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FREE CONVECTION FLOW ON A NONISOTHERMAL FLAT PLATE UNDER NONUNIFORM GRAVITY

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Abstract—In this paper, we present results obtained by using a numerical procedure for the free convection flow along a rotating nonisothermal plate subject to a nonuniform gravity field. Several specific forms for the temperature distributions of the plate are considered. For these instances the skin-friction and heat transfer rate on the wall at selected values of the distance from the leading edge and for some values of Prandtl numbers are presented. The method employed is shown to be very accurate in comparison with previous solutions.

NOMENCLATURE

$a_0, a_1, a_2, \ldots$, constants;
C_f, local skin-friction coefficient;
F, reduced stream function;
$F''(\xi, 0)$, wall skin-friction parameter;
$g(x)$, nonuniform gravity field in the direction opposite of the x-axis, $\pm\omega^2(x_0 \pm x)$;
g_0, uniform gravity field, $\pm\omega^2 x_0$;
G, dimensionless temperature function;
$G'(\xi, 0)$, wall heat transfer parameter;
Gr_x, local Grashof number, $g_0\beta(T_w - T_\infty)x^3/v^2$;
h_w, local heat transfer coefficient;
k, thermal conductivity;
Nu, local Nusselt number, $h_w x/k$;
$P(\xi)$, wall temperature function;
Pr, Prandtl number, v/α;
q_w, local surface heat transfer rate per unit area;
Re, Reynolds number, $u_r x_0/v$;
$S_w(\xi)$, dimensionless wall temperature;
T, temperature;
u, velocity component in x direction;
v, velocity component in y direction;
x, axial coordinate;
x_0, distance of leading edge of the plate from the center of rotation;
y, coordinate measured normal to the plate.

Greek symbols
α, thermal diffusivity;
β, bulk coefficient of thermal expansion;
η, transformed coordinate in y direction;
θ, dimensionless temperature;
μ, dynamic viscosity;
v, kinematic viscosity;
ξ, transformed coordinate in x direction;
ρ, density of fluid;
τ_w, wall skin-friction;
Ψ, stream function;
ω, angular velocity of rotating plate.

Subscripts
r, reference condition;
w, wall condition;
∞, ambient condition.

Superscripts
$'$, differentiation with respect to η;
$\bar{}$, dimensionless condition.

1. INTRODUCTION

Recent developments in engineering have led to increased interest in natural free convection flows from isothermal surfaces subject to nonuniform gravity fields. As it is well-known, centrifugal gravity fields play an important role in the understanding of particular flow problems that involve convection on rotating and/or curved plates at the earth's surface. For example centrifugal gravity fields arise in many rotating machinery applications.

Although similarity solutions have been obtained for the free convection flow on isothermal surfaces under constant gravity, they do not exist for a nonuniform gravity and/or walls with an arbitrary temperature distribution. Attempts to obtain practical solutions, exact or approximate, to the complete set of boundary layer free convection equations from isothermal surfaces under variation of the gravity field have been made by some research workers. Thus, the problem of the effect of nonuniform gravity caused by rotation of an isothermal flat plate has been considered in several papers [1–6]. The theoretical analyses of this problem were carried out using momentum integral and series expansion methods, and numerical local nonsimilarity or finite-difference procedures. The numerical evidence of Lienhard *et al.* [5] strengthened the conviction that the integral method is only an approximate approach and it is rather difficult to determine the range for which the solution is valid. Also the series expansion method is somewhat laborious to apply and it requires many terms for large distance, x, from the leading edge of the plate. The local nonsimilarity method, on the other hand, does not predict sufficiently accurate results for large x. This conclusion is borne out by the detailed study of Nath [6]. Later, these approaches were refined by Venkatachala and Nath [7] by using a finite-difference formulation.

