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INTERNATIONAL CENTRE FOR
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ABSTRACT

Magnetohydrodynamic forced and free convection flow of an electrically conducting viscous incompressible fluid past a vertical flat plate with uniform heat flux in the presence of a magnetic field acting normal to the plate that moves with the fluid has been studied near the leading edge of the plate. The coupled non-linear equations are solved by the method of superposition for the values of the Prandtl number ranges from 0.01 to 10.0. The velocity and the temperature profiles are presented graphically and the values of the wall shear stress as well as the heat transfer rate are presented in tabular form showing the effect of the buoyancy force and the applied magnetic field. To show the accuracy of the present method some typical values are compared with the available one.

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I. INTRODUCTION

We are frequently concerned with natural convection flow and the consequent heat transfer that arises over surfaces which are at a temperature different from that of the ambient medium. In the case of a heated body cooling in an extensive isothermal medium, the fluid flows adjacent to the hot surface of the body, and this heated fluid eventually rises above the body as a buoyant flow or wake. Similarly, a body colder than the ambient fluid would cause a flow opposite to that due to the heated body, since the fluid adjacent to the body becomes colder and hence heavier than the ambient fluid, resulting in a flow in the direction of the gravitational force. In nature too, many natural or free convection flows occurs adjacent to heated or cooled surfaces. Free convection can have significant effect on forced flows over solid bodies, too. It can alter the flow field and hence the heat transfer rate and wall-shear distribution. The simplest physical model is two-dimensional, mixed forced and free convection along a flat plate. Recent examples of application of this model can be found in the areas of reactor safety, combustion flames, and solar collectors, as well as building energy conservation.

Extensive studies [1-9] have been conducted on mixed convection along vertical, horizontal, or inclined surfaces. It has been generally recognized that $\xi(= Gr/Re^2\infty)$, where Gr is the Grashof number and Re is the Raynolds number, in the governing parameter for a vertical plate. Forced convection exists as a limit when ξ goes to zero which occurs at the leading edge, and the free-convection limit can be reached if ξ becomes large. Perturbation solutions have been developed for both limits, since both forced convection and free convection have similarity solutions. Empirical patching of two perturbation solutions has also been carried out to provide a solution by Rajn *el al.* [10] which cover the whole range of ξ. A finite difference solution has been obtained by him applying an algebraic transformation $z = 1(1+\xi^2)$. For horizontal plate, the axial pressure gradient induced by buoyancy force is $0(Gr/Re^{5/2})$. Numerous solutions have been developed by considering the free-convection effect as a perturbation quantity. Again, forced convection exists as a limit for small ξ and the free convection can be reached as ξ approaches infinitely. Recently, Tingwei *et al.* [11], have studied the effect of forced and free convection along a vertical flat plate with uniform heat flux considering that the buoyancy parameter ξ to be small.

Effects of transversely applied magnetic field on free convection of an electrically conducting fluid past a semi-infinite plate were studied by many researches [12-15], because of its application in nuclear engineering in connection with the cooling of reactors. In the present paper, therefore, we propose to investigate the combined forced and free convection of an electrically conducting fluid past a vertical flat plate at whose surface, the heat flux is uniform and a magnetic field is applied parallel to the direction normal to the plate and is allowed to pass it along with the fluid. The equations governing the flow are developed in Section 2 and are solved numerically using the method of superposition for small values of ξ, the buoyancy parameter.

2. FORMULATION OF THE PROBLEM

Consider the free convection flow of an electrically conducting and viscous incompressible fluid up a heated semi-infinite flat plate extended vertically in the upward direction. Let the temperature of the free-stream be T_0 having the velocity U_0 which is uniform. A magnetic field of strength $B(x)$ is considered to be applied parallel to the y-axis which is normal to the plate and is allowed to move past the plate with fluid. Here we assume that the induced magnetic field produced by the motion of the electrically conducting fluid is neglible. This assumption is valid for smaller magnetic Reynolds number. Further, since no external electric field is applied and the effect of polarization of the ionized fluid is neglible, we may also assume that the electric field $E = 0$. Under the above assumption the boundary layer equations governing the flow past a plate at whose surface the heat flux q is uniform, are (Cobble [14]):

