NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3986

COMPRESSIBLE LAMINAR BOUNDARY LAYER OVER A YAWED INFINITE CYLINDER WITH HEAT TRANSFER AND ARBITRARY PRANDTL NUMBER

By

Eli Reshotko

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

and

Ivan E. Beckwith

Langley Aeronautical Laboratory
Langley Field, Virginia

Washington
June 1957

TABLE OF CONTENTS

4132

CG-1

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3986

COMPRESSIBLE LAMINAR BOUNDARY LAYER OVER A YAWED INFINITE CYLINDER WITH HEAT TRANSFER AND ARBITRARY PRANDTL NUMBER[1]

By Eli Reshotko and Ivan E. Beckwith

SUMMARY

The equations for development of the compressible laminar boundary layer over a yawed infinite cylinder are presented. For compressible flow with a pressure gradient the chordwise and spanwise flows are not independent. By use of the Stewartson transformation and a linear viscosity-temperature relation, a set of three simultaneous ordinary differential equations is obtained in a form yielding similar solutions. These equations are solved for stagnation-line flow for surface temperatures from zero to twice the free-stream stagnation temperature and for a wide range of yaw angle and free-stream Mach number.

The results indicate that the effect of yaw on the heat-transfer coefficient at the stagnation line depends markedly on the free-stream Mach number. For subsonic Mach numbers the decrease in heat-transfer coefficient with yaw angle Λ is about $\sqrt{\cos \Lambda}$, which is the decrease for incompressible flow. However, for stream Mach numbers greater than about 2, the variation in heat-transfer coefficient with yaw angle is somewhat less than $\cos \Lambda$, except when the normal component of the stream Mach number is subsonic; then the variation tends to approach $\sqrt{\cos \Lambda}$. This decrease in heat-transfer coefficient with yaw angle is practically independent of wall temperature and Prandtl number for the values of these parameters used in the present calculations. The recovery factor, defined in terms of the local external temperature, can be approximated as the square root of the Prandtl number for the range of yaw angle, Mach number, and Prandtl number included in the calculations.

---

[1]This report combines the results of two independent investigations, one at the Lewis Flight Propulsion Laboratory and the other at the Langley Aeronautical Laboratory. The principal results of the investigation at the Lewis laboratory were presented by the senior author before the 1956 Heat Transfer and Fluid Mechanics Institute at Stanford University on June 22, 1956. A brief written version of that talk appears in the proceedings of the institute (ref. 1).

An unusual result of the solutions is that for large yaw angles and stream Mach numbers the chordwise velocity within the boundary layer exceeds the local external chordwise velocity, even for a highly cooled wall.

INTRODUCTION

As flight speeds are increased, the problem of aerodynamic heating 4132
becomes more serious, and the temperatures of critical areas such as the nose of an aircraft or the wing leading edge may exceed the design specifications. An accurate knowledge of the laminar-boundary-layer characteristics then becomes desirable, not only for predicting heat-transfer rates, but also for the purpose of calculating the stability of the boundary-layer flow. The yawed infinite cylinder simulates approximately the leading edge of a swept-back wing or of a body of high fineness ratio at angle of attack and also allows a basic simplification of the boundary-layer theory.

Almost simultaneously, Prandtl (ref. 2), Struminsky (ref. 3), Jones (ref. 4), and Sears (ref. 5) observed that for incompressible flow over a yawed infinite cylinder the boundary-layer development in the chordwise direction (normal to the cylinder axis) is independent of the spanwise flow. For compressible flow, however, this "independence principle" does not apply, because the density variation must depend on the velocities in both the chordwise direction and the spanwise direction (refs. 3 and 6).

Where the independence principle applies, the solutions for boundary-layer development in the chordwise plane are those which have been obtained for incompressible two-dimensional flow. A number of investigators have integrated the spanwise momentum equation for the various solutions to this problem. Sears (ref. 5) has obtained the spanwise solution corresponding to the series-type solution about a cylinder. Wild (ref. 7), by an integral technique, has obtained the spanwise solution for Howarth's elliptic cylinder, and Cooke (ref. 8) has tabulated the spanwise solutions corresponding to Hartree's solutions (ref. 9) to the equations of Falkner and Skan. Further, Goland (ref. 10) has shown that the heat-transfer coefficient of a yawed cylinder varies as the square root of the Reynolds number based on the normal component of the stream velocity. Thus, for a given stream velocity, the heat-transfer coefficient decreases as the square root of the cosine of the yaw angle. This decrease in heat-transfer coefficient is associated with the increase in boundary-layer thickness due to yaw.

For compressible flow where the independence principle does not apply, the momentum equations for both the chordwise flow and the spanwise flow must be solved simultaneously. Solutions to the compressible-flow problem with zero heat transfer and a Prandtl number of 1 have been given by

Crabtree (ref. 11) and Tinkler (ref. 12). Both of these solutions are for flows where the spanwise Mach number at the stagnation line of the cylinder is 1 or less. Consequently, for high stream Mach numbers these solutions apply only to cases where the yaw angle is small. From the observation that for a Prandtl number of 1 the energy equation and the spanwise momentum equations are similar (ref. 6), Moore (ref. 13) has indicated the form that Crabtree's equations take for a noninsulated surface.

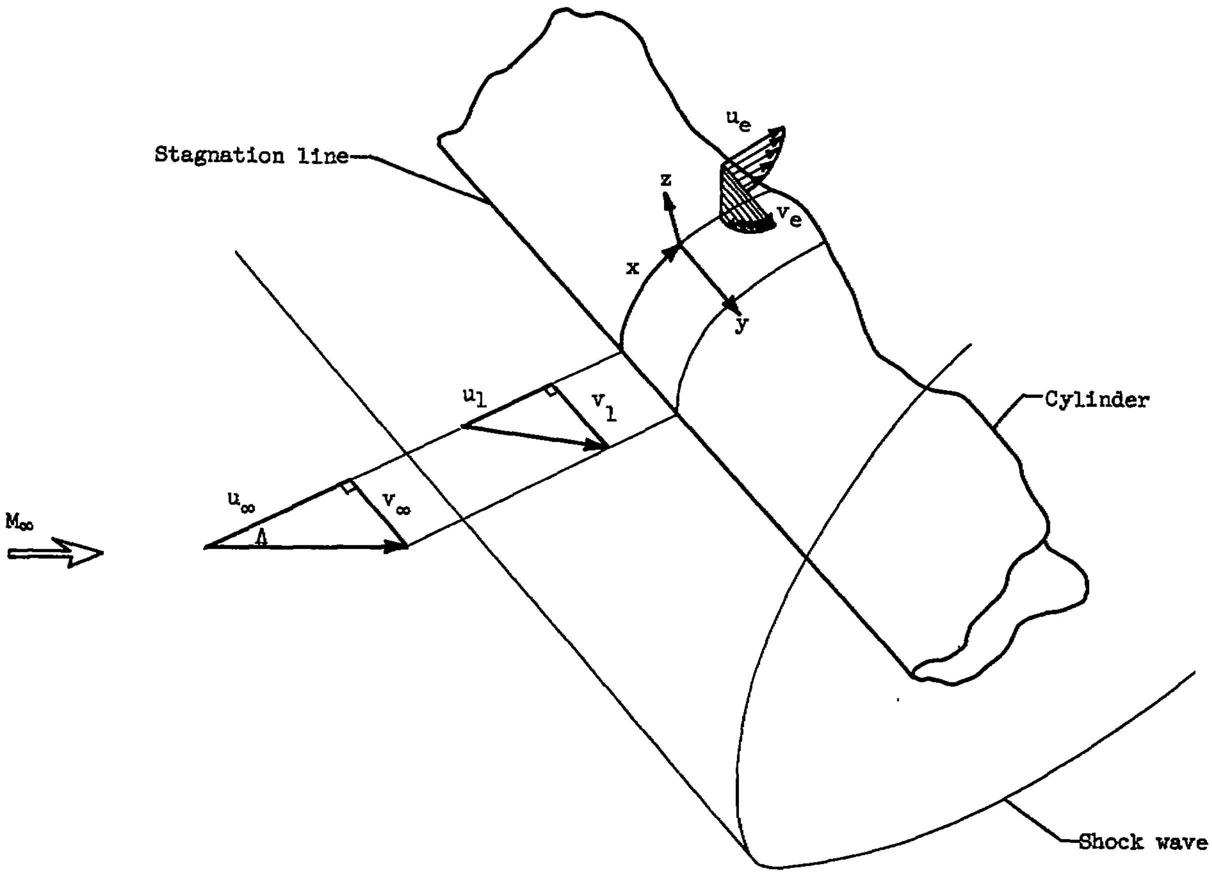
The present report extends the work of Crabtree, Tinkler, and Moore to the more general case of arbitrary Prandtl number and an isothermal wall at arbitrary temperature in flows where both Mach number and yaw angle may be large. The boundary-layer equations are first simplified by the assumption of a linear viscosity-temperature relation and by the application of Stewartson's transformation (ref. 14). The resulting system of partial differential equations is simplified further by assuming an external chordwise velocity distribution of the Falkner-Skan type in the transformed coordinate system. The conditions required to reduce the system to ordinary differential equations are discussed. Numerical solutions for stagnation-line flow with Prandtl numbers of 1 and 0.7 are presented. Expressions are given for shear, heat transfer, and the variation of heat-transfer coefficient with yaw angle.

GENERAL EQUATIONS

Boundary-Layer Equations

The compressible-boundary-layer equations for a three-dimensional flow are obtained by application of the Prandtl boundary-layer assumptions to the general equations governing the motion of a compressible, viscous, heat-conducting gas (see, e.g., refs. 6 and 13). One of these assumptions which may be emphasized for the present application is that the boundary-layer thickness is small compared with the local radius of curvature of the surface. Consequently, the pressure gradient normal to the surface may be neglected, and the boundary-layer equations are expected to be valid in the region of the stagnation line on a yawed cylinder.

The boundary-layer equations for a yawed infinite cylinder are obtained from the three-dimensional boundary-layer equations by noting that all spanwise derivatives are identically zero. The coordinate system used is defined by the following sketch:



where the x-coordinate is the distance along the cylinder surface measured in the chordwise direction from the leading-edge stagnation line, y is the spanwise coordinate, and z is the coordinate normal to the cylinder surface. (All symbols are defined in appendix A.)

The equations of motion of the steady compressible laminar boundary layer over a yawed infinite cylinder are therefore:

Continuity:

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho w)}{\partial z} = 0 \qquad (1)$$

Momentum:

$$\rho u \frac{\partial u}{\partial x} + \rho w \frac{\partial u}{\partial z} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\left(\mu \frac{\partial u}{\partial z}\right) \tag{2a}$$

$$\rho u \frac{\partial v}{\partial x} + \rho w \frac{\partial v}{\partial z} = \frac{\partial}{\partial z}\left(\mu \frac{\partial v}{\partial z}\right) \tag{2b}$$

$$\frac{\partial p}{\partial z} = 0 \tag{2c}$$

Energy:

$$\rho u \frac{\partial H}{\partial x} + \rho w \frac{\partial H}{\partial z} = \frac{\partial}{\partial z}\left(\frac{\mu}{Pr} \frac{\partial H}{\partial z}\right) - \frac{\partial}{\partial z}\left[\mu\left(\frac{1}{Pr} - 1\right) \frac{\partial}{\partial z}\left(\frac{u^2 + v^2}{2}\right)\right] \tag{3}$$

where H is the total or stagnation enthalpy.

