0.1$ ,  $K_0 = 0.2$  and  $\omega t = 0$

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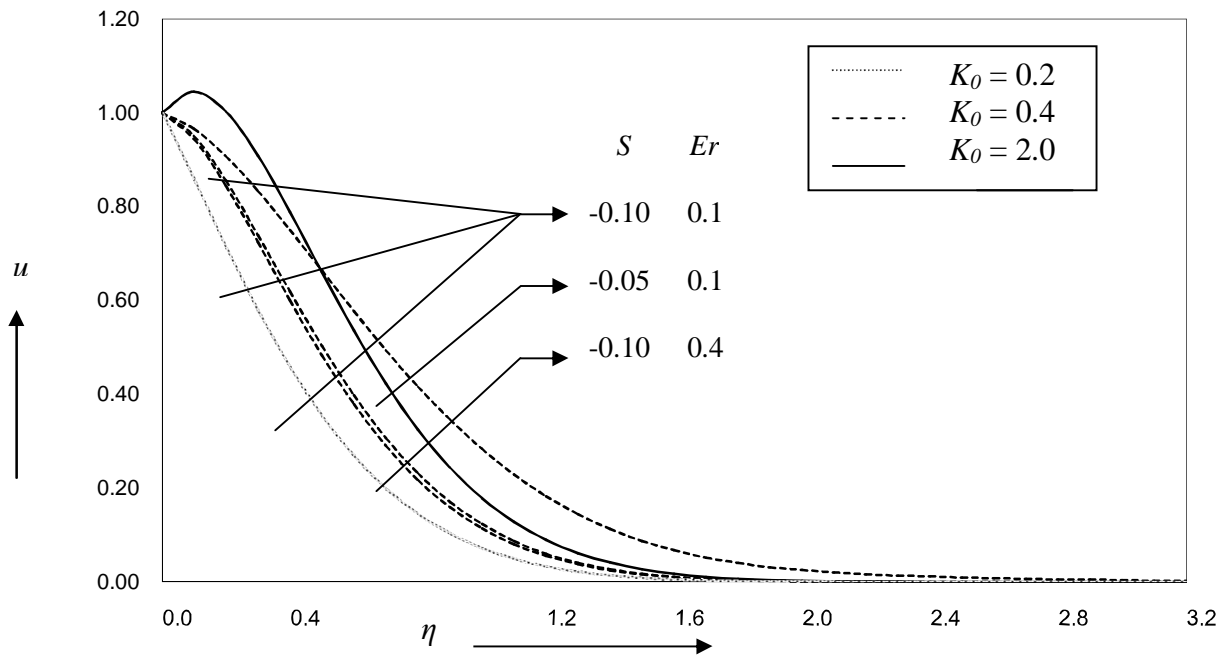


Fig. 7 Velocity profiles at fixed values of  $M = 0.5$ ,  $Gr = 5.0$ ,  $Gc = 2.0$ ,  $Pr = 1.0$ ,  $Sc = 1.0$ ,  $a = 0.5$  and  $\omega t = 0$