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = g\beta(T - T_0) - \sigma\frac{B^2(x)}{\rho}\,(U_0 - u) + v\frac{\partial^2 u}{\partial y^2} \tag{1}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = k\frac{\partial^2 T}{\partial y} \tag{2}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{3}$$

subject to the boundary conditions

$$u = v = 0, \quad -k\left(\frac{\partial T}{\partial y}\right) = q \quad \text{at} \quad y = 0$$

$$u \longrightarrow U_0 \quad T \longrightarrow T_0 \quad \text{as} \quad y \longrightarrow \infty. \tag{4}$$

Here (u, v) are velocity components associated with the direction of increasing coordinates (x, y) measured along and normal to the plate, respectively. T is the temperature of the fluid in the boundary layer, g the acceleration due to gravity, β the co-efficient of thermal expansion, k the thermal conductivity, σ the electric conductivity, ν the kinematic viscosity of the fluid and ρ the reference density of the surrounding fluid.

In formulating Eqs.(1)–(3) it has been assumed that (i) the ratio of thermal diffusivity to magnetic diffusivity is small compared to unity, (ii) fluid property variations are limited to density variation which is taken into account only in so far as it effects the buoyancy terms only, (iii) the short circuit assumption applies and (iv) the viscous and electrically dissipation effects are neglected.

Now to reduce Eqs.(1)–(3) to ordinary differential equations, we are to introduce the stream function ψ throughout Eqs.(1)–(3), which is defined in the relation (5). These yield the expressions to be transformed Eqs.(6) and (7):

$$u = \frac{\partial\psi}{\partial y}, \quad v = -\frac{\partial\psi}{\partial x} \tag{5}$$

$$\frac{\partial\psi}{\partial y}\,\frac{\partial^2\psi}{\partial x\partial y} - \frac{\partial\psi}{\partial x}\,\frac{\partial^2\psi}{\partial y^2} = g_B(T - T_0) + \frac{\sigma B^2}{\rho}\Big(U_0 - \frac{\partial\psi}{\partial y}\Big) + \nu\,\frac{\partial^3\psi}{\partial y^3} \tag{6}$$

$$\frac{\partial\psi}{\partial y}\,\frac{\partial T}{\partial x} - \frac{\partial\psi}{\partial x}\,\frac{\partial T}{\partial y} = k\,\frac{\partial^2 T}{\partial y^2} \tag{7}$$

We now introduce the following set of transformation of Tingwei *et al.* [11] for the dependent and the independent variables:

$$\left.\begin{array}{lll} & \eta = (U_0/\nu x)^{1/2}y, & \psi(x,y) = (\nu U_0 x)^{1/2} f(\xi,\eta) \\ & T - T_0 = \left(\frac{U_0 x}{\nu}\right)^{1/2}\left(\frac{qx}{k}\right)\theta(\xi,\eta), & B(x) = B_0 x^{1/2} \\ \text{where} & & \\ & \xi = Gr/Re^{5/2} & \\ \text{with} & & \\ & Gr = g\beta q x^4/k\nu^2, & Re = U_0 x/\nu \end{array}\right\} \tag{8}$$

into Eqs.(6) and (7) as well as in the boundary conditions (4), we find

$$f''' + \frac{1}{2}ff'' = \xi\left[\frac{3}{2}f'\frac{\partial f'}{\partial\xi} - \frac{3}{2}f''\frac{\partial f}{\partial\xi} - M(f' - 1) - \theta\right] \tag{9}$$

$$\theta'' + \frac{1}{2}\sigma(f\theta' - f'\theta) = \frac{3}{2}\sigma\xi\left(f'\frac{\partial\theta}{\partial\xi} - \theta'\frac{\partial f}{\partial\xi}\right) \tag{10}$$

$$\left.\begin{array}{ll} f(\xi,0) = f'(\xi,0) = 0, & \theta'(\xi,0) = -1 \\ f'(\xi,\infty) = 1, & \theta(\xi,\infty) = 0 \end{array}\right\} \tag{11}$$

Here primes denote differentiations of the functions with respect to η only, $\sigma (= \nu/k)$ the Pandtl number and $M\left[= \frac{\sigma B_0^2 k}{\rho g\beta q}\,(U_0^3\nu)^{-1/2}\right]$ is the magnetic field parameter.