State:

$$p = \rho R t \tag{4}$$

The boundary conditions for equations (1) to (4) are:

At $z = 0$

$$u = v = w = 0 \quad \text{and} \quad H = H_w \quad \text{or} \quad \frac{\partial H}{\partial z} = 0$$

At $z \to \infty$

$$u = u_e, \; v = v_e, \; \text{and} \quad H = H_e$$

The viscosity is assumed to be a linear function of the temperature according to the relation

$$\mu = \frac{\mu_w}{t_w} t$$

where t_w is a known function of x, and μ_w may be taken as any desired function of t_w, such as the Sutherland viscosity-temperature equation. The chordwise velocity outside the boundary layer satisfies the following form of Bernoulli's equation:

$$\rho_e u_e \frac{du_e}{dx} = -\frac{dp_e}{dx} = -\frac{\partial p}{\partial x} \tag{5}$$

since from equation (2c) the pressure is constant in the direction normal to the surface.

Stewartson's Transformation

The velocities in the equations of motion (eqs. (1) to (3)) can be replaced through the definition of a stream function:

$$\left.\begin{aligned} \psi_z &\equiv \frac{\rho u}{\rho_0} \\ \psi_x &\equiv -\frac{\rho w}{\rho_0} \end{aligned}\right\} \tag{6}$$

so that the continuity equation (eq. (1)) is automatically satisfied.

Stewartson's transformation (ref. 14) is now introduced, and in a slightly modified form may be written

$$X = \int_0^x \left(\frac{\mu_w}{\mu_0} \frac{t_0}{t_w}\right) \frac{a_e}{a_0} \frac{p_e}{p_0} \, dx \tag{7}$$

$$Z = \frac{a_e}{a_0} \int_0^z \frac{\rho}{\rho_0} \, dz \tag{8}$$

The quantity $\left(\frac{\mu_w}{\mu_0} \frac{t_0}{t_w}\right)$ of equation (7) is exactly the quantity λ of reference 15. The transformed coordinates are now represented by uppercase letters (X,Z), and the subscript e refers to local conditions at the outer edge of the boundary layer (external). The subscript 0 refers to free-stream stagnation values.

With the assumptions of constant Prandtl number, constant specific heat, and an isothermal surface and by use of the adiabatic energy equation for the external flow

$$a_0^2 = a_e^2 + \frac{\gamma - 1}{2}\left(u_e^2 + v_e^2\right) \tag{9}$$

equations (2a), (2b), and (3) become

$$\psi_Z \psi_{XZ} - \psi_X \psi_{ZZ} = U_e U_{e_X} \left\{1 + \left(\frac{t_0}{t_{N_0}} - 1\right)(1 - g^2) + \left(\frac{t_w}{t_0} - 1\right)\left(\frac{t_0}{t_{N_0}}\right)(1 - \theta)\right\} + \nu_0 \psi_{ZZZ} \tag{10}$$

$$\psi_Z g_X - \psi_X g_Z = \nu_0 g_{ZZ} \tag{11}$$

$$\psi_Z \theta_X - \psi_X \theta_Z = -\frac{\nu_0}{Pr}\frac{(1-Pr)(\gamma-1)}{2a_0^2\left(1 - \frac{t_w}{t_0}\right)}\left\{\left(\frac{a_e}{a_0}\right)^2 (\psi_Z^2)_{ZZ} + v_e^2\, g^2_{ZZ}\right\} + \frac{\nu_0}{Pr}\theta_{ZZ} \tag{12}$$

4132

where

$$g = \frac{v}{v_e} \tag{13}$$

$$\theta = \frac{H - H_w}{H_e - H_w} \tag{14}$$

and

$$\frac{t_0}{t_{N_0}} = \frac{1 + \frac{\gamma - 1}{2} M_\infty^2}{1 + \frac{\gamma - 1}{2} M_\infty^2 \cos^2 \Lambda} \tag{15}$$

The ratio $\frac{t_0}{t_{N_0}}$ combines the effect of both yaw angle and Mach number in a single parameter. The physical interpretation of this parameter is simply the ratio of the total or stagnation temperature of the stream to the stagnation temperature of the normal component of the stream. The variation of the parameter with yaw angle for various Mach numbers is shown in figure 1. It is seen that $\frac{t_0}{t_{N_0}} \leq \sec^2 \Lambda$ and becomes large only for large yaw angles combined with high Mach numbers.

For a Prandtl number of 1, $g = \theta$, since equations (11) and (12) are similar and since the functions g and θ satisfy the same boundary conditions.

In terms of the transformed velocities, which are defined

$$\left.\begin{aligned} U &\equiv \psi_Z \\ W &\equiv -\psi_X \end{aligned}\right\} \tag{16}$$

equations (10) to (12) can be written

$$UU_X + WU_Z = U_e U_{e_X}\left[1 + \left(\frac{t_0}{t_{N_0}} - 1\right)(1 - g^2) + \left(\frac{t_w}{t_0} - 1\right)\frac{t_0}{t_{N_0}}(1 - \theta)\right] + \nu_0 U_{ZZ} \tag{17}$$

$$Ug_X + Wg_Z = \nu_0 g_{ZZ} \tag{18}$$

$$U\theta_X + W\theta_Z = \frac{\nu_0}{Pr}\left\{\theta_{ZZ} - \left(\frac{\gamma - 1}{2a_0^2}\right)\left(\frac{1 - Pr}{1 - \frac{t_w}{t_0}}\right)\left[\left(\frac{a_e}{a_0}\right)^2 (U^2)_{ZZ} + v_e^2 g_{ZZ}^2\right]\right\} \tag{19}$$

These equations should be useful in formulating integral methods for calculation of laminar boundary layers over yawed cylinders.

Similar Solutions

To obtain similar solutions, an external flow of the Falkner-Skan type

$$U_e = CX^m \tag{20}$$

is assumed, which together with the transformation

$$\left.\begin{aligned} \psi &= f(\eta)\sqrt{\frac{2\nu_0 U_e X}{m + 1}} \\ g &= g(\eta) \\ \theta &= \theta(\eta) \\ \eta &= Z\sqrt{\frac{m + 1}{2}\frac{U_e}{\nu_0 X}} \end{aligned}\right\} \tag{21}$$

yields the system of differential equations

$$f''' + ff'' = \beta\left[f'^2 - 1 - \left(\frac{t_0}{t_{N_0}} - 1\right)(1 - g^2) - \frac{t_0}{t_{N_0}}\left(\frac{t_w}{t_0} - 1\right)(1 - \theta)\right] \tag{22a}$$

$$g'' + fg' = 0 \tag{22b}$$

4132

CG-2

$$\theta'' + \Pr f\theta' = \frac{1 - \Pr}{\left(1 - \frac{t_w}{t_0}\right)}\left[\frac{\gamma - 1}{2}\left(\frac{u_e}{a_0}\right)^2 (f'^2)'' + \left(1 - \frac{t_{N_0}}{t_0}\right)(g^2)''\right] \tag{22c}$$

where

$$\beta = \frac{2m}{m + 1} \tag{23}$$

The boundary conditions for the system of equations (22) are:

$$\left.\begin{aligned} &\text{At } \eta = 0 \qquad f = f' = g = \theta = 0 \\ &\text{At } \eta \to \infty \qquad f' = g = \theta = 1 \end{aligned}\right\} \tag{24}$$

Since u_e may in general depend on x, the right member of the energy equation (eq. (22c)) is not yet functionally consistent with the left member for arbitrary u_e and $\Pr$. The right member of the equation must be zero or a function of η to be consistent with the left member. This may be achieved in the following ways: (1) The external chordwise velocity may be a constant other than zero, (2) the external chordwise velocity may be zero, (3) the Prandtl number may equal 1, (4) the factor $\left[\frac{\gamma - 1}{2}\left(\frac{u_e}{a_0}\right)^2\right]$ may approach the constant $t_{N_0}/t_0 = \cos^2 \Lambda$ corresponding to hypersonic flow, or (5) the ratio of specific heats γ may equal 1.

Independence Principle

The independence principle can be demonstrated from the general system of equations (22). The chordwise momentum equation (eq. (22a)) is independent of the spanwise momentum and energy equations under the following conditions:

(1) Flat-plate flows ($m = \beta = 0$) for all Mach numbers, Prandtl numbers, and heat transfers

(2) The conditions $t_0 = t_{N_0}$, $t_w = t_0$, which correspond to incompressible flow

Independence does not exist for compressible flow with pressure gradient, even for zero heat transfer.

Stagnation-Line Flow

All solutions presented in this report are for stagnation-line flow where $m = \beta = 1$. Two of the previously described requirements for similarity are separately considered in these solutions. The first requirement is that of Prandtl number equal to 1. The system of equations (22) for this case is reduced to the following two differential equations, since equations (22b) and (22c) become identical: 4132

$$f''' + ff'' = f'^2 - 1 - \left(\frac{t_0}{t_{N_0}} - 1\right)(1 - \theta^2) - \frac{t_0}{t_{N_0}}\left(\frac{t_w}{t_0} - 1\right)(1 - \theta) \qquad (25a)$$

$$\theta'' + f\theta' = 0 \qquad (25b)$$

with the boundary conditions:

$$\left.\begin{aligned} &\text{At } \eta = 0 \qquad f = f' = \theta = 0 \\ &\text{At } \eta \to \infty \qquad f' = \theta = 1 \end{aligned}\right\} \qquad (26)$$

For the case of zero yaw, equations (25) reduce to those presented in reference 15, while for the insulated surface $\left(\frac{t_w}{t_0} = 1 \text{ for } Pr = 1\right)$ they reduce to those of Crabtree (ref. 11).

The second requirement considered is that of zero external chordwise velocity which allows arbitrary Prandtl number. For this case equations (22) become:

$$f''' + ff'' = f'^2 - 1 - \left(\frac{t_0}{t_{N_0}} - 1\right)(1 - g^2) - \frac{t_0}{t_{N_0}}\left(\frac{t_w}{t_0} - 1\right)(1 - \theta) \qquad (27a)$$

$$g'' + fg' = 0 \qquad (27b)$$

$$\theta'' + Prf\theta' = (1 - Pr)\frac{\left(1 - \frac{t_{N_0}}{t_0}\right)}{\left(1 - \frac{t_w}{t_0}\right)}(g^2)'' \qquad (27c)$$

With heat transfer the boundary conditions of equations (27) are equations (24).

For the case of the insulated wall an additional boundary condition is necessary, since the wall temperature is no longer arbitrary. The heat-transfer rate to the wall may be expressed

$$q_w = k_w\left(\frac{\partial t}{\partial z}\right)_w \tag{28}$$

4132

which for stagnation-line flow becomes, with use of expressions (8), (14), and (21),

$$q_w = \frac{\rho_w}{\rho_0}\frac{a_e}{a_0}\sqrt{\frac{C}{\nu_0}}\,k_w(t_0 - t_w)\theta_w' \tag{29}$$

CG-2 back

For the insulated surface, $q_w = 0$; and since with arbitrary Prandtl number the surface temperature is generally not equal to the stagnation temperature, the additional boundary condition from equation (29) is

$$\theta_w' = 0 \tag{30}$$

Thus, for the insulated surface with arbitrary Prandtl number, equations (27) are solved subject to the conditions of equations (24) and (30). For convenience in computing, the temperature ratio t_w/t_0 was replaced by the following expression involving the local recovery factor ζ_w:

$$\frac{t_w}{t_0} = \frac{t_{aw}}{t_0} = \zeta_w\left(1 - \frac{t_{N_0}}{t_0}\right) + \frac{t_{N_0}}{t_0} \tag{31}$$

Values of ζ_w then resulted from the solutions.

Equations (25) and (27) were solved numerically for both insulated and noninsulated surfaces. The techniques used at the two laboratories were different. These techniques are discussed in appendix B. It is interesting and gratifying to note that the different techniques yielded numerical results which were in excellent agreement.