The purpose of this paper is to present a description of the steady nonisothermal laminar free convection flows along (i) an infinite cold plate rotating at ω rad s^{-1} in a radial plane with its leading edge being at a distance x_0 from the axis of rotation, and (ii) a finite hot plate of length x_0, rotating at ω rad s^{-1} in a radial plane about the line $x = 0$, for the case in which gravity varies with the distance x. In the following we shall restrict ourselves to considering gravity fields varying linearly with this distance. The extension to other realistic cases, whilst straightforward in principle, would offer interesting problems as well. For each problem considered here the temperature distributions of the plates are assumed to be polynomials of first and second degree, respectively. In the analysis, an efficient and very accurate finite-difference method due to Keller [8] is employed to solve the system of transformed boundary-layer equations. This method has proved to be a very convenient technique for the numerical study of a variety of nonsimilar flow problems. Numerical solutions for the problems under consideration were obtained and the results for the skin-friction and heat transfer rate are presented for Prandtl numbers 0.7, 1.0, 10 and 100.

2. MATHEMATICAL FORMULATION

Consider an infinite cold plate rotating at ω rad s^{-1} in a radial plane with its leading edge beginning at a distance x_0 from the axis of rotation, or a finite hot plate of length x_0, rotating at ω rad s^{-1} in a radial plane about the line $x = 0$ subject to a nonuniform gravity field $g(x)$. The main effort in the present study is centered on the cases where the plates temperature distributions $T_w(x)$ have specific forms.

Let the coordinates be chosen such that x measures the distance from the leading edge of the plate and y measures the distance normal to the plate. The flow is assumed to be steady and incompressible. The boundary layer approximations are adopted along with the requirement that $\beta(T_w - T_\infty) \ll 1$ (large Taylor number). Thus, the equations governing the conservation of mass, momentum and energy can be written as

$$\frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} = 0, \tag{1}$$

$$\bar{u}\frac{\partial \bar{u}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{v}}{\partial \bar{y}} = \bar{g}(\bar{x})S_w(\bar{x})\theta + \frac{\partial^2 \bar{u}}{\partial \bar{y}^2}, \tag{2}$$

$$\bar{u}\left[\frac{\partial \theta}{\partial \bar{x}} + \theta\frac{\mathrm{d}\ln S_w(\bar{x})}{\mathrm{d}\bar{x}}\right] + \bar{v}\frac{\partial \theta}{\partial \bar{y}} = \frac{1}{Pr}\frac{\partial^2 \theta}{\partial \bar{y}^2}, \tag{3}$$

with the boundary conditions

$$\begin{aligned} \bar{y} = 0: &\quad \bar{u} = \bar{v} = 0, \quad \theta = 1, \\ \bar{y} = \infty: &\quad \bar{u} = 0, \quad \theta = 0. \end{aligned} \tag{4}$$

Equations (1)–(4) appear in dimensionless form, based on the following relations:

$$\bar{x} = \frac{x}{x_0}, \quad \bar{y} = \frac{y}{x_0}Re^{1/2}, \quad \bar{u} = \frac{u}{u_r},$$
$$\bar{v} = \frac{v}{u_r}Re^{1/2} \quad \theta = \frac{T - T_\infty}{T_w(\bar{x}) - T_\infty}, \quad \bar{g} = \frac{g}{g_0}, \tag{5}$$
$$u_r = [g_0\beta(T_r - T_\infty)x_0]^{1/2}, \quad S_w(\bar{x}) = \frac{T_w(\bar{x}) - T_\infty}{T_r - T_\infty},$$
$$Re = \frac{u_r x_0}{\nu}.$$

In the foregoing equations, the standard symbols are defined in the nomenclature.

To facilitate a numerical solution, equations (1)–(4) are transformed from the $(\bar{x}, \bar{y})$ coordinates to (ξ, η) new coordinates and dependent variables defined as

$$\xi = \bar{x}, \quad \eta = \frac{S_w(\bar{x})^{1/4}}{(4\bar{x})^{1/4}}\bar{y},$$
$$F(\xi,\eta) = \frac{\Psi}{(64)^{1/4}\bar{x}^{3/4}S_w(\bar{x})^{1/4}}, \quad G(\xi,\eta) = \theta \tag{6}$$

where $F(\xi,\eta)$ is a reduced stream function and $G(\xi,\eta)$ a dimensionless temperature function. Making use of the relations (6), the basic equations (1)–(4) can be transformed into the following system of equations:

$$F''' + [3 + P(\xi)]FF'' - 2[1 + P(\xi)](F')^2 + \bar{g}(\xi)G = 4\xi\left(F'\frac{\partial F'}{\partial \xi} - F''\frac{\partial F}{\partial \xi}\right), \tag{7}$$

$$\frac{1}{Pr}G'' + [3 + P(\xi)]FG' - 4P(\xi)F'G = 4\xi\left(F'\frac{\partial G}{\partial \xi} - G'\frac{\partial F}{\partial \xi}\right) \tag{8}$$

with the boundary conditions

$$\begin{aligned} \eta = 0: &\quad F(\xi,0) = F'(\xi,0) = 0, \quad G(\xi,0) = 1, \\ \eta = \infty: &\quad F'(\xi,\infty) = 0, \quad G(\xi,\infty) = 0 \end{aligned} \tag{9}$$

where the primes denote differentiation with respect to η and the function $P(\xi)$ of the variable surface temperature is defined by

$$P(\xi) = \frac{\xi}{S_w(\xi)}\frac{\mathrm{d}S_w}{\mathrm{d}\xi}. \tag{10}$$

Now these equations are of a form which is convenient for numerical integration.

The physical quantities of primary interest are the local skin-friction coefficient C_f and the local Nusselt number Nu which can be written, respectively, in the form

$$C_f = \frac{\tau_w}{\rho\left(\frac{\nu}{x}\right)^2}, \quad Nu = \frac{h_w x}{k}. \quad (11)$$

From the definitions of wall skin-friction $\tau_w = \mu(\partial u/\partial y)_{y=0}$ and local heat transfer coefficient $h_w = q_w/(T_w - T_\infty)$, where $q_w = -k(\partial T/\partial y)_{y=0}$, it can be readily shown that

$$C_f = 4\left(\frac{Gr_x}{4}\right)^{3/4} F''(\xi, 0),$$
$$Nu = -\left(\frac{Gr_x}{4}\right)^{1/4} G'(\xi, 0). \quad (12)$$

3. NUMERICAL SOLUTION

To solve equations (7) and (8), along with the boundary conditions given by equation (9), we use Keller's box method [8], a method that has been shown to be particularly accurate for parabolic problems. According to this method, we first convert the partial differential equations (7) and (8) into a system of five first-order partial differential equations by introducing new unknown functions of η-derivatives. This system is then put into finite-difference form in which the nonlinear difference equations are linearized by the method of quasilinearization. The resulting linear difference equations, along with the corresponding boundary conditions, are finally solved by an efficient block-tridiagonal factorization method. The details of the computational procedure can be found elsewhere [9–11].

A wide range of numerical results have been derived using this method but we present here just a small selection. Four sets of results obtained are for $Pr = 0.7$, 1.0, 10 and 100, respectively. In order to compare our numerical integrations with other available results, we shall suppose the gravity $\bar{g}(\xi)$ represented in the form

$$\bar{g}(\xi) = 1 \pm \xi, \quad 0 \leqslant \xi \leqslant 1 \quad (13)$$

where the positive sign is taken for the cold rotating plate and negative sign for the hot rotating plate, respectively.

In the next section calculations are first performed for the case of isothermal plates, i.e. $S_w = \text{const.}$, followed by the case of nonisothermal plates where $S_w(\xi)$ is variable. In the later situation we will consider the class of wall temperature distributions defined, for instance, as

$$S_w(\xi) = a_0 + a_1\xi + a_2\xi^2 + \cdots \quad (14)$$

and therefore we find that

$$P(\xi) = \frac{\xi}{S_w(\xi)} \frac{dS}{d\xi} = \frac{a_1\xi + a_2\xi^2 + \cdots}{a_0 + a_1\xi + a_2\xi^2 + \cdots}. \quad (15)$$

Thus, the function $P(\xi)$ can be evaluated once the constants a_i are specified.