In the present problem the buoyancy force is proportional to $\xi\ (= Gr/Re^{5/2})$. The solution can be expanded as an asymptotic series in ξ. This series solution is valid for small ξ, that is, for a forced-convection near the leading edge of the plate; at this region the free convection effect is also smaller (Yao, [9]). Therefore, we consider here ξ to be smaller so that we get the combined forced and free convection effects on the flow near the leading edge. Accordingly, we expand the functions $f(\xi,\eta)$ and $\theta(\xi,\eta)$ in powers of ξ, that is,

$$f(\xi,\eta) = f_0(\eta) + \xi f_1(\eta) + \xi^2 f_2(\eta) + \ldots \tag{12}$$

$$\theta(\xi,\eta) = \theta_0(\eta) + \xi\theta_1(\eta) + \xi^2\theta_2(\eta) + \ldots \tag{13}$$

substituting these series into Eqs.(9)-(11) and collecting the terms upto $0(\xi^2)$ only, we get order 0:

$$f_0''' + \frac{1}{2} f_0 f_0'' = 0 \quad (14)$$

$$\theta_0'' + \frac{1}{2}\sigma(f_0\theta_0' - f_0'\theta_0) = 0 \quad (15)$$

$$f_0(0) = f_0'(0) = 0, \; \theta_0'(0) = -1$$

$$f_0'(\infty) = \theta_0(\infty = 0 \quad (16)$$

$0(\xi)$:

$$f_1''' + \frac{1}{2} f_0 f_1'' - \frac{3}{2} f_0' f_1' + 2 f_0'' f_1 = M(f_0' - 1) - \theta_0 \quad (17)$$

$$\theta_1'' + \frac{1}{2}\sigma(f_0\theta_1' - 4 f_0'\theta_1) = \frac{1}{2}\sigma(\theta_0 f_1' - 4\theta_0' f_1) \quad (18)$$

$$f_1(0) = f_1'(0) = \theta_1'(0) = 0, \quad f_1'(\infty) = \theta_1(\infty) = 0 \quad (19)$$

$0(\xi^2)$:

$$f_2''' + \frac{1}{2} f_0 f_2'' - 3 f_0' f_2' + \frac{7}{2} f_0'' f_2 = \frac{3}{2} f_1'^2 - 2 f_1 f_1'' + M f_1 - \theta_1 \quad (20)$$

$$\theta_2'' + \frac{1}{2}\sigma(f_0\theta_2' - 7 f_0'\theta_2) = \sigma(2 f_1'\theta_1 + \frac{1}{2}\theta_0 f_2' - 2\theta_1' f_1 - \frac{7}{2}\theta_0' f_2) \quad (21)$$

$$f_2(0) = f_2'(0) = \theta_2'(0) = 0, \quad f_2'(\infty) = \theta_2(\infty) = 0 \quad (22)$$

The present problem, in absence of magnetic field, had been studied by Tingwei *et al.* [11] using the modified fourth order Rungee–Kutla method of Lapidus and Seinfeld [16]. But, in the present paper we are proposing to study the problem in a different approach, the details of which are given in the following section.

3. METHOD OF SOLUTIONS

From the previous section it is evident that the set of Eqs.(15)-(22) are linear and may be solved independently one after another, since the first Eq.(14) is the well-known Blasius equation solution of which is already available. Therefore, we first propose to solve Eq.(15). Since the function $f_0(\eta)$ is known, we may reduce the boundary value problem provided with Eq.(15) and the boundary conditions (16) by the method of superposition (Na, [17]) as given below. We now write the solution of Eq.(15) in the following form:

$$\theta_0(\eta) = \theta_{01}(\eta) + \lambda\, \theta_{02}(\eta) \quad (23)$$

and substitute this into Eq.(14) and the boundary conditions (15) to get

$$\theta_{01}'' + \frac{1}{2}\sigma(f_0\theta_{01}' - f_0'\theta_{01}) = 0 \quad (24)$$

$$\theta_{02}'' + \frac{1}{2}\sigma(f_0\theta_{02}' - f_0'\theta_{02}) = 0 \quad (25)$$

$$\theta_{01}(0) = 0, \quad \theta_{01}'(0) = -1, \quad \theta_{02}(0) = 1, \quad \theta_{02}'(0) = 0 \quad (26)$$

The initial conditions (26) are obtained on the assumption that $\theta_0(0) = \lambda$.