PROPERTIES OF SOLUTIONS

In the following sections the solutions obtained in this study are presented and their properties discussed. All solutions are presented in tabular form. Table I shows the values of f, f', f'', θ, and θ' tabulated against η for a Prandtl number of 1. Table II presents f, f', f'', g, g', θ, and θ' against η for a Prandtl number of 0.7. Table III presents a summary of the values of f_w'' (related to wall shear), g_w' (related to spanwise shear), and θ_w' (related to heat transfer) for the cases of tables I and II.[2]

4132

Velocity and Enthalpy Profiles

The chordwise and spanwise velocity and enthalpy profiles obtained from the tabulated solutions are presented as functions of η in figures 2 and 3.

The chordwise velocity ratio can be expressed

$$\frac{u}{u_e} = f' \tag{32}$$

from the definitions of ψ, z, and η. It should be remembered that for the $Pr = 1$ solutions the normalized temperature and spanwise velocity profiles are identical. For $Pr = 0.7$ (fig. 3) the spanwise velocity and enthalpy profiles are separately plotted. The distance z normal to the surface at a given station x in the physical plane is related to the similarity variable η through relations (8) and (21) and may be expressed

$$z = \frac{a_0}{a_e}\frac{p_0}{p_e}\sqrt{\frac{\nu_0 x}{U_e}\left(\frac{2}{m+1}\right)}\int_0^{\eta}\frac{t}{t_0}\,d\eta \tag{33}$$

where

$$\frac{t}{t_0} = 1 + \left(\frac{t_w}{t_0} - 1\right)(1 - \theta) - \frac{\gamma - 1}{2}\left(\frac{u_e}{a_0}\right)^2 f'^2 - \left(1 - \frac{t_{N_0}}{t_0}\right)g^2 \tag{34}$$

---

[2]Comparison of the results of reference 11 with the solution given here for $Pr = 1$, $t_w/t_0 = 1$, $t_0/t_{N_0} = 1.2$ shows that the present values for f' and θ (corresponding to $f_1' + \omega f_2'$ and $g_1 + \omega g_2$ in the notation of ref. 11) are considerably larger than the values given in reference 11 at the same η. According to private communication with Dr. Crabtree, the original numerical results of reference 11 were in error. The corrected results obtained from Dr. Crabtree, also by private communication, are in substantial agreement with the present solution.

At the stagnation line, equations (33) and (34) become

$$z = \frac{t_0}{t_w}\sqrt{\frac{\nu_w}{\left(\frac{du_e}{dx}\right)}}\int_0^{\eta}\left[1 + \left(\frac{t_w}{t_0} - 1\right)(1 - \theta) - \left(1 - \frac{t_{N_0}}{t_0}\right) g^2\right]d\eta \quad (35)$$

The differences in the profiles for different values of the yaw-angle parameter t_0/t_{N_0} and the wall-temperature parameter t_w/t_0 (fig. 2) can be attributed to the effect of compressibility, since for incompressible flow the chordwise velocity profiles and the temperature profiles are independent of the spanwise flow. The chordwise velocity ratios are especially affected by compressibility; for large values of t_0/t_{N_0} these ratios are greater than 1 within the boundary layer, even for cases where the wall is highly cooled. This same phenomenon has been observed in solutions of the two-dimensional compressible boundary layer (e.g., refs. 15 and 16) for cases of a heated wall and favorable pressure gradient and in reference 15 was termed velocity overshoot. According to reference 15, the physical explanation for this effect is that when the wall is heated the density in the outer part of the boundary layer is reduced sufficiently so that the local flow is accelerated more than the external flow. The same basic explanation appears plausible in the present solutions, except that the additional heat required to reduce the local density is generated by the shear of the spanwise boundary layer, and hence the phenomenon can occur even when the wall temperature is less than the recovery temperature. The solutions given by Moore for the compressible-boundary-layer equations for a cone at large angle of attack (ref. 17) also show similar results; that is, the circumferential velocity ratios are greater than unity within the boundary layer. Furthermore, this effect becomes larger as the angle of attack of the cone is reduced.[3] In the present solutions this is analogous to increasing the yaw angle, which also has the effect of increasing the excess of the local velocities over the external velocity. Note also that this excess chordwise velocity is reduced by reducing the wall temperature, as might be expected from the preceding discussion.

Six solutions were computed with $Pr = 0.7$; three of these are for zero heat transfer and give a recovery factor, and three are for a temperature ratio $t_w/t_0 = 0.5$ corresponding to a cooled wall. The velocity and enthalpy profiles for these solutions are shown in figure 3, and the numerical values of the functions are given in tables II and III.

---

[3]The angle of yaw as defined herein is the complement of the cone angle of attack.

For corresponding values of t_0/t_{N_0} and for $(t_w/t_0) = 0.5$, the f', g, and θ profiles are almost the same as those for $Pr = 1$. For $t_w = t_{aw}$, the f' and g profiles are also similar to those for $Pr = 1$ with $t_w = t_0$; however, the θ profiles for $Pr = 0.7$ and $t_w = t_{aw}$ (fig. 3(b)) are considerably different from the corresponding profiles for $Pr = 1$. The fact that $\theta > 1$ for this case indicates that the local stagnation enthalpy within the boundary layer exceeds the stagnation enthalpy outside the boundary layer. This excess of local stagnation enthalpy over the external value for zero heat transfer (and also to a lesser extent for a cooled wall) is apparently caused by the relative increase in the quantity of heat conducted away from the wall into the outer layers of the boundary layer when $Pr < 1$. For $Pr = 1$ and zero heat transfer $(t_w = t_0)$ the relative effects of viscosity and conductivity are balanced and $\frac{H}{H_e} = 1$ throughout the boundary layer. These same effects have been previously noted in solutions of the flat-plate boundary layer (e.g., ref. 18).

4132

The domains of velocity and temperature overshoot can be identified with the aid of the asymptotic solution to equations (27)(appendix C). For simplicity the discussion that follows is restricted to a Prandtl number of 1. A more general treatment is given in appendix C.

The asymptotic expressions for chordwise and spanwise velocity functions for a Prandtl number of 1 from appendix C are, respectively,

$$\tilde{f}' = 1 + \frac{A_1}{4}\left[2\left(\frac{t_0}{t_{N_0}} - 1\right) + \frac{t_0}{t_{N_0}}\left(\frac{t_w}{t_0} - 1\right)\right](\eta - \varkappa)^{-1} \exp\left[-\frac{(\eta - \varkappa)^2}{2}\right] + A_3(\eta - \varkappa)^{-3} \exp\left[-\frac{(\eta - \varkappa)^2}{2}\right] \tag{36}$$

and

$$\tilde{g} = 1 - \frac{A_1}{2}(\eta - \varkappa)^{-1} \exp\left[-\frac{(\eta - \varkappa)^2}{2}\right] \tag{37}$$

Examination of equation (36) shows that for large η the term involving A_1 is dominant, and thus $(\tilde{f}' - 1)$ will have the same sign as A_1. Since the g function for a Prandtl number of 1 (fig. 2) always approaches its boundary condition from below, A_1 is always positive, and consequently the existence of chordwise velocity overshoot depends directly on whether

4132

the quantity $\left[2\left(\frac{t_O}{t_{N_O}} - 1\right) + \frac{t_O}{t_{N_O}}\left(\frac{t_w}{t_O} - 1\right)\right]$ is positive. This quantity is positive when $t_w + t_O > 2t_{N_O}$. The domain of chordwise velocity overshoot is shown in figure 4. It may be seen that for cold surfaces there is only a small range of yaw angles in which no overshoot occurs.

For Prandtl numbers other than 1, the behavior of the stagnation-temperature profile must be considered separately from the spanwise velocity profile. From appendix C the asymptotic variation of θ is

$$\tilde{\theta} = 1 + A_1 \frac{\left(1 - \frac{t_{N_O}}{t_O}\right)}{\left(\frac{t_w}{t_O} - 1\right)} (\eta - x)^{-1} \exp\left[-\frac{(\eta - x)^2}{2}\right]$$

$$- \frac{A_1}{2}\left[\frac{2\left(1 - \frac{t_{N_O}}{t_O}\right) + \frac{t_w}{t_O} - 1}{\left(\frac{t_w}{t_O} - 1\right)}\right] (\eta - x)^{-1} \exp\left[-\frac{Pr(\eta - x)^2}{2}\right] \tag{38}$$

Figure 3 indicates that even for a Prandtl number of 0.7 the obtained spanwise velocity profiles approach the boundary condition from below; hence A_1 is positive from equation (37). For Prandtl numbers less than 1 the dominant term in equation (38) is the last one; thus the existence of temperature overshoot is dependent on whether the quantity $\left[\frac{2\left(1 - \frac{t_{N_O}}{t_O}\right) + \frac{t_w}{t_O} - 1}{\frac{t_w}{t_O} - 1}\right]$ is negative. The quantity is negative when the numerator is positive with $t_w/t_O < 1$. It must of course be realized that for $t_w/t_O > 1$ the stagnation temperatures in the boundary layer are always higher than the stream stagnation temperature. In appendix C it is shown that the chordwise velocity overshoot domain for a Prandtl number of 0.7 is the same as for a Prandtl number of 1. Thus for a cold wall with $Pr = 0.7$, velocity overshoot and enthalpy overshoot occur simultaneously. The various regions of overshoot are summarized in figure 4.

Skin Friction

The chordwise and spanwise components of shear stress at the wall are defined, respectively, as

$$\tau_c \equiv \mu_w\left(\frac{\partial u}{\partial z}\right)_w = \mu_w u_e f_w'' \sqrt{\frac{U_e}{\nu_0 X}\,\frac{m+1}{2}\,\frac{\rho_w}{\rho_0}\,\frac{a_e}{a_0}} \tag{39}$$

$$\tau_s \equiv \mu_w\left(\frac{\partial v}{\partial z}\right)_w = \mu_w v_e g_w' \sqrt{\frac{U_e}{\nu_0 X}\,\frac{m+1}{2}\,\frac{\rho_w}{\rho_0}\,\frac{a_e}{a_0}} \tag{40}$$

These can be represented in dimensionless form by local skin-friction coefficients;

$$\frac{\tau_e}{\frac{1}{2}\rho_w u_e^2}\sqrt{\frac{u_e x}{\nu_w}} = 2f_w'' \sqrt{\frac{m+1}{2}\,\frac{d\ \ln X}{d\ \ln x}} \tag{41}$$

$$\frac{\tau_s}{\frac{1}{2}\rho_w v_e^2}\sqrt{\frac{v_e x}{\nu_w}} = 2\sqrt{\frac{u_e}{v_e}}\, g_w' \sqrt{\frac{m+1}{2}\,\frac{d\ \ln X}{d\ \ln x}} \tag{42}$$

For the specific case of stagnation-line flow $U_e = CX$ the quantity C is related to the physical chordwise velocity gradient as follows:

$$C = \frac{U_e}{X} = \frac{dU_e}{dX} = \left[\frac{1 + \frac{\gamma - 1}{2}\left(\frac{u_e}{a_e}\right)^2}{\frac{\mu_w}{\mu_0}\,\frac{t_0}{t_w}\left(\frac{a_e}{a_0}\right)^2\frac{p_e}{p_0}}\right]\left(\frac{du_e}{dx}\right) \tag{43}$$

By use of equation (43), equations (39) and (40) can then be written in the form of skin-friction coefficients based on free-stream conditions, which for stagnation-line flow are

$$c_{f,c} = \frac{\tau_c}{\frac{1}{2}\rho_\infty\left(u_\infty^2 + v_\infty^2\right)} = 2f_w''\,\frac{\rho_w}{\rho_\infty}\,\frac{u_e}{u_\infty^2}\cos^2\Lambda\left\{\left[1 + \frac{\gamma - 1}{2}\left(\frac{u_e}{a_e}\right)^2\right]\nu_w\left(\frac{du_e}{dx}\right)\right\}^{\frac{1}{2}} \tag{44}$$

$$c_{f,s} = \frac{\tau_s}{\frac{1}{2}\rho_\infty\left(u_\infty^2 + v_\infty^2\right)} = g_w' \frac{\rho_w}{\rho_\infty} \frac{\sin 2\Lambda}{u_\infty}\left\{\left[1 + \frac{\gamma - 1}{2}\left(\frac{u_e}{a_e}\right)^2\right]\nu_w\left(\frac{du_e}{dx}\right)\right\}^{\frac{1}{2}} \tag{45}$$

At the stagnation line itself the chordwise velocity in the boundary layer is identically zero; hence there is zero chordwise viscous shearing stress. The dimensionless wall-shear function f_w'' is nevertheless of interest, since it can be used in calculating $c_{f,c}$ from equation (44) in the region close to the stagnation line. For the presented solutions, values of f_w'' are summarized in table III and plotted in figure 5. Significant increases in the wall-shear function occur with increases in the yaw parameter t_0/t_{N_0}. This is an indication of the effect of lack of independence between the spanwise and chordwise flows.