4. RESULTS AND DISCUSSION

4.1. *Isothermal plate*

In this particular case equation (10) takes the form $P(\xi) = 0$, and the equations (7) and (8) are markedly simplified, with a considerable reduction in the computational effort required. As an indication of the accuracy of the present method, we shall write below the series solutions by Lienhard *et al.* [5] for parameters C_f and Nu in the form

$$C_f = 4\left(\frac{Gr_x}{4}\right)^{3/4}\left[\sum_{n=0}^{\infty}(-1)^{nl}\frac{F_n''(0)}{n!}\xi^n\right], \quad (16)$$

$$Nu = \left(\frac{Gr_x}{4}\right)^{1/4}\left[-\sum_{n=0}^{\infty}(-1)^{nl}\frac{\theta_n'(0)}{n!}\xi^n\right] \quad (17)$$

where $l = 0$ if the positive sign is chosen in equation (13) whereas $l = 1$ for the case in which minus sign is chosen in equation (13). A summary of surface derivatives $F_n''(0)$ and $\theta_n'(0)$ so obtained for different values of Pr s and ns is given in Lienhard's paper (Table 3). The comparison of predicted skin-friction and Nusselt number calculated at this stage is shown in Table 1 for a cold rotating plate when $Pr = 0.7$, and in Table 2 for a hot rotating plate when $Pr = 10$, respectively. As can be seen from these tables, for small locations ξ the agreement between series and present numerical solution is very good. As ξ is increased, the series solution becomes less accurate. This is more sensitive for large Prandtl numbers because the level of accuracy of the results using a finite number of terms in the series depends largely on the convergence of the series, i.e. on the Prandtl number and the range of ξ.

To provide further perspectives about the numerical results obtained in this way and the data from other sources, as mentioned, Figs. 1 and 2 have been prepared. They refer to the relative changes in the local skin-friction $F''(\xi, 0)/F''(0, 0)$ and local heat transfer $G'(\xi, 0)/G'(0, 0)$ for representative values of ξ and three sets of Pr (0.7, 1.0 and 10). We have to note from the results shown in Figs. 1 and 2 that although the method of series solution is not expected to be valid for large ξ,

Table 1. Summary of numerical results for an isothermal cold rotating plate when $Pr = 0.7$

ξ	$C_f/4(Gr_x/4)^{3/4}$ Series	Present	$Nu/(Gr_x/4)^{1/4}$ Series	Present
0	0.6789	0.6789	0.4995	0.4995
0.0375	0.6958	0.6958	0.5043	0.5043
0.1034	0.7254	0.7250	0.5125	0.5124
0.1488	0.7449	0.7449	0.5178	0.5178
0.2426	0.7855	0.7855	0.5286	0.5286
0.3539	0.8328	0.8326	0.5408	0.5406
0.4825	0.8864	0.8860	0.5542	0.5537
0.5713	0.9230	0.9221	0.5633	0.5623
0.6003	0.9349	0.9338	0.5662	0.5651
0.6565	0.9578	0.9564	0.5718	0.5703
0.7710	1.0044	1.0017	0.5834	0.5805
0.9451	1.0750	1.0694	0.6034	0.5952

Table 2. Summary of numerical results for an isothermal hot rotating plate when $Pr = 10$

ξ	$C_f/4(Gr_x/4)^{3/4}$ Series	$C_f/4(Gr_x/4)^{3/4}$ Present	$Nu/(Gr_x/4)^{1/4}$ Series	$Nu/(Gr_x/4)^{1/4}$ Present
0	0.4192	0.4192	1.1693	1.1695
0.0516	0.4041	0.4040	1.1521	1.1523
0.0746	0.3973	0.3972	1.1442	1.1444
0.1363	0.3788	0.3788	1.1223	1.1225
0.2476	0.3446	0.3445	1.0799	1.0799
0.2729	0.3366	0.3365	1.0697	1.0695
0.3036	0.3269	0.3268	1.0571	1.0566
0.4006	0.2955	0.2952	1.0147	1.0133
0.4574	0.2766	0.2760	0.9882	0.9854
0.5020	0.2616	0.2606	0.9664	0.9621
0.5537	0.2437	0.2423	0.9401	0.9332
0.6167	0.2216	0.2193	0.9063	0.8948
0.7395	0.1768	0.1713	0.8349	0.8060
0.7756	0.1632	0.1560	0.8124	0.7745
0.7764	0.1629	0.1557	0.8119	0.7737

the finite-difference results compare favourably with those of local nonsimilarity method (three equation model) even for a fairly large range of ξ. Accordingly, the present method produces accurate results for a particular plate temperature distribution and it can be used with full confidence for other forms of the plate temperature distributions. Moreover, its simplicity lends strong support to the use of the method. Again, both Figs. 1 and 2 show quite clearly, as to be expected, that $\bar{g}(\xi)$ has a significant effect on C_f and Nu.