Eqs.(24)-(26) now constitute a set of initial value problems that can be integrated without interation by the use of any initial value solver to give θ_{01} and θ_{02}. The integrations are carried out in the domain $0 \leq \eta \leq \eta_\infty$ for $\eta_\infty = 12.0$. From the above integration knowing the values of the functions $\theta_{01}(\eta)$ and $\theta_{02}(\eta)$ at η_∞, we find the parameter λ, using the condition $\theta_0(\infty) = 0$, from the following relation:

$$\lambda = -\theta_{01}(\infty)/\theta_{02}(\infty). \quad (27)$$

Finally, knowing the value of λ from (27), we find easily the solutions for $\theta_0(\eta)$ from the relation (23).

Following the same method all other boundary value problems (17) through (22) are solved one after another. During the course of integration for some values of σ the gride size $\Delta\eta$ had to be changed. For example, for $\sigma \geq 1.0$, and $\sigma \leq 0.1$ the value of $\Delta\eta$ is used to be 0.0125 and 0.1, respectively. But for $0.1 < 0 < 1, \Delta\eta$ is taken 0.05. Table 1 compares the value of $f_0''(0), \theta_0(0), f_1''(0), \theta_1(0), f_2''(0)$ and $\theta_2(0)$ with that of Tingwei *et al.* [11] for different values of the Prandtl number σ.

Once we know the functions $f_0, f_1, f_2, \theta_0, \theta_1$ and θ_2, we may find the velocity distribtion from the relation (28)

$$u/U_0 = f_0'(\eta) + \Big(\frac{Gr}{Re^{5/2}}\Big) f_1'(\eta) + \Big(\frac{Gr}{Re^{5/2}}\Big) f_2'(\eta) + \ldots \quad (28)$$

and the temperature distribution from the relation

$$\frac{T - T_0}{T_w - T_0} = \frac{\theta_0(\eta) + (Gr/Re^{5/2})\theta_1(\eta) + (Gr/Re^{5/2})^2\theta_2(\eta) + \ldots}{\theta_0(0) + (Gr/Re^{5/2})\theta_1(0) + (Gr/Re^{5/2})\theta_2(0) + \ldots} \quad (29)$$

Knowing the velocity and the temperature distribution one can easily know the wall shear-stress and the heat transfer rate. The wall shear-stress may be expressed in terms of the local skin-friction co-efficient as given below:

$$c_f = \frac{2\tau_0}{\rho U_0^2}$$

Substitution of Eq.(28) to which yields

$$\frac{1}{2}Re^{1/2}c_f = f''(\xi,0)$$
$$= f_0'' + \Big(\frac{Gr}{Re^{5/2}}\Big)f_1''(0)\Big(\frac{Gr}{Re^{5/2}}\Big)^2 f_2''(0) + ... \quad (30)$$

Finally, in terms of the Nusselt number, the heat transfer may be expressed as

$$Re^{-1/2}Nu = \frac{qx}{(T_w - T_0)k}$$
$$= \Big[\theta_0(0) + \Big(\frac{Gr}{Re^{5/2}}\Big)\theta_1(0) + \Big(\frac{Gr}{Re^{5/2}}\Big)^2\theta_2(0) + ...\Big]^{-1} \quad (31)$$

In the following section the results obtained from the above analysis are discussed in detail.

4. RESULTS AND DISCUSSIONS

In fact, assumptions used to establish to governing equation are particularly appropriate to liquid metals. Moreover, as liquid metals are currently used as coolants in nuclear engineering, we have pursued solutions into the lower Pandtl number range, e.g. 0.05 for lithium, 0.01 for mercury and 0.005 for sodium. In fact, detailed numerical solutions having obtained for $\sigma = 10, 1, 0.7, 0.5, 0.1, 0.05, 0.02$ and 0.01. Associated numerical data is available from the authors. Finally, the numerical integrations of Eqs.(14) to (22) for the above values of σ were carried out on *Gould*/9000 mainframe of the ICTP, Trieste, Italy.