In the evaluation of the spanwise skin-friction coefficient for a Prandtl number of 1, the function g_w' is exactly θ_w', as indicated in table III and in figure 6. For a Prandtl number of 0.7 the values of g_w' for the obtained solutions are listed in table III. It may be readily seen from the table that for corresponding values of surface temperature and yaw parameter t_0/t_{N_0} there is very little effect of Prandtl number on the spanwise shear parameter g_w'.

Secondary Flow

Secondary flows are generally present in boundary layers whenever the direction of the pressure gradient impressed by the free-stream flow is different from the external flow direction. A comparison of the directions of the surface streamline and a corresponding streamline in the external flow provides a measure of the degree of secondary flow in the boundary layer.

The direction α of the streamline in the vicinity of the surface is given by the expression

$$\tan \alpha_w = \frac{\left(\frac{\partial u}{\partial z}\right)_w}{\left(\frac{\partial v}{\partial z}\right)_w} = \frac{\tau_c}{\tau_s} = \frac{u_e f_w''}{v_e g_w'} \tag{46}$$

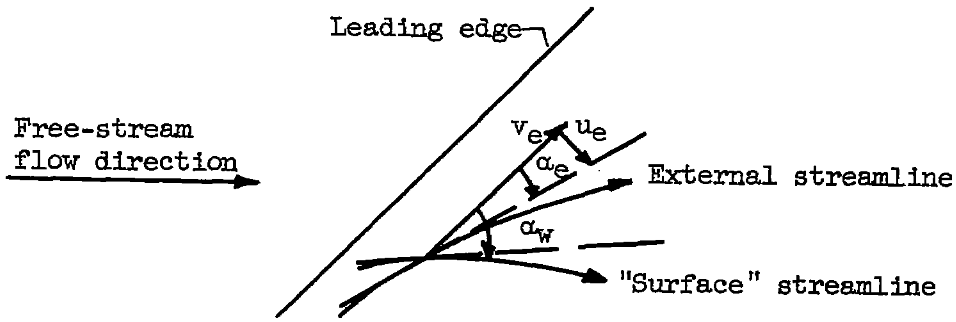
and the direction of the external streamline is

$$\tan \alpha_e = \frac{u_e}{v_e} \tag{47}$$

The ratio

$$\frac{\tan \alpha_w}{\tan \alpha_e} = \frac{f_w''}{g_w'} \tag{48}$$

is then indicative of the degree of secondary flow in the boundary layer. The angles α_e and α_w are defined in the following sketch:



Values of the ratio f_w''/g_w' for the obtained solutions are given in table III and are also plotted in figure 7. As the yaw parameter is increased, large relative increases in the secondary flow are obtained.

Heat Transfer and Adiabatic Wall Temperature

The heat-transfer coefficient is defined as $h = \dfrac{q_w}{t_{aw} - t_w}$ and by use of equations (7), (8), (21), and (28) may be written in the dimensionless form

$$\frac{Nu}{\sqrt{Re_w}} \equiv \frac{hx}{k_w}\sqrt{\frac{\nu_w}{u_e x}} = \left(\frac{t_0 - t_w}{t_{aw} - t_w}\right)\theta_w' \sqrt{\frac{m+1}{2}\frac{d \ln X}{d \ln x}} \tag{49}$$

In terms of physical quantities the heat-transfer coefficient for stagnation-line flow may be expressed

$$h = \left[\left(\frac{t_0 - t_w}{t_{aw} - t_w}\right)\theta_w'\right]\frac{k_w}{\sqrt{\nu_w}}\sqrt{\left(\frac{du_e}{dx}\right)\left[1 + \frac{\gamma - 1}{2}\left(\frac{u_e}{a_e}\right)^2\right]} \tag{50}$$

The pertinent parameter from the exact solutions is the quantity $\left(\dfrac{t_0 - t_w}{t_{aw} - t_w}\right)\theta_w'$. For a Prandtl number of 1, where $t_{aw} = t_0$, this quantity reduces just to θ_w'. However, for Prandtl numbers other than 1, the complete expression is necessary, and the adiabatic wall temperature is required. The quantity $\left(\frac{t_O - t_w}{t_{aw} - t_w}\right)\theta_w'$ for stagnation-line flow is plotted in figure 6 for the present solutions. Figures 5 and 6 show that, while yaw tends to increase both the wall-shear and the heat-transfer functions, the magnitude of the effect on heat transfer is much smaller than the corresponding effect on wall shear. For instance, for $\frac{t_O}{t_{N_O}} \leqslant 2$ and $\Lambda \leqslant 45^\circ$, which from figure 1 includes all free-stream Mach numbers, the heat-transfer parameter is increased less than 13 percent over the value for $\frac{t_O}{t_{N_O}} = 1$. This indicates that for many practical problems the effects of lack of independence on heat transfer may not be of great significance.

A comparison of the solutions for $Pr = 0.7$ and $Pr = 1$ at $\frac{t_w}{t_O} = 0.5$ indicates that the effect of Prandtl number on the heat-transfer parameter is essentially independent of the yaw parameter and can be approximately accounted for by the unyawed stagnation-point flow modification proposed by Squire (ref. 19):

$$\left[\left(\frac{t_O - t_w}{t_{aw} - t_w}\right)\theta_w'\right]_{Pr} = Pr^{0.4}(\theta_w')_{Pr=1} \tag{51}$$

The adiabatic wall or recovery temperature at the stagnation line can be calculated from equation (31), where the quantity ζ_w is the local recovery factor defined

$$\zeta_w = \frac{t_{aw} - t_{N_O}}{t_O - t_{N_O}} \tag{52}$$

Values of ζ_w have been calculated and are presented in table IV. The values for incompressible flow $(t_O/t_{N_O} = 1)$ have been calculated by the method described in appendix D, while those for $t_O/t_{N_O} > 1$ and $Pr = 0.7$ were obtained by solving equations (27) subject to the boundary conditions of equations (24) and (30), as described in the section entitled Similar Solutions.

The results for $t_0/t_{N_0} = 1$ may be closely represented by $Pr^{0.46}$, and for $t_0/t_{N_0} > 1$ there is only a slight rise in recovery factor from the incompressible value. It is thus felt that the use of the conventional laminar recovery factor $Pr^{1/2}$ would be adequate for most purposes.

The local recovery factor may be converted to a recovery factor $\mathscr{R}$ based on free-stream temperature through the expression

$$\mathscr{R} \equiv \frac{t_{aw} - t_\infty}{t_0 - t_\infty} = 1 - (1 - \zeta_w)\sin^2 \Lambda \tag{53}$$

4132

Reynolds Analogy

From equations (41) and (49) a Reynolds analogy parameter between heat transfer and chordwise shear may be written

$$\frac{\left(\frac{\tau_c}{\frac{1}{2}\rho_w u_e^2}\right)\left(\frac{u_e x}{\nu_w}\right)}{\left(\frac{hx}{k_w}\right)} = \frac{2f_w''}{\left(\frac{t_0 - t_w}{t_{aw} - t_w}\right)\theta_w'} \tag{54}$$

For a Prandtl number of 1 this reduces to $2f_w''/\theta_w'$, which is just twice the secondary-flow parameter listed in table III and plotted in figure 7.

A more interesting and perhaps more useful Reynolds analogy can be written in terms of the spanwise shear. From equations (42), (49), and (51),

$$\frac{\left(\frac{\tau_s}{\frac{1}{2}\rho_w v_e^2}\right)\left(\frac{v_e x}{\nu_w}\right)}{\left(\frac{hx}{k_w}\right)} = \frac{2g_w'}{\left(\frac{t_0 - t_w}{t_{aw} - t_w}\right)\theta_w'} \approx \frac{2}{Pr^{0.4}} \tag{55}$$

This latter approximate relation applies to all the present solutions, since for a Prandtl number of 1, $g_w' = \theta_w'$; and the results shown in table III indicate that $(g_w')_{Pr=1}$ is approximately equal to $(g_w')_{Pr=0.7}$. The resemblance of equation (55) to the conventional flat-plate Reynolds analogy is due to the zero pressure gradient in the spanwise direction.

4132

Boundary-Layer Thickness

The boundary-layer thickness in the physical plane can be computed from equation (35). By definition of the boundary-layer thickness δ as the value of z at which $\theta = 0.9990$ (i.e., $\eta = \eta_\delta$), the expression for boundary-layer thickness for a Prandtl number of 1 becomes (from eq. (35))

$$\delta\sqrt{\frac{u_\infty}{\nu_w D}\left(\frac{D}{u_\infty}\frac{du_e}{dx}\right)}\frac{t_w}{t_0} = \int_0^{\eta_\delta}\left[\left(1 - \frac{t_w}{t_0}\right)\theta - \left(1 - \frac{t_{N_0}}{t_0}\right)\theta^2 + \frac{t_w}{t_0}\right]d\eta \quad (56)$$

This expression has been evaluated for a range of values of t_w/t_0, and the results are shown in figure 8. The actual boundary-layer thickness may then be computed easily for any given combination of flow variables and wall temperature.

ENGINEERING HEAT-TRANSFER RELATIONS FOR STAGNATION-LINE FLOW

The local rate of heat transfer to the wall per unit wall area is calculated from the relation

$$q_w = h(t_{aw} - t_w) \quad (57)$$

which requires a knowledge of the heat-transfer coefficient h and the adiabatic wall temperature t_{aw}.

The adiabatic wall temperature at the stagnation line is obtained from equation (52) with the recovery factor evaluated from table IV.

The expression for heat-transfer coefficient is

$$h = \frac{k_w}{\sqrt{\nu_w}}\left[\left(\frac{t_0 - t_w}{t_{aw} - t_w}\right)\theta_w'\right]\sqrt{\left(\frac{du_e}{dx}\right)\left[1 + \frac{\gamma - 1}{2}\left(\frac{u_e}{a_e}\right)^2\right]} \quad (50)$$

To evaluate the heat-transfer coefficient h in the stagnation-line region of a given yawed cylinder, it is necessary to evaluate the fluid properties at the wall, the chordwise velocity gradient (du_e/dx) and the heat-transfer parameter $\left(\frac{t_0 - t_w}{t_{aw} - t_w}\right)\theta_w'$. The evaluation of these items with consideration of the effects of yaw is discussed in the following paragraphs.