4.2. *Nonisothermal plate*

Let us now consider the class of wall temperature distributions defined by equation (14). We shall assign values to the constants a_i and denote the problems thus defined as the cases

$$\begin{aligned} &\text{I } S_w = 1 - \tfrac{1}{2}\xi, \\ &\text{II } S_w = 1 + \tfrac{1}{2}\xi, \\ &\text{III } S_w = 1 - \tfrac{1}{2}\xi + \tfrac{1}{4}\xi^2. \end{aligned} \tag{18}$$

It should be stressed, however, that from a practical point of view, there are also important problems with exponential, sinusoidal or step change in the wall temperature variations. The application of such physically realistic situations to the problem of free convection flow along a non-rotating vertical flat plate has recently been published [9].

Figures 3 and 4 cover the results for the skin-friction and heat transfer in the cases I–III evaluated at various ξ locations when $Pr = 0.7$. For the sake of comparison, the profiles in the particular case of isothermal plates (S_w = const.) are also plotted at the same distances ξ (full lines). Some marked differences are immediately apparent. The skin-friction is greater in the case I than in the cases II and III of variation of the wall temperature. Then, for the cold rotating plate the skin-friction increases with the increase of ξ, but for the hot plate the effect of ξ is just the opposite. The results represented in Fig. 4 indicate that the heat transfer is

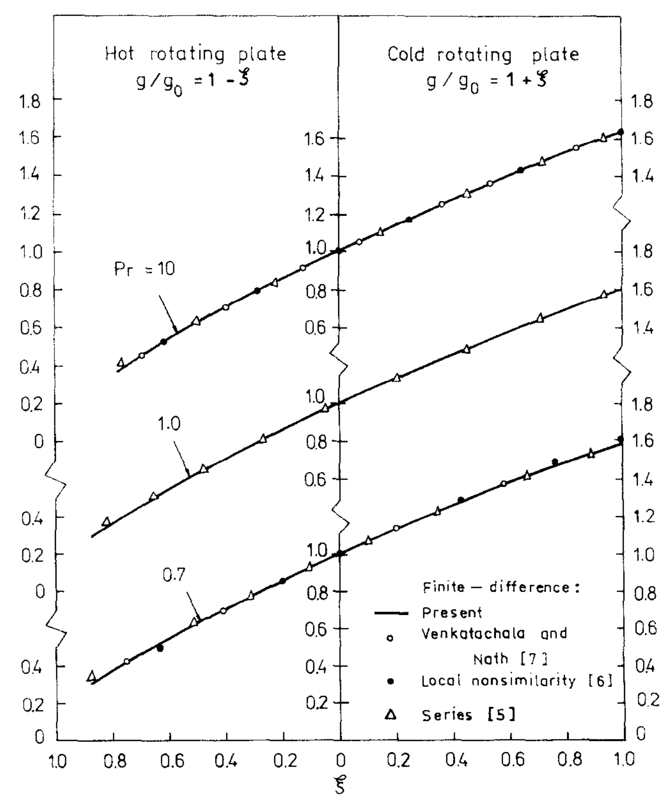
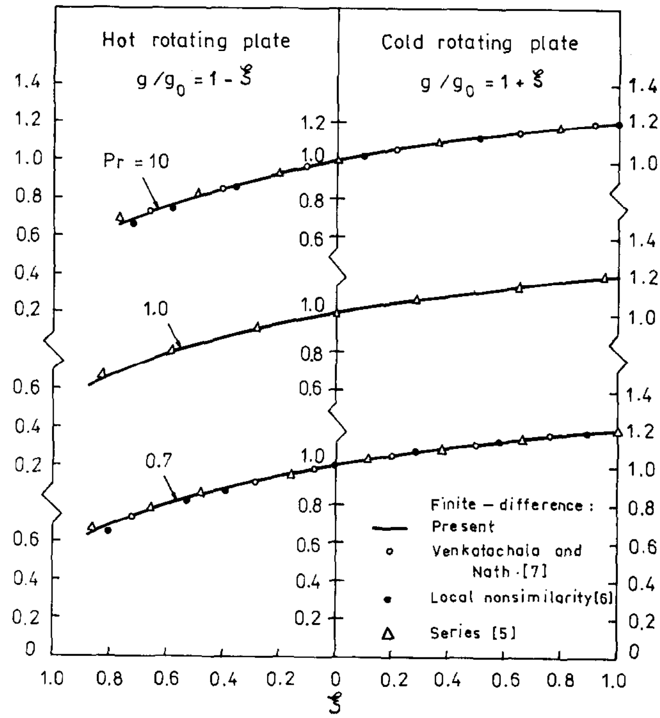