In Table 1 we have entered the values of $f_0''(0), f_1''(0), f_2''(0), \theta_0(0), \theta_1(0)$ and $\theta_2(0)$ for different values of σ in absence of the magnetic field for comparison with the results of Tingwei *et al.* [11]. It can be easily seen that the largest computational difference between the present values and the corresponding values of Tingwei *et al.* are less than 2%. The value of $f_1''(0)$ for $\sigma = 0.1$ obtained by Tingwei *et al.*, which is 8.54192, must be a misprint, since a more accurate one is 6.54192.

Table 2 represents the values of wall shear-stress as well as the heat transfer rate for $M = 0.0, 0.5, 1.0, 2.0$ and $\sigma = 0.01, 0.1$ and 0.7. It is observed that for all Prandtl number, the wall shear-stress decreases and the rate of heat transfer increases due to the increase of the magnetic field.

The velocity and the temperature distribution are shown graphically in Figs.1 to 3. In Figs.1a and 1b the dotted curves represent respectively the velocity and the temperature profiles in absence of magnetic field when the fluid is air and the value of the buoyancy parameter ξ is 0.1. Other curves are in presence of magnetic field. From these

it is observed that the presence as well as the increase in the magnetic field leads to the decrease in the velocity field and to increase in the temperature field. The velocity and the temperature profiles for different fluids and with different buoyancy forces are shown in Fig.2a when the value of the magnetic field parameter is 1.0. In this figure, the dotted curves are for $\xi = 0.02$, the broken for $\xi = 0.07$ and the solids are for $\xi = 0.12$. Comparing these curves we may conclude that the buoyancy force leads to the increase in both the temperature and the velocity field. On the other hand, the fluid velocity decreases and the temperature distribution increases due to the decrease in the value of the Prandtl number. Finally, Figs.3a and 3b represent the velocity as well as the temperature fields with the effect of the magnetic field for different kind of fluids ($\sigma = 0.01, 0.05$ and 0.1) at $\xi = 0.1$.

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TABLE CAPTIONS

Table 1 Values of $f_0''(0), f_1''(0).f_2''(0), \theta_0(0), \theta_1(0)$ and $\theta_2(0)$ in absence of magnetic field.

Table 2 Values of local skin-friction co-efficient and the Nusselt number for $\xi = 0.1$.

Table 1

σ	f_0''	$\theta_0(0)$	$f_1''(0)$	$-\theta_1(0)$	$-f_2''(0)$	$\theta_2(0)$
0.01	0.3306	8.74748*	13.0633*	17.9801*	126.949*	407.404*
		8.74754	13.0602	17.9301	126.909	407.235
0.10	0.3306	4.93984*	8.54192*	11.5080*	38.0465*	147.422*
		4.94009	6.54073	11.5086	39.0515	142.406
0.70	0.3306	2.46371*	2.48689*	2.84295*	6.24779*	14.8624*
		2.46420	2.48731	2.84355	6.24994	14.8677
1.0	0.3306	2.17879*	2.05983*	2.15080*	4.35316*	9.45458*
		2.17933	2.0603	2.15154	4.35509	9.46015
10.00	0.3306	1.00212*	0.55473*	0.30196*	0.33816*	0.38178*
		1.00234	0.55492	0.30208	0.33915	0.38216

* The values are due to Tingwei *et al.* [11]

Table 2

M		$2\sqrt{Re}c_f$			$-Re^{1/2}Nu$		
	σ	0.01	0.1	0.7	0.01	0.1	0.7
0.0		0.36389	0.59561	0.51829	0.09066	0.19181	0.42945
0.5		0.29276	0.57852	0.54226	0.08832	0.18610	0.42729
1.0		0.21064	0.55553	0.56035	0.08598	0.18012	0.42240
2.0		0.2878	0.49190	0.57885	0.08141	0.16766	0.40523

FIGURE CAPTIONS

Fig.1a Velocity profiles against η for $\sigma = 0.7, \xi = 0.1$.