Fluid Properties at the Wall

The thermal conductivity and absolute viscosity can be considered as functions of temperature alone, but the density varies also with the pressure according to the equation of state. The static pressure is determined from the inviscid flow. When the chordwise component of the free-stream velocity is supersonic, the wall pressure at the stagnation line is that which would be sensed by a pitot tube placed normal to the shock. This pressure is related to the free-stream static pressure by the expression

$$\frac{p_{w_{sl}}}{p_\infty} = \left(\frac{\gamma + 1}{2} M_{N_\infty}^2\right)^{\frac{\gamma}{\gamma-1}} \left[\frac{\gamma + 1}{2\gamma M_{N_\infty}^2 - (\gamma - 1)}\right]^{\frac{1}{\gamma-1}} \tag{58}$$

(where $M_{N_\infty} = M_\infty \cos \Lambda$). For subsonic chordwise flow

$$\frac{p_{w_{sl}}}{p_\infty} = \left(1 + \frac{\gamma - 1}{2} M_{N_\infty}^2\right)^{\frac{\gamma}{\gamma-1}} \tag{59}$$

Chordwise Velocity Gradient

Based on the observation (refs. 20 and 21) that for normal circular cylinders at free-stream Mach numbers greater than 2 the pressure coefficient varies about the cylinder as

$$\frac{C_p}{C_{p,max}} \approx \cos^2\left(\frac{2x}{D}\right) \tag{60}$$

an expression for the velocity gradient at the stagnation line $\left(\frac{du_e}{dx}\right)$ was derived. This relation in dimensionless form is

$$\frac{D}{u_\infty}\left(\frac{du_e}{dx}\right) = \frac{2a_0}{M_\infty a_\infty}\sqrt{\frac{2}{\gamma}\left(1 - \frac{p_\infty}{p_{w_{sl,\Lambda=0}}}\right)} \tag{61}$$

Penland (ref. 20) further observed that equation (60) reasonably represents the chordwise pressure distribution over a yawed cylinder. Therefore, equation (61) for a yawed cylinder becomes just a function of the normal Mach number. With a normal Mach number greater than about 2 and upon introduction of the proper stagnation-line fluid properties, equation (61) becomes

$$\frac{D}{u_\infty}\frac{du_e}{dx} = \frac{2a_{N_0}}{a_\infty M_{N_\infty}}\sqrt{\frac{2}{\gamma}\left(1 - \frac{p_\infty}{p_{w_{sl,\Lambda}}}\right)} \tag{62}$$

It must be remembered that in equation (62) u_∞ is the chordwise component of the free-stream velocity.

For subsonic chordwise flow (according to ref. 22),

$$\frac{D}{u_\infty}\frac{du_e}{dx} = 4\left(1 - 0.416\ M_{N_\infty}^2 - 0.164\ M_{N_\infty}^4\right) \tag{63}$$

Relations (62) and (63) are plotted in figure 9 along with available data on the chordwise velocity gradient from references 20 and 23 to 25. It is to be noted that for subsonic normal Mach numbers the experimental values of $\frac{D}{u_\infty}\frac{du_e}{dx}$ differ somewhat from the values of equation (63). It is therefore recommended that these experimental values be used in place of the equation. The broken line in figure 9 in the region $0.8 < M_\infty \cos\Lambda < 1.5$ was drawn as an estimate of the velocity-gradient variation, since neither equation (62) nor equation (63) is strictly applicable and there are no experimental data available for that range.

Heat-Transfer Parameter

For the general case of arbitrary Prandtl number and surface temperature it is reasonable to assume from equation (51) that

$$\left[\left(\frac{t_0 - t_w}{t_{aw} - t_w}\right)\theta_w'\right]_{Pr} = \left(\theta_w'\right)_{Pr=1} Pr^{0.4} \tag{64}$$

Values of $\left(\theta_w'\right)_{Pr=1}$ may be obtained from either table III or figure 6.

When equations (58) to (64) are combined as required, equation (50) becomes, for the stagnation line of a yawed cylinder,

$$h_\Lambda = k_w\left(\theta_w'\right)_{Pr=1} Pr^{0.4}\sqrt{\frac{u_\infty}{\mu_w D}\frac{p_\infty}{Rt_w}\left(\frac{p_{w_{sl,\Lambda}}}{p_\infty}\right)\left(\frac{D}{u_\infty}\frac{du_e}{dx}\right)} \tag{65}$$

Effect of Yaw Angle and Mach Number on Heat-Transfer

Coefficient at the Stagnation Line

The ratio of yawed to normal heat-transfer coefficient for a given cylinder with the same conditions of free-stream and surface temperatures is from equation (65)

$$\frac{h_\Lambda}{h_{\Lambda=0}} = \left(\frac{\theta'_{w_\Lambda}}{\theta'_{w_{\Lambda=0}}}\right)_{Pr=1} \sqrt{\cos\Lambda \frac{\left(\frac{p_{w_{sl,\Lambda}}}{p_\infty}\right)\left(\frac{D}{u_\infty}\frac{du_e}{dx}\right)_{M_{N_\infty}}}{\left(\frac{p_{w_{sl,\Lambda=0}}}{p_\infty}\right)\left(\frac{D}{u_\infty}\frac{du_e}{dx}\right)_{M_\infty}}} \tag{66}$$

4132

This relation is plotted in figure 10 as a function of yaw angle and Mach number for an essentially insulated surface $\left(\frac{t_w}{t_0} \approx 1\right)$. The value of $\left(\frac{D}{u_\infty}\frac{du_e}{dx}\right)$ for these calculations was taken as the modified Newtonian value for $M_\infty \cos\Lambda > 1.5$ (eq. (62)) and from the dotted line of figure 9 for $M_\infty \cos\Lambda < 1.5$.

For incompressible flow $\left(\frac{t_0}{t_{N_0}} = 1\right)$ the ratio of yawed to normal heat-transfer coefficient becomes

$$\left(\frac{h_\Lambda}{h_{\Lambda=0}}\right)_{M_\infty=0} = (\cos\Lambda)^{1/2} \tag{67}$$

which is exactly that indicated experimentally for hot wires by Schubauer and Klebanoff (ref. 26). For subsonic speeds the yaw effect is very close to that for incompressible flow. The curve for $M_\infty = 1$ is in some doubt because of the lack of suitable experimental information on the chordwise velocity gradient. The effect of yaw for supersonic flow depends on the normal component of the stream Mach number. In the region where the normal component of the stream Mach number is supersonic, the curves of the ratio of yawed to normal heat-transfer coefficient are all very close to each other and somewhat below $\cos\Lambda$ (fig. 10). As the normal Mach number becomes transonic, the ratio exceeds $\cos\Lambda$, and at large yaw angle where the normal Mach number is subsonic, the curves tend to approach a $(\cos\Lambda)^{1/2}$ variation.

The influence of the exact solutions reported herein can be seen by comparing the curve for $M_\infty = 7$ with that for the same Mach number but for θ_w' assumed constant at the zero-yaw value. For a Mach number of infinity the ratio of yawed to normal heat-transfer coefficient (not shown in fig. 10) is only slightly below that for $M_\infty = 7$ and from equations (58) and (66) is given by the relation

$$\left(\frac{h_\Lambda}{h_{\Lambda=0}}\right)_{M_\infty \to \infty} = \frac{(\theta_w')_{t_0/t_{N_0}=\sec^2\Lambda}}{(\theta_w')_{\Lambda=0}} (\cos \Lambda)^{3/2} \tag{68}$$

The application of the results of this investigation must be stopped short of the case of the parallel cylinder ($\Lambda = 90^\circ$), since the initial hypothesis that spanwise derivatives are identically zero does not apply.

The effect of heating or cooling on the ratio of yawed to normal heat-transfer coefficient is shown in figure 11 for a Prandtl number of 1 in terms of a modification factor to the nearly insulated result. The factor is

$$\frac{\left(\dfrac{h_\Lambda}{h_{\Lambda=0}}\right)_{t_w/t_0}}{\left(\dfrac{h_\Lambda}{h_{\Lambda=0}}\right)_{t_w/t_0=1}} = \frac{\left(\dfrac{\theta_{w_\Lambda}'}{\theta_{w_{\Lambda=0}}'}\right)_{t_w/t_0}}{\left(\dfrac{\theta_{w_\Lambda}'}{\theta_{w_{\Lambda=0}}'}\right)_{t_w/t_0=1}} \tag{69}$$

The effect of surface-temperature level from absolute zero to twice free-stream stagnation temperature on the ratio of heat-transfer coefficients is shown in figure 11 to be within ±10 percent of the insulated heat-transfer-coefficient ratio for t_0/t_{N_0} less than 6.5.

The curves of figures 10 and 11 are essentially independent of Prandtl number, since the effect of Prandtl number on heat transfer has been approximately included through a modification to the $Pr = 1$ solutions. The effect of Prandtl number is accounted for exactly through the expression

$$\frac{\left(\dfrac{h_\Lambda}{h_{\Lambda=0}}\right)_{Pr=0.7}}{\left(\dfrac{h_\Lambda}{h_{\Lambda=0}}\right)_{Pr=1}} = \frac{\left[\dfrac{\left(\dfrac{t_0 - t_w}{t_{aw} - t_w}\right)\theta_{w_\Lambda}'}{\left(\dfrac{t_0 - t_w}{t_{aw} - t_w}\right)\theta_{w_{\Lambda=0}}'}\right]_{Pr=0.7}}{\left(\dfrac{\theta_{w_\Lambda}'}{\theta_{w_{\Lambda=0}}'}\right)_{Pr=1}} \tag{70}$$

which is shown in figure 12 for $t_w/t_0 = 0.5$. For a Prandtl number 0.7 there is at most about a 2-percent effect at this temperature level.

SUMMARY OF RESULTS

The equations for compressible-boundary-layer development over a yawed infinite cylinder with heat transfer have been presented and solutions obtained for stagnation-line flow. The following are among the results obtained: 4132

1. The ratio of yawed to normal heat-transfer coefficient for the stagnation line of a given cylinder varies with yaw angle Λ as $(\cos \Lambda)^{1/2}$ for incompressible flow and shows nearly that variation for much of the subsonic range. Where the velocity normal to the cylinder is supersonic, this ratio is again almost a unique function of yaw angle, the ratio being in this case somewhat lower than $\cos \Lambda$. Most of this decrease in heat-transfer coefficient with yaw angle can be accounted for by the change in local flow quantities outside the boundary layer that occurs as the normal Mach number and strength of the bow shock change with yaw angle.

2. The effect of large amounts of heating or cooling on the ratio of yawed to normal heat-transfer coefficient is less than 10 percent for values of the yaw parameter t_0/t_{N_0} less than 6 for surface-temperature levels from absolute zero to twice free-stream stagnation temperature. Changing the Prandtl number from 1 to 0.7 had at most a 2-percent effect on the ratio of yawed to normal heat-transfer coefficient.

3. The local recovery factor at the stagnation line of yawed cylinders is closely represented by $Pr^{0.46}$. For most purposes this may be approximated by the square root of the Prandtl number.

4. Where the independence principle does not apply, the effects of yaw on chordwise wall shear are much larger on a percentage basis than the corresponding effects on spanwise shear or heat transfer. For yaw angles up to 45° and for all Mach numbers, values of a local heat-transfer parameter $\frac{Nu}{\sqrt{Re_w}}$ for stagnation-line flow are less than 13 percent above the zero-yaw value.

5. For favorable pressure gradient a chordwise velocity overshoot is obtained where the sum of the surface temperature and the free-stream stagnation temperature is greater than twice the external temperature ($t_w + t_0 > 2t_{N_0}$). While in the unyawed case velocity overshoot is

obtained only for heated surfaces, with yaw it is obtained also for cooled surfaces. Another unusual effect noted was that for Prandtl numbers less than unity, when velocity overshoot was obtained for an insulated or cooled surface, the local stagnation enthalpy within the boundary layer exceeded the stream stagnation enthalpy.