FIG. 1. Comparison of $F''(\xi,0)/F''(0,0)$ for the free convection along rotating isothermal plates.



G. 2. Comparison of $G'(\xi, 0)/G'(0, 0)$ for the free convection along rotating isothermal plates.

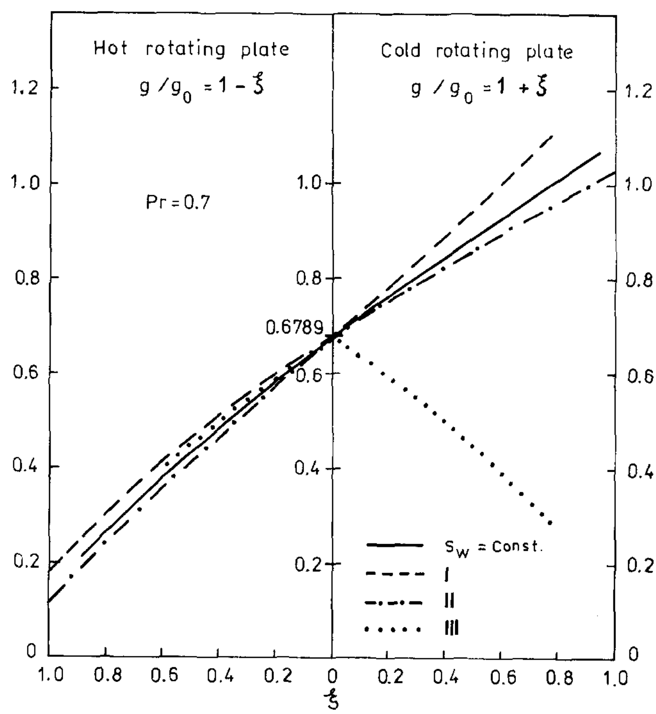


FIG. 3. Skin-friction results for nonisothermal rotating plates, $Pr = 0.7$.

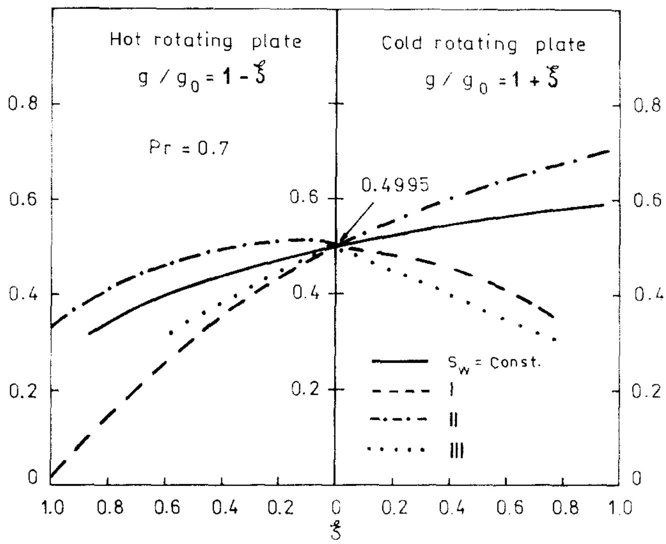


Fig. 4. Heat transfer results for nonisothermal rotating plates, $Pr = 0.7$.

greater in the case II than in the cases I and III. Apart from this, for the cold plate an increase in ξ results in an increase in the heat transfer in the cases of an isothermal and a linearly increasing or linearly decreasing plate temperature. However, both C_f and Nu are seen to decrease in the case III as the distance ξ increases. Furthermore, a noteworthy behaviour in the heat transfer profile for the case of a hot rotating plate is that it shows a maximum (at $\xi = 0.0375$) when the plate temperature increases (case II).