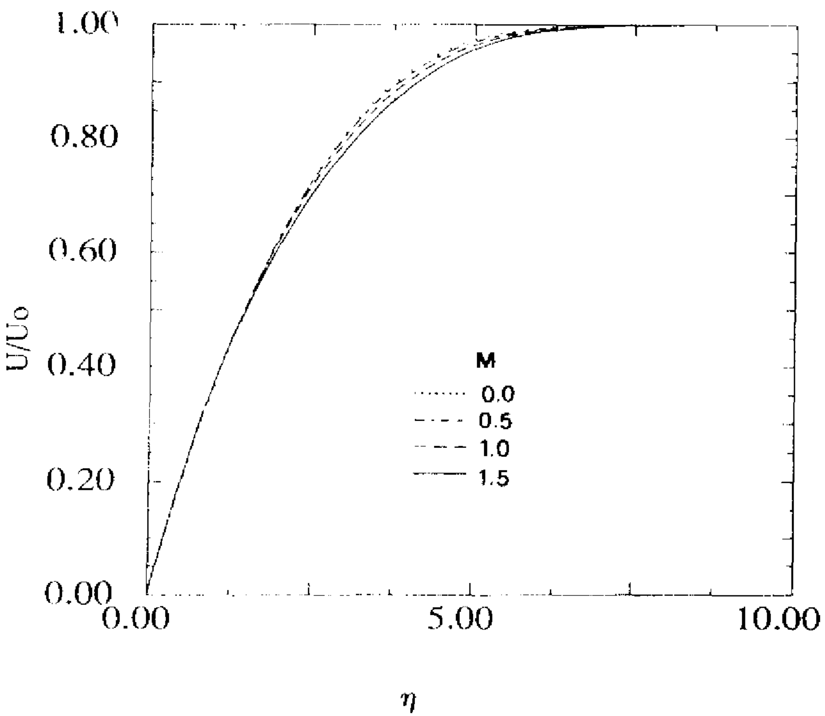
Fig.1b Temperature profiles against η for $\sigma = 0.7, \xi = 0.1$.

Fig.2a Velocity profiles against η for $M = 1.0$ and for different values of σ and ξ.

Fig.2b Temperature profiles against η for $M = 1.0$ and for different values of σ and ξ.

Fig.3a Velocity profiles against η for $\xi = 0.1$ and for different values of σ and M.

Fig.3b Temperature profiles against η for $\xi = 0.1$ and for different values of σ and M.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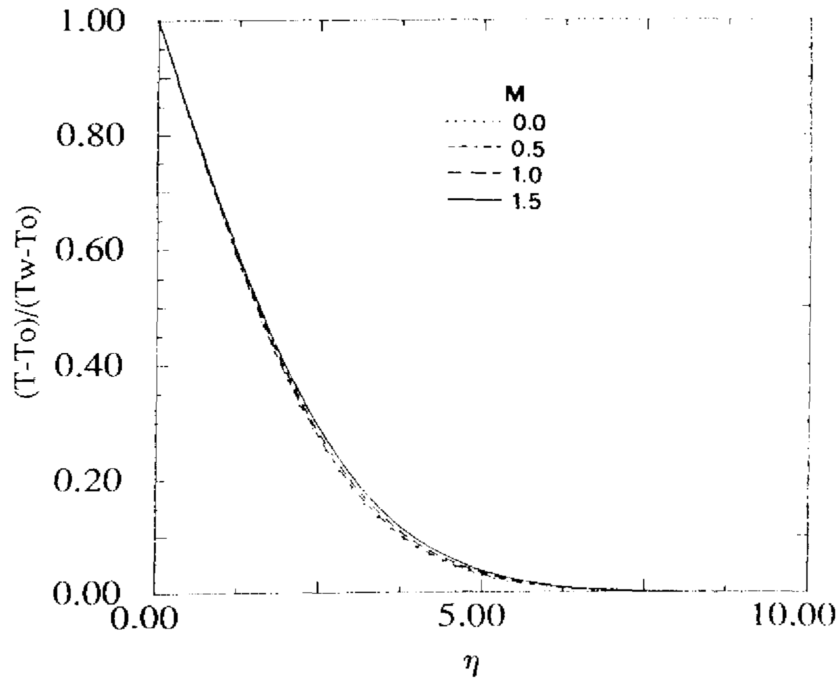
0.80
0.60
0.40
0.20
0.00
U/Uo
M
0.0
0.5
1.0
1.5
0.00
5.00
10.00
η