6. The degree of secondary flow, as evidenced by the deflection of the "wall" streamline compared to the external streamline, increased with wall temperature and yaw-angle parameter.

4132

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 4, 1957

CG-4 back

APPENDIX A

SYMBOLS

$A_1, A_2, \cdots$	constants in asymptotic solution
a	sonic velocity
C	stagnation-line chordwise velocity gradient; $C = \frac{U_e}{X} = \frac{dU_e}{dX}$
C_p	pressure coefficient, $\frac{p - p_\infty}{\frac{1}{2} \rho_\infty u_\infty^2}$
c_f	local skin-friction coefficient
c_p	specific heat at constant pressure
D	diameter of cylinder at stagnation line
f	function related to stream function, $\psi\sqrt{\frac{m + 1}{2\nu_0 U_e X}}$
g	spanwise velocity variable
H	total enthalpy, $c_p t + \frac{u^2 + v^2}{2}$
h	heat-transfer coefficient
k	thermal conductivity
k_{Su}	Sutherland's constant
M	Mach number
m	exponent from $U_e = CX^m$
Nu	Nusselt number, hx/k_w
Pr	Prandtl number
p	pressure
q	heat-transfer rate to wall per unit area
R	gas constant

4132

4132

$\mathscr{R}$	free-stream recovery factor, $\frac{t_{aw} - t_\infty}{t_0 - t_\infty}$
Re_w	Reynolds number, $\frac{\rho_w u_e x}{\mu_w}$
t	static temperature
U	transformed chordwise velocity component
u	chordwise velocity component
v	spanwise velocity component
W	transformed normal velocity component
w	normal velocity component
X	transformed chordwise coordinate
x	chordwise coordinate
y	spanwise coordinate
Z	transformed normal coordinate
z	normal coordinate
α	streamline inclination
β	pressure-gradient parameter, $\frac{2m}{m + 1}$
γ	ratio of specific heats
δ	boundary-layer thickness
ζ	spanwise temperature-difference parameter
ζ_w	local recovery factor
η	similarity variable, $Z\sqrt{\frac{m + 1}{2}}\frac{U_e}{\nu_0 X}$
θ	normalized enthalpy function, $\frac{H - H_w}{H_e - H_w}$
$\varkappa$	constant in asymptotic solution

Λ	yaw angle
λ	$\lambda = \dfrac{(\mu/\mu_0)}{(t/t_0)} = \left(\dfrac{t_0 + k_{Su}}{t_w + k_{Su}}\right)\sqrt{\dfrac{t_w}{t_0}}$
μ	absolute viscosity
ν	kinematic viscosity
ρ	density
τ	wall shear stress
ψ	stream function

4132

Subscripts:

aw	adiabatic wall
c	chordwise
e	local flow outside boundary layer (external)
max	maximum
N	component normal to cylinder axis
s	spanwise
sl	stagnation line
w	wall or surface value
∞	free-stream quantity ahead of bow shock wave
0	free-stream stagnation value
Λ	quantity pertaining to yawed cylinder
Λ=0	quantity pertaining to normal cylinder

Superscripts:

'	differentiation with respect to η
~	asymptotic quantity

4132

APPENDIX B

SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS

Solutions to equations (25) were obtained independently at both the Lewis and Langley laboratories of the NACA. The solutions to equations (27) were obtained at the Langley laboratory. The procedure used at the Lewis laboratory is the forward integration technique described in appendix B of reference 27 and is based on five-point integration formulas. This is the same procedure as that used in obtaining some of the solutions presented in reference 15. An IBM card-programmed electronic calculator was used.

At the Langley laboratory the step-by-step integration procedure described in reference 28 was used. This procedure seems somewhat superior to the five-point technique and will therefore be described in some detail. This particular procedure is a modification of the Runge-Kutta method and was developed primarily for automatic digital computing machines. The Bell Telephone Laboratories X-66744 relay computer at Langley is one of this type and was used for the present solutions. A step size of 0.2 was used for all the solutions, although a few solutions were also calculated with a step size of 0.1 for the purpose of evaluating the error due to step size. The calculations were carried out to $\eta = 6.0$, since the results showed that the stream boundary conditions could always be satisfied to the desired degree of accuracy for $\eta \leqslant 6.0$.

Convergence to Boundary Conditions

The integration of the present equations constitutes a "two-point boundary-value problem" in which the correct initial values at $\eta = 0$ (such that the boundary conditions for large η are satisfied) of the functions or their derivatives are usually found by a trial-and-error or interpolation method.

The procedure used to obtain convergence for the present solutions involved an adaptation of Newton's method to three variables and the idea that for large η the value of the functions depends on the assumed initial values at $\eta = 0$. Applying this procedure to equations (27) with boundary conditions of equations (24) results in the following general functional forms:

$$\left.\begin{aligned} f'_\infty &= f'_\infty(f''_w,\theta'_w,g'_w) \\ \theta_\infty &= \theta_\infty(f''_w,\theta'_w,g'_w) \\ g_\infty &= g_\infty(f''_w,\theta'_w,g'_w) \end{aligned}\right\} \tag{B1}$$

where the subscripts ∞ and w denote the computed values of the function at large η and at $\eta = 0$, respectively. The error in the functions at large η is then given by

$$\left.\begin{aligned}
df'_\infty &= \frac{\partial f'_\infty}{\partial f''_w}\,df''_w + \frac{\partial f'_\infty}{\partial \theta'_w}\,d\theta'_w + \frac{\partial f'_\infty}{\partial g'_w}\,dg'_w \\
d\theta_\infty &= \frac{\partial \theta_\infty}{\partial f''_w}\,df''_w + \frac{\partial \theta_\infty}{\partial \theta'_w}\,d\theta'_w + \frac{\partial \theta_\infty}{\partial g'_w}\,dg'_w \\
dg_\infty &= \frac{\partial g_\infty}{\partial f''_w}\,df''_w + \frac{\partial g_\infty}{\partial \theta'_w}\,d\theta'_w + \frac{\partial g_\infty}{\partial g'_w}\,dg'_w
\end{aligned}\right\} \tag{B2}$$

The various partial derivatives in equations (B2) may be evaluated approximately from four trial solutions according to the following table:

Trial solution	Initial values			Partial derivative
	f''_w	θ'_w	g'_w	
1	f''_{w_1}	θ'_{w_1}	g'_{w_1}	$\partial/\partial f''_w$ (solutions 1, 2)
2	f''_{w_2}	θ'_{w_1}	g'_{w_1}	$\dfrac{\partial}{\partial \theta'_w}$ (solutions 2, 3)
3	f''_{w_2}	θ'_{w_2}	g'_{w_1}	$\partial/\partial g'_w$ (solutions 3, 4)
4	f''_{w_2}	θ'_{w_2}	g'_{w_2}	

The best solution of these four, say solution i, is then used to obtain the errors, which from equations (24) are

$$\left.\begin{aligned}
df'_\infty &= f'(\infty) - f'_{\infty_i} = 1 - f'_{\infty_i} \\
d\theta_\infty &= \theta(\infty) - \theta_{\infty_i} = 1 - \theta_{\infty_i} \\
dg_\infty &= g(\infty) - g_{\infty_i} = 1 - g_{\infty_i}
\end{aligned}\right\} \tag{B3}$$

where f'_{∞_i}, θ_{∞_i}, and g_{∞_i} are the computed values at large η from the best solution.

Equations (B2) are then solved simultaneously for df''_w, $d\theta'_w$, and dg'_w. The corrected initial values are

$$\left.\begin{aligned} f''_{w_3} &= f''_{w_i} + df''_w \\ \theta'_{w_3} &= \theta'_{w_i} + d\theta'_w \\ g'_{w_3} &= g'_{w_i} + dg'_w \end{aligned}\right\} \tag{B4}$$

4132

which may be used for repeating the whole procedure until convergence is attained. In the present problem, however, satisfactory convergence was attained by computing a trial solution with the corrected initial values and then using the results of this new solution to reevaluate df'_∞, $d\theta_\infty$, and dg_∞ from equations (B3); equations (B2) were then solved for df''_w, $d\theta'_w$, and dg'_w by using the partial derivatives already obtained. A new set of initial values is computed from equation (B4) and the results of the new solution, and the procedure is repeated until the boundary conditions are satisfied to the desired degree of accuracy. In most cases four or five more trial solutions were required for this purpose, which made a total of about nine trial solutions for any one case. Note, however, that in accordance with Newton's method the above procedure cannot be expected to give satisfactory convergence unless the errors df'_∞, $d\theta_\infty$, and dg_∞ from the original four solutions are reasonably small. In the present problem these errors were limited to about 0.4 before the partial derivatives were evaluated.

CG-5

Accuracy of Solution

The inherent error in the Runge-Kutta method is of the order of the step size to the fifth power. A discussion of the errors in the integration procedure used here is given in reference 28.

An example of the errors due to step size and initial values for one of the present solutions is given in the following table for the case $t_w/t_0 = 1.5$, $t_0/t_{N_0} = 1.2$, and $Pr = 1$:

Step size	Initial values		Boundary conditions at $\eta = 6.0$	
	f''_w	θ'_w	$f'(6.0)$	$\theta(6.0)$
0.2	1.664076	0.610859	0.999684	0.999998
.2	1.664085	.610863	.999987	.999999
.1	1.664085	.610863	.999328	1.000027

Inspection of the table indicates that the value of f' at large η is relatively sensitive to both the initial values and the step size. This is in accordance with the values of the partial derivatives, which for this case were

$$\frac{\partial f'_\infty}{\partial f''_w} = 28.4 \qquad \frac{\partial f'_\infty}{\partial \theta'_w} = 15.4$$

$$\frac{\partial \theta_\infty}{\partial f''_w} = -0.51 \qquad \frac{\partial \theta_\infty}{\partial \theta'_w} = 1.56$$

4132

In general, all the solutions were repeated until the maximum error in the boundary conditions was at most 0.0001 in f' and 0.00001 in θ or g at $\eta = 6.0$ with a step size of 0.2. Reducing the step size to 0.1 gives a more accurate solution, which can be used to evaluate the errors in the initial values f''_w and θ'_w for the 0.2 step size. Thus, the sample solutions given in the table indicate that reducing the step size to 0.1, but using the same initial values, increases the errors in the outer boundary conditions by 0.00066 for $f'(6.0)$ and by 0.00003 for $\theta(6.0)$. Adding these changes to the maximum allowable computing errors of 0.0001 in $f'(6.0)$ and 0.00001 in $\theta(6.0)$ results in an improved evaluation of the actual errors, which would be approximately 0.0007 in $f'(6.0)$ and 0.00004 in $\theta(6.0)$. From these errors in f' and θ and the values of the partial derivatives just given, the <u>maximum</u> errors in the initial values as obtained from equations (B2)(modified for the case of $Pr = 1$) are

$$df''_w = \pm 0.00001$$

$$d\theta'_w = \pm 0.00003$$

Thus, the initial values are accurate to at least the fourth decimal place, assuming that a further decrease in step size would not have much additional effect on the solutions. The functions f' and θ are evidently accurate to the third and fourth decimal places, respectively, for large values of η.