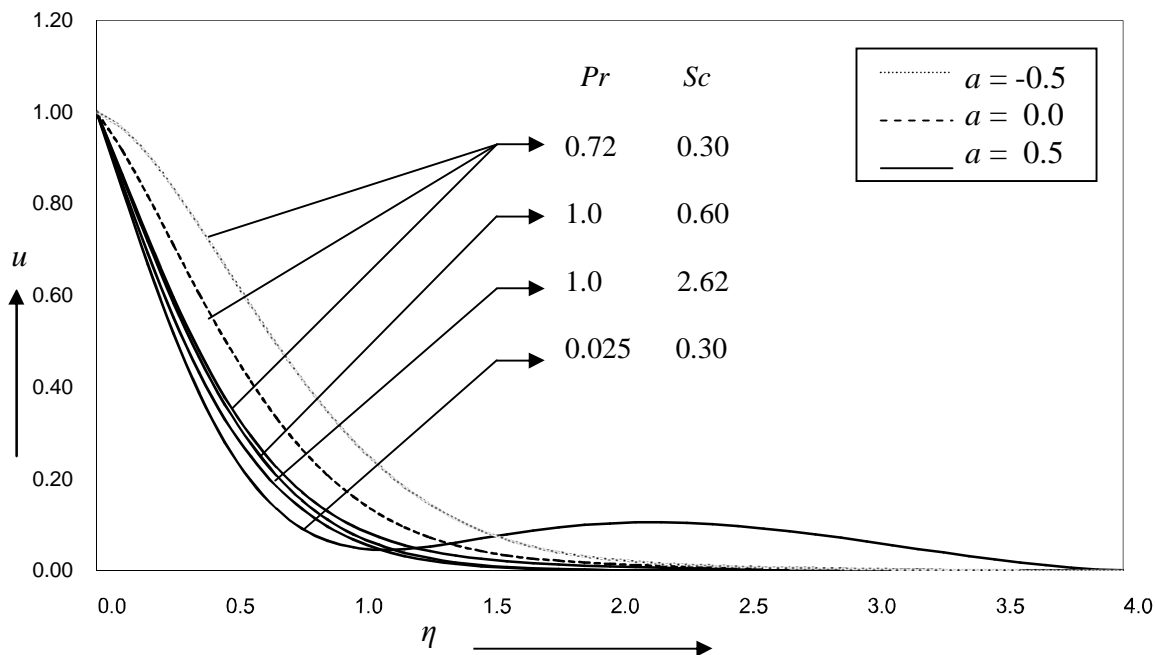


Fig. 8 Velocity profiles at fixed values of  $M = 0.5$ ,  $Gr = 5.0$ ,  $Gc = 2.0$ ,  $Er = 0.1$ ,  $S = -0.10$ ,  $K_0 = 0.2$  and  $\omega t = 0$

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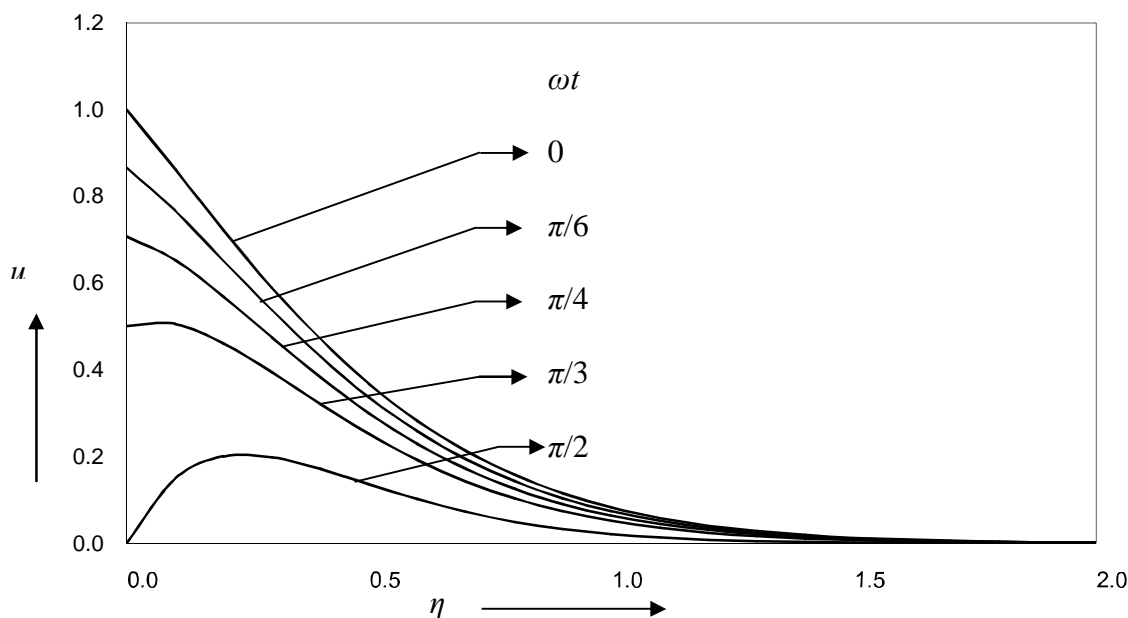


Fig. 9 Velocity profiles at fixed values of  $M = 0.5$ ,  $Gr = 5.0$ ,  $Gc = 2.0$ ,  $Pr = 0.72$ ,  $Sc = 1.0$ ,  $a = 0.5$ ,  $Er = 0.1$ ,  $S = -0.10$  and  $K_0 = 0.2$

## IV. CONCLUSIONS

1. Since the curve of  $c_f$  and rate of heat transfer becomes asymptotic for  $t \geq 0.6$ . It may be concluded that the oscillating flow is reduced to steadiness after time  $t = 0.6$ .
2. Due to viscous heating and sink strength the free convection velocity increases.
3. Presence of foreign species reduces the skin friction and velocity.
4. Thermal boundary layer thickness decreases as sink strength increases and its increases with Eckert number for both mercury and electrolyte solution.
5. Concentration in boundary layers decreases as the Schmidt number increases.
6. When the plate moves upward (i.e when  $Cos\omega t$  is positive) the fluid near the plate moves with greater velocity due to convection.

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