Fig.1a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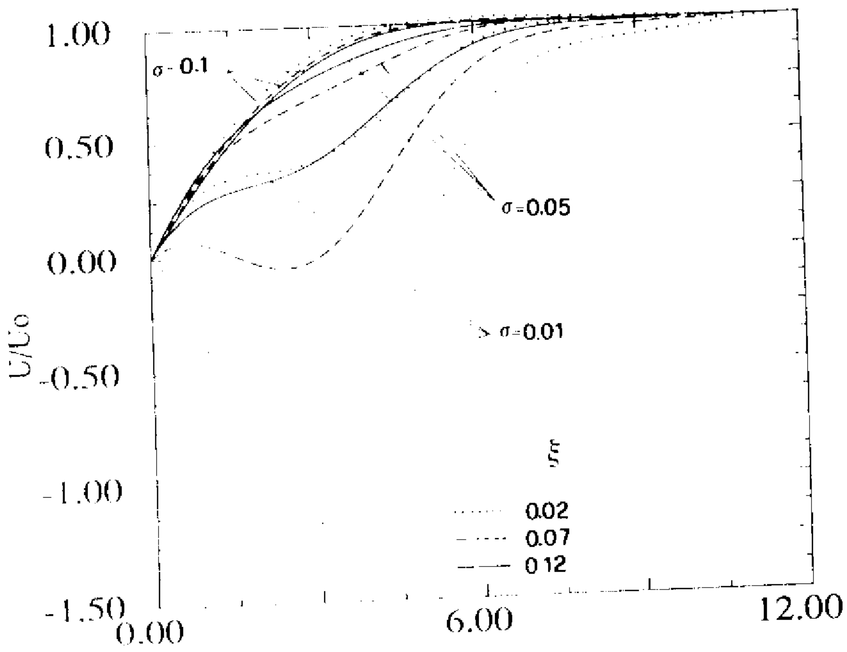
0.80
0.60
0.40
0.20
0.00
(T-To)/(Tw-To)
M
0.0
0.5
1.0
1.5
0.00
5.00
10.00
η

Fig.1b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0.50
0.00
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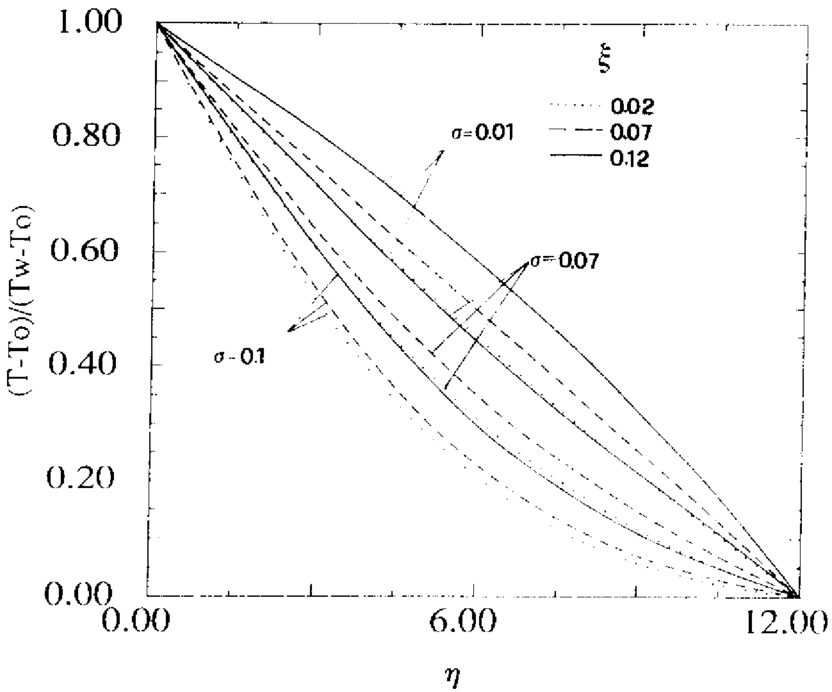
-1.00
-1.50
0.00
6.00
12.00
U/Uo
η
σ - 0.1
σ = 0.05
σ = 0.01
ξ
0.02
0.07
0.12