4132

CG-5 back

Comparison of the Two Techniques

Among the cases calculated, three for $t_w/t_0 = 1$ were done independently by both techniques. Comparisons of values of f''_w and θ'_w as well as values of f, f', f'', θ, and θ' at $\eta = 4$ are given in the following tables:

t_0/t_{N_0}	f''_w		θ'_w	
	Five-point	Runge-Kutta	Five-point	Runge-Kutta
1.1	1.29887	1.29886	0.57760	0.57763
1.2	1.36401	1.36400	.58446	.58447
3.0	2.40863	2.40857	.67698	.67699

t_0/t_{N_0}	$f(4)$		$f'(4)$		$f''(4)$		$\theta(4)$		$\theta'(4)$	
	Five-point	Runge-Kutta	Five-point	Runge-Kutta	Five-point	Runge-Kutta	Five-point	Runge-Kutta	Five-point	Runge-Kutta
1.1	3.3902	3.3901	1.0000	1.0000	0.0001	0	0.9996	0.9996	0.0016	0.0016
1.2	3.4265	3.4263	1.0002	1.0000	0	-.0001	.9997	.9996	.0015	.0015
3.0	3.8946	3.8947	1.0002	1.0001	-.0006	-.0007	.9999	.9999	.0004	.0004

There is a difference of not more than 0.0001 in the initial values and not more than 0.0002 in the functions near the outer edge of the boundary layer. An examination of other values of the functions shows them to differ by 0.0002 or less for all values of η. It is felt therefore that all tabulated values in tables I, II, and III are certainly correct to three decimal places and that most of the tabulations are probably correct to ± 0.0005.

APPENDIX C

ASYMPTOTIC SOLUTION

To examine the behavior of the presented solutions near the outer edge of the boundary layer, it is useful to find a solution of the system

$$f''' + ff'' = f'^2 - 1 - \left(\frac{t_O}{t_{N_O}} - 1\right)(1 - g^2) - \frac{t_O}{t_{N_O}}\left(\frac{t_w}{t_O} - 1\right)(1 - \theta) \tag{27a}$$

$$g'' + fg' = 0 \tag{27b}$$

$$\theta'' + \Pr f\theta' = (1 - \Pr)\frac{\left(1 - \frac{t_{N_O}}{t_O}\right)}{\left(1 - \frac{t_w}{t_O}\right)}(g^2)'' \tag{27c}$$

for large η.

The asymptotic form for f (designated $\tilde{f}$) is assumed to consist of a sum of terms, each smaller than the preceding. Only the first two terms are considered herein. The corresponding solutions for the spanwise velocity function $\tilde{g}$ and the stagnation enthalpy function $\tilde{\theta}$ are also obtained.

Let

$$\tilde{f} = \tilde{f}_1 + \tilde{f}_2 \tag{C1}$$

where

$$\tilde{f}_2 \ll \tilde{f}_1$$

$$\tilde{f}_2' \ll \tilde{f}_1'$$

Since $\lim_{\eta\to\infty} f' = 1$, let

$$\tilde{f}_1 = \eta - \varkappa \tag{C2}$$

where $\varkappa$ is an undetermined constant. If $\tilde{f}_1$ is inserted into equation (27), the corresponding spanwise velocity function $\tilde{g}_1$ and enthalpy

4132

4132

function $\tilde{\theta}_1$ must both be 1. Inserting equations (C1) and (C2) into equations (27) and dropping higher order terms result in

$$\tilde{f}_2''' + (\eta - x)\tilde{f}_2'' = 2\tilde{f}_2' + 2\left(\frac{t_0}{t_{N_0}} - 1\right)\tilde{g}_2 + \frac{t_0}{t_{N_0}}\left(\frac{t_w}{t_0} - 1\right)\tilde{\theta}_2 \tag{C3}$$

$$\tilde{g}_2'' + (\eta - x)\tilde{g}_2' = 0 \tag{C4}$$

$$\tilde{\theta}_2'' + \Pr(\eta - x)\tilde{\theta}_2' = - \frac{2(1 - \Pr)}{\left(\frac{t_w}{t_0} - 1\right)}\left(1 - \frac{t_{N_0}}{t_0}\right)\tilde{g}_2'' \tag{C5}$$

Equations (C3), (C4), and (C5) are very similar to equations (B3) of reference 15. For $\Pr = 1$ and $t_0/t_{N_0} = 1$, they are identical. The procedure for obtaining the asymptotic solution is similar to that in appendix B of reference 15. Equation (C4) can be integrated directly to give

$$\tilde{g}_2' = A_1 e^{-\frac{(\eta - x)^2}{2}} \tag{C6}$$

which integrates once again to the complementary error function

$$\tilde{g}_2 = - \frac{A_1}{\sqrt{2}} \int_\eta^\infty e^{-\frac{(\eta - x)^2}{2}} \, d\eta$$

or

$$\tilde{g}_2 = - \frac{A_1}{\sqrt{2}} \frac{\sqrt{\pi}}{2} \operatorname{cerf}\left[\frac{(\eta - x)}{\sqrt{2}}\right] \tag{C7}$$

By use of equations (C4) and (C6), equation (C5) can now be written

$$\tilde{\theta}_2'' + \Pr(\eta - x)\tilde{\theta}_2' = \frac{2(1 - \Pr)}{\left(\frac{t_w}{t_0} - 1\right)}\left(1 - \frac{t_{N_0}}{t_0}\right)(\eta - x)A_1 e^{-\frac{(\eta - x)^2}{2}} \tag{C8}$$

which has as its complete solution

$$\tilde{\theta}_2 = \frac{A_1}{\sqrt{2}} \frac{2}{\left(\frac{t_w}{t_0} - 1\right)} \left(1 - \frac{t_{N_0}}{t_0}\right) \frac{\sqrt{\pi}}{2} \operatorname{cerf}\left[\frac{(\eta - x)}{\sqrt{2}}\right]$$

$$- A_2\sqrt{\frac{Pr}{2}} \frac{\sqrt{\pi}}{2} \operatorname{cerf}\left[(\eta - x)\sqrt{\frac{Pr}{2}}\right] \tag{C9}$$

4132

where the coefficient A_2 may be evaluated by recognizing that the asymptotic forms $\tilde{g}_2$ and $\tilde{\theta}_2$ are identical for a Prandtl number of 1. From equations (C7) and (C9) with $Pr = 1$,

$$A_2 = A_1\left[\frac{2\left(1 - \frac{t_{N_0}}{t_0}\right) + \left(\frac{t_w}{t_0} - 1\right)}{\left(\frac{t_w}{t_0} - 1\right)}\right] \tag{C10}$$

Assume that this expression holds for $Pr \neq 1$. Equation (C9) then becomes

$$\tilde{\theta}_2 = \frac{A_1}{\sqrt{2}}\left\{\frac{2\left(1 - \frac{t_{N_0}}{t_0}\right)}{\left(\frac{t_w}{t_0} - 1\right)} \frac{\sqrt{\pi}}{2} \operatorname{cerf}\left[\frac{(\eta - x)}{\sqrt{2}}\right]\right.$$

$$\left. - \sqrt{Pr}\left[\frac{2\left(1 - \frac{t_{N_0}}{t_0}\right) + \left(\frac{t_w}{t_0} - 1\right)}{\left(\frac{t_w}{t_0} - 1\right)}\right] \frac{\sqrt{\pi}}{2} \operatorname{cerf}\left[(\eta - x)\sqrt{\frac{Pr}{2}}\right]\right\} \tag{C11}$$

The expressions (C7) and (C11) for $\tilde{g}_2$ and $\tilde{\theta}_2$, respectively, may now be substituted into the differential equation (C3) for $\tilde{f}_2'$:

$$\tilde{f}_2''' + (\eta - x)\tilde{f}_2'' - 2\tilde{f}_2' =$$

$$- A_1\sqrt{\frac{Pr}{2}}\left[2\left(\frac{t_0}{t_{N_0}} - 1\right) + \frac{t_0}{t_{N_0}}\left(\frac{t_w}{t_0} - 1\right)\right] \frac{\sqrt{\pi}}{2} \operatorname{cerf}\left[(\eta - x)\sqrt{\frac{Pr}{2}}\right] \tag{C12}$$

4132

For large η the right side of equation (C12) can be rewritten using the leading term of the following expansion of the complementary error function

$$\frac{\sqrt{\pi}}{2} \operatorname{cerf} x = \frac{e^{-x^2}}{2x}\left[1 - \frac{1}{2x^2} + \ldots\right] \tag{C13}$$

Equation (C12) then becomes

$$\tilde{f}_2''' + (\eta - \varkappa)\tilde{f}_2'' - 2\tilde{f}_2' =$$

$$-\frac{A_1}{2}\left[2\left(\frac{t_0}{t_{N_0}} - 1\right) + \frac{t_0}{t_{N_0}}\left(\frac{t_w}{t_0} - 1\right)\right](\eta - \varkappa)^{-1} \exp\left[-\frac{Pr}{2}(\eta - \varkappa)^2\right] \tag{C14}$$

A particular solution to equation (C14) is sought wherein the leading term is of the form

$$\tilde{f}_2' = B(\eta - \varkappa)^N e^{-\frac{Pr}{2}(\eta-\varkappa)^2} \tag{C15}$$

Substituting equation (C15) into equation (C14) and examining the results separately for $Pr \neq 1$ and for $Pr = 1$ results in the following particular solutions:

For $Pr \neq 1$

$$\tilde{f}_{2p}' = -\frac{A_1}{2Pr(Pr - 1)}\left[2\left(\frac{t_0}{t_{N_0}} - 1\right) + \frac{t_0}{t_{N_0}}\left(\frac{t_w}{t_0} - 1\right)\right](\eta - \varkappa)^{-3} \exp\left[-\frac{Pr}{2}(\eta - \varkappa)^2\right] \tag{C16}$$

and for $Pr = 1$

$$\tilde{f}_{2p}' = \frac{A_1}{4}\left[2\left(\frac{t_0}{t_{N_0}} - 1\right) + \frac{t_0}{t_{N_0}}\left(\frac{t_w}{t_0} - 1\right)\right](\eta - \varkappa)^{-1} \exp\left[-\frac{(\eta - \varkappa)^2}{2}\right] \tag{C17}$$

It is to be noted that for $Pr < 1$, equations (C16) and (C17) have the same qualitative behavior; that is, they are both positive or negative depending on whether the quantity $\left[2\left(\frac{t_0}{t_{N_0}} - 1\right) + \frac{t_0}{t_{N_0}}\left(\frac{t_w}{t_0} - 1\right)\right]$ is positive or negative.

The complementary function for $\tilde{f}_2'$ can be found by noting that the homogeneous part of equation (C12) is Weber's equation. Hartree (ref. 9) gives the general solution for large values of the argument $\eta - \varkappa$, which can be written

$$\tilde{f}_2' = A_3(\eta - \varkappa)^{-3} \exp\left[-\frac{(\eta - \varkappa)^2}{2}\right] + A_4(\eta - \varkappa)^2 \qquad \text{(C18)}$$

In order to satisfy the boundary condition $\lim_{\eta \to \infty} \tilde{f}_2' = 0$, it is necessary to take $A_4 = 0$ in equation (C18). 4132

The asymptotic variations of velocity and enthalpy functions are, from equations (C7), (C11), (C13), (C16), (C17), and (C18):

$$(\tilde{f}')_{Pr\neq 1} = 1 + \frac{A_1}{2Pr(1 - Pr)}\left[2\left(\frac{t_0}{t_{N_0}} - 1\right) + \frac{t_0}{t_{N_0}}\left(\frac{t_w}{t_0} - 1\right)\right](\eta - \varkappa)^{-3} \exp\left[-\frac{Pr}{2}(\eta - \varkappa)^2\right]$$
$$+ A_3(\eta - \varkappa)^{-3} \exp\left[-\frac{(\eta - \varkappa)^2}{2}\right] \qquad \text{(C19)}$$

$$(\tilde{f}')_{Pr=1} = 1 + \frac{A_1}{4}\left[2\left(\frac{t_0}{t_{N_0}} - 1\right) + \frac{t_0}{t_{N_0}}\left(\frac{t_w}{t_0} - 1\right)\right](\eta - \varkappa)^{-1} \exp\left[-\frac{(\eta - \varkappa)^2}{2}\right]$$
$$+ A_3(\eta - \varkappa)^{-3} \exp\left[-\frac{(\eta - \varkappa)^2}{2}\right] \qquad (36)$$

$$\tilde{g} = 1 - \frac{A_1}{2}(\eta - \varkappa)^{-1} \exp\left[-\frac{(\eta - \varkappa)^2}{2}\right] \qquad (37)$$

$$\tilde{\theta} = 1 + A_1 \frac{\left(1 - \frac{t_{N_0}}{t_0}\right)}{\left(\frac{t_w}{t_0} - 1\right)}(\eta - \varkappa)^{-1} \exp\left[-\frac{(\eta - \varkappa)^2}{2}\right]$$
$$- \frac{A_1}{2}\left[\frac{2\left(1 - \frac{t_{N_0}}{t_0}\right) + \left(\frac{t_w}{t_0} - 1\right)}{\left(\frac{t_w}{t_0} - 1\right)}\right](\eta - \varkappa)^{-1} \exp\left[-\frac{Pr}{2}(\eta - \varkappa)^2\right] \qquad (38)$$

An examination of equations (C18) for $Pr < 1$ and equation (36) for $Pr = 1$ shows that the velocity functions in these cases have the same qualitative asymptotic behavior, since the A_1 terms in both cases dominate over the A_3 terms.