Figures 5 and 6 show the calculated values of C_f and Nu in the case I at successive distances ξ and for various Prandtl numbers ($Pr = 0.7$, 1.0, 10 and 100, respectively). An examination of these figures reveals that at a given station ξ, there is a tendency for the effect of Pr to decrease C_f and to increase Nu as Pr increases; this tendency seems to accelerate with the increasing Prandtl number. However, one can observe that both C_f and Nu tend to become less sensitive to the variation of relatively small Prandtl numbers. As shown in Fig. 5, on the other hand the gravity field causes the increase of the skin-friction in the case of a cold plate, while an

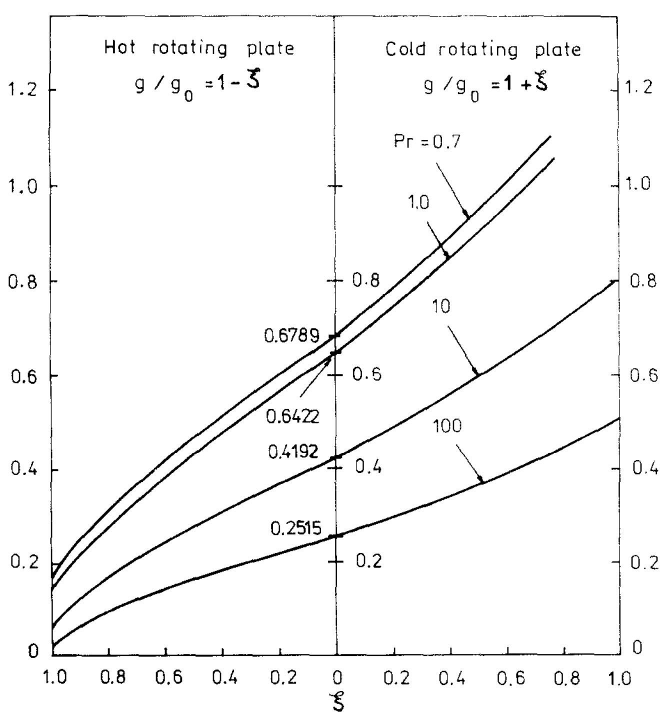


Fig. 5. Skin-friction results for nonisothermal rotating plates, case I, $Pr = 0.7$, 1.0, 10 and 100.

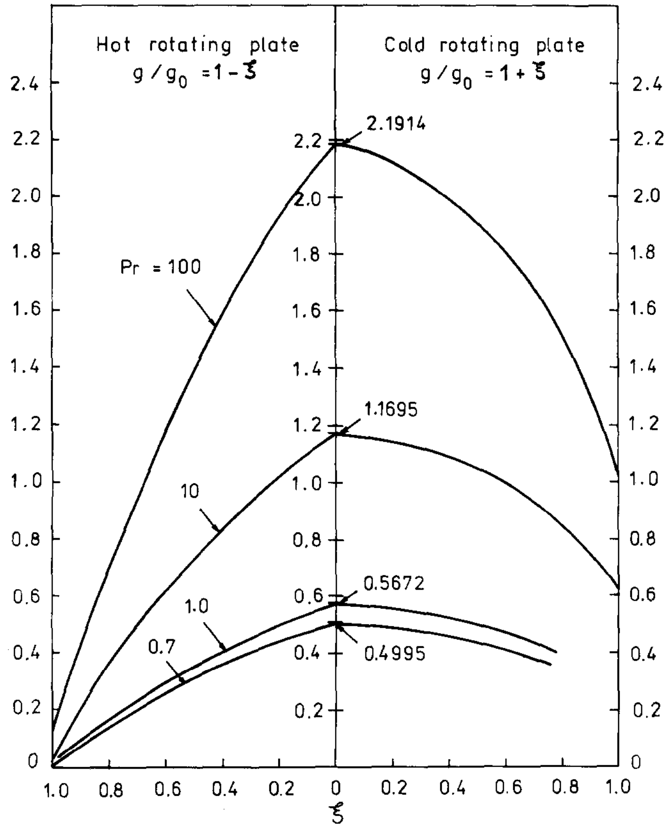


FIG. 6. Heat transfer results for nonisothermal rotating plates, case I, Pr = 0.7, 1.0, 10 and 100.