Fig.2a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0.40
0.20
0.00
0.00
6.00
12.00
(T-To)/(Tw-To)
η
ξ
0.02
0.07
0.12
σ = 0.01
σ = 0.07
σ - 0.1

Fig.2b

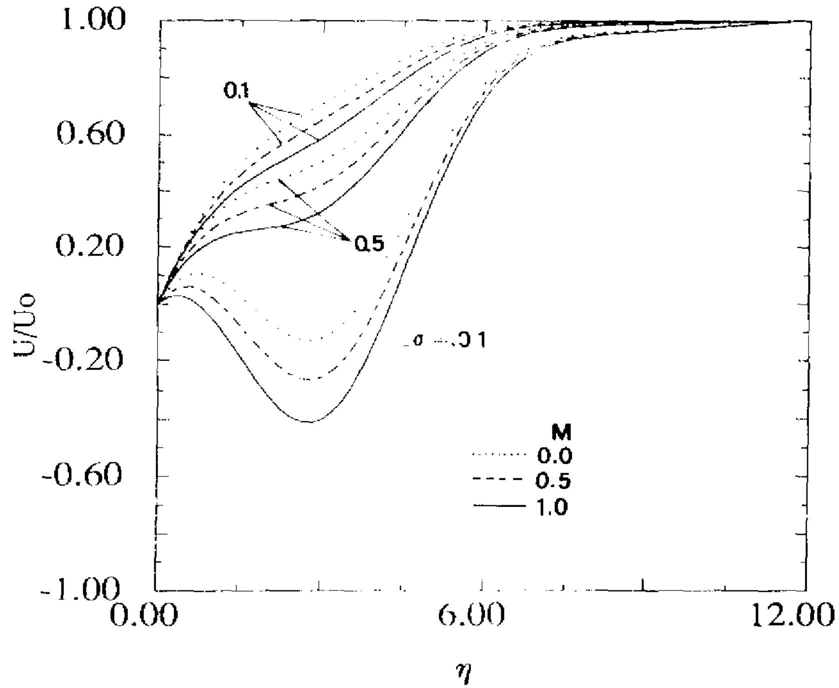

Fig.3a

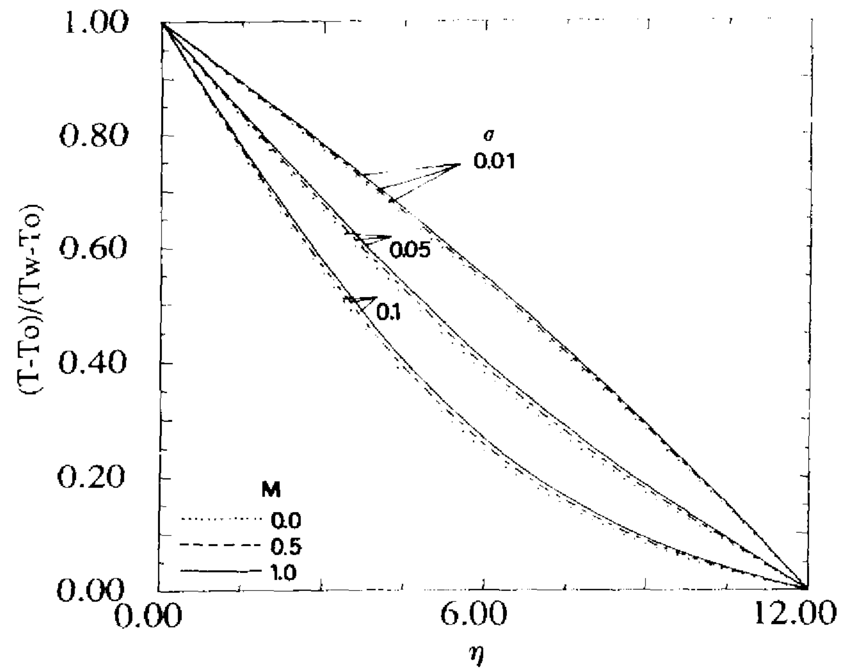

Fig.3b

Stampato in proprio nella tipografia
del Centro Internazionale di Fisica Teorica