opposite trend is observed for the hot plate. But the gravity field will hardly act on the decrease of the heat transfer with increasing distance ξ.

Also included in these figures are the similarity solutions for $F''(0)$ and $-G'(0)$ obtained by putting $\xi = 0$ and $\bar{g} = 1$ in equations (7) and (8). We may mention that the data for Pr = 0.7, 1.0 and 10 are in excellent agreement with those from Table 3 of ref. [5], a confirmation of the reliability of the present method.

Finally, it is worth noting that the numerical scheme used allows computations to be carried out close to the centre of rotation of the heated plate, i.e. near $\xi = 1$, where the boundary layers are very thin.

5. CONCLUSIONS

A numerical study has been made for the free convection flow over isothermal and a nonisothermal rotating flat plates subject to a linear variation of the gravity field; both the cases of the cold and hot plates are considered. The problems formulated here are more general than those appearing in previous publications and include the unpublished results of variable wall temperature distributions.

The results have been shown to be very accurate when compared with known solutions for an isothermal plate. It is found that the local skin-friction and local Nusselt number results exhibit a strong dependence on the Prandtl number and gravity field. The tabulated results of the skin-friction and heat transfer parameters provide a family of numerical data against which the results from various approximate methods can be compared.

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CONVECTION LIBRE SUR UNE PLAQUE PLANE NON-ISOTHERME SOUS GRAVITATION NON-UNIFORME

Résumé—On présente des résultats obtenus par une procédure numérique pour la convection libre autour d'une plaque tournante non-isotherme et soumise à un champ gravitationnel non-uniforme. Plusieurs formes spécifiques pour la distribution de température sur la plaque sont considérees. On présente le frottement pariétal et le flux de chaleur pour des valeurs choisies de la distance au bord d'attaque et pour quelques valeurs du nombre de Prandtl. La méthode employée se révèle très précise en comparaison des solutions antérieures.

FREIE KONVEKTIONSSTRÖMUNG AN EINER NICHTISOTHERMEN EBENEN PLATTE UNTER BEDINGUNGEN UNGLEICHFÖRMIGER SCHWERKRAFT

Zusammenfassung—In dieser Arbeit werden die Ergebnisse eines numerischen Rechenverfahrens für die freie Konvektionsströmung an einer rotierenden nichtisothermen Platte mitgeteilt, die einem ungleichförmigen Schwerkraftfeld ausgesetzt ist. Es werden einige spezielle Formen der Temperaturverteilung der Platte behandelt. Für diese Fälle wird die Oberflächenreibung und die an die Wand übertragene Wärmemenge für verschiedene Prandtl-Zahlen in einigen Punkten mit einer bestimmten Entfernung von der Anströmkante berechnet. Die verwendete Methode erweist sich als sehr genau im Vergleich zu früheren Lösungen.

СВОБОДНОКОНВЕКТИВНОЕ ТЕЧЕНИЕ НА НЕИЗОТЕРМИЧЕСКОЙ ПЛОСКОЙ ПЛАСТИНЕ В НЕОДНОРОДНОМ ПОЛЕ СИЛЫ ТЯЖЕСТИ

Аннотация—Представлены результаты численных расчетов свободноконвективного обтекания вращающейся неизотермической пластины в неоднородном поле силы тяжести. Рассмотрено несколько частных случаев распределения температуры пластины, и для них представлены значения поверхностного трения и скорости теплоотдачи на стенке для различных расстояний от передней кромки и при нескольких значениях числа Прандтля. Показана высокая точность предложенного метода по сравнению с ранее использовавшимися решениями.