4132

CG-6

APPENDIX D

STAGNATION-LINE RECOVERY FACTOR FOR YAWED CYLINDER

The evaluation of the recovery factor for the stagnation line of a yawed cylinder in essentially incompressible flow is accomplished by rewriting equations (27) with the quantity t_{N_0}/t_0 replaced by the equivalent expression $1 - \frac{v_e^2}{2c_p t_0}$, where $\frac{v_e^2}{2c_p t_0} \ll 1$ and with $\left(1 - \frac{t_w}{t_0}\right) \ll 1$. The resulting equations are

$$f''' + ff'' = f'^2 - 1 \tag{D1}$$

$$g'' + fg' = 0 \tag{D2}$$

$$\theta'' + \Pr f\theta' = (1 - \Pr) \frac{\frac{v_e^2}{2c_p t_0}}{\left(1 - \frac{t_w}{t_0}\right)} (g^2)'' \tag{D3}$$

4132

The first two of these equations are recognized as the momentum equations for chordwise and spanwise incompressible stagnation-line flow over a yawed cylinder. The energy equation (eq. (D3)) must be further reduced by writing θ in terms of the temperature-difference parameter

$$\zeta = \frac{t - t_e}{\frac{v_e^2}{2c_p}} \tag{D4}$$

The expression for θ in terms of ζ becomes from equations (14) and (D4)

$$\theta = 1 + \frac{(g^2 + \zeta - 1) \frac{v_e^2}{2c_p}}{t_0 - t_w} \tag{D5}$$

Substitution of relations (D5) and (D2) into equation (D3) yields for finite $\frac{v_e^2}{2c_p t_0}$

$$\zeta'' + \Pr f\zeta' + 2\Pr g'^2 = 0 \tag{D6}$$

4132
CG-6 back

Equation (D6) is identical to that of Schuh (ref. 29). With the boundary conditions:

At $\eta = 0$

$$\zeta' = 0$$

At $\eta \to \infty$

$$\zeta = 0$$

the value of ζ at the wall becomes the recovery factor and from equations (D1), (D2), and (D6) can be written

$$\zeta_w = -2\mathrm{Pr}g_w'^2 \int_\eta^\infty e^{-\int_0^\eta \mathrm{Pr}f d\eta} \int_0^\eta e^{-(\mathrm{Pr}-2)\int_0^\eta f d\eta} d\eta d\eta \tag{D7}$$

where

$$g_w' = \frac{1}{\int_0^\infty e^{-\int_0^\eta f d\eta} d\eta} \tag{D8}$$

For the present paper values of ζ_w were obtained for $\mathrm{Pr} = 0.7$, 0.8, 0.9, and 1 and are shown in table IV. The value indicated for $\mathrm{Pr} = 0.7$ agrees with that of Schuh.

A recovery factor for the stagnation line defined in terms of free-stream static temperature is related to ζ_w as follows:

$$\mathscr{R} \equiv \frac{t_{aw} - t_\infty}{t_0 - t_\infty} = 1 - (1 - \zeta_w)\sin^2 \Lambda \tag{D9}$$

REFERENCES

1. Reshotko, Eli: Heat Transfer to a Yawed Infinite Cylinder in Compressible Flow. Proc. 1956 Heat Transfer and Fluid Mech. Inst., Stanford Univ. Press, June 1956, pp. 205-220.

2. Prandtl, L.: On Boundary Layers in Three-Dimensional Flow. Rep. and Trans. No. 64, British M.A.P., May 1, 1946.

3. Struminsky, V. V.: Sideslip in a Viscous Compressible Gas. NACA TM 1276, 1951.

4. Jones, Robert T.: Effects of Sweepback on Boundary Layer and Separation. NACA Rep. 884, 1947. (Supersedes NACA TN 1402.)

5. Sears, W. R.: The Boundary Layer of Yawed Cylinders. Jour. Aero. Sci., vol. 15, no. 1, Jan. 1948, pp. 49-52.

6. Moore, Franklin K.: Three-Dimensional Compressible Laminar Boundary-Layer Flow. NACA TN 2279, 1951.

7. Wild, J. M.: The Boundary Layer of Yawed Infinite Wings. Jour. Aero. Sci., vol. 16, no. 1, Jan. 1949, pp. 41-45.

8. Cooke, J. C.: The Boundary Layer of a Class of Infinite Yawed Cylinders. Proc. Cambridge Phil. Soc., pt. 4, vol. 46, Oct. 1950, pp. 645-648.

9. Hartree, D. R.: On an Equation Occurring in Falkner and Skan's Approximate Treatment of the Equations of the Boundary Layer. Proc. Cambridge Phil. Soc., pt. 2, vol. 33, Apr. 1937, pp. 223-239.

10. Goland, Leonard: A Theoretical Investigation of Heat Transfer in the Laminar Flow Regions of Airfoils. Jour. Aero. Sci., vol. 17, no. 7, July 1950, pp. 436-440.

11. Crabtree, L. F.: The Compressible Laminar Boundary Layer on a Yawed Infinite Wing. Aero. Quarterly, vol. 5, May-Nov. 1954, pp. 85-100.

12. Tinkler, J.: Effect of Yaw on the Compressible Laminar Boundary Layer. FM 2269, British ARC, June 29, 1955.

13. Moore, Franklin K.: Three-Dimensional Boundary Layer Theory. Vol. IV of Advances in Appl. Mech., Academic Press, Inc., 1956, pp. 159-228.

14. Stewartson, K.: Correlated Incompressible and Compressible Boundary Layers. Proc. Roy. Soc. (London), ser. A, vol. 200, no. A1060, Dec. 22, 1949, pp. 84-100.

15. Cohen, Clarence B., and Reshotko, Eli: Similar Solutions for the Compressible Laminar Boundary Layer with Heat Transfer and Pressure Gradient. NACA Rep. 1293, 1956. (Supersedes NACA TN 3325.)

16. Brown, W. Byron, and Donoughe, Patrick L.: Tables of Exact Laminar-Boundary-Layer Solutions When the Wall is Porous and Fluid Properties are Variable. NACA TN 2479, 1951.

4132

17. Moore, Franklin K.: Laminar Boundary Layer on Cone in Supersonic Flow at Large Angle of Attack. NACA Rep. 1132, 1953. (Supersedes NACA TN 2844.)

18. Van Driest, E. R.: Investigation of Laminar Boundary Layer in Compressible Fluids Using the Crocco Method. NACA TN 2597, 1952.

4132 19. Goldstein, Sydney, ed.: Modern Development in Fluid Dynamics. Vol. 2. Clarendon Press (Oxford), 1938, pp. 631-632.

20. Penland, Jim A.: Aerodynamic Characteristics of a Circular Cylinder at Mach Number 6.86 and Angles of Attack up to 90°. NACA TN 3861, 1956. (Supersedes NACA RM L54A14.)

21. Lees, Lester: Hypersonic Flow. Preprint No. 554, Inst. Aero. Sci., June 1955.

22. Reshotko, Eli, and Cohen, Clarence B.: Heat Transfer at the Forward Stagnation Point of Blunt Bodies. NACA TN 3513, 1955.

23. Gowen, Forrest E., and Perkins, Edward W.: Drag of Circular Cylinders for a Wide Range of Reynolds Numbers and Mach Numbers. NACA TN 2960, 1953. (Supersedes NACA RM A52C20.)

24. Knowler, A. E., and Pruden, F. W.: On the Drag of Circular Cylinders at High Speeds. R. & M. No. 1933, British ARC, Feb. 18, 1944.

25. Bursnall, William J., and Loftin, Laurence K., Jr.: Experimental Investigation of the Pressure Distribution About a Yawed Circular Cylinder in the Critical Reynolds Number Range. NACA TN 2463, 1951.

26. Schubauer, G. B., and Klebanoff, P. S.: Theory and Application of Hot-Wire Instruments in the Investigation of Turbulent Boundary Layers. NACA WR W-86, 1946. (Supersedes NACA ACR 5K27.)

27. Ostrach, Simon: An Analysis of Laminar Free-Convection Flow and Heat Transfer About a Flat Plate Parallel to the Direction of the Generating Body Force. NACA Rep. 1111, 1953. (Supersedes NACA TN 2635.)

28. Gill, S.: A Process for the Step-by-Step Integration of Differential Equations in an Automatic Digital Computing Machine. Proc. Cambridge Phil. Soc., pt. 1, vol. 47, Jan. 1951, pp. 96-108.

29. Schuh, H.: Aerodynamic Heating on Yawed Infinite Wings and on Bodies of Arbitrary Shape. KTH AERO TN 35, Div. Aero., Royal Inst. Tech., Stockholm, July 5, 1955.

TABLE I. - STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER

WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 0;\ \frac{t_0}{t_{N_0}} = 1.0$					
η	f	f'	f''	θ	θ'
0	0.0000	0.0000	0.6489	0.0000	0.5067
.2	.0129	.1291	.6393	.1013	.5062
.4	.0514	.2546	.6128	.2023	.5032
.6	.1143	.3734	.5728	.3023	.4951
.8	.2001	.4830	.5226	.3999	.4800
1.0	.3068	.5819	.4654	.4937	.4564
1.2	.4321	.6690	.4045	.5819	.4240
1.4	.5736	.7437	.3427	.6627	.3835
1.6	.7288	.8062	.2828	.7349	.3368
1.8	.8953	.8571	.2270	.7972	.2863
2.0	1.0709	.8973	.1769	.8494	.2353
2.2	1.2536	.9283	.1338	.8915	.1865
2.4	1.4417	.9513	.0980	.9243	.1424
2.6	1.6337	.9680	.0694	.9489	.1047
2.8	1.8285	.9795	.0476	.9666	.0741
3.0	2.0253	.9874	.0315	.9790	.0504
3.2	2.2233	.9924	.0201	.9872	.0330
3.4	2.4221	.9956	.0124	.9925	.0207
3.6	2.6214	.9976	.0073	.9958	.0125
3.8	2.8211	.9987	.0042	.9977	.0073
4.0	3.0209	.9993	.0023	.9988	.0040
4.2	3.2208	.9997	.0012	.9994	.0022
4.4	3.4208	.9999	.0006	.9997	.0011
4.6	3.6207	.9999	.0003	.9999	.0006
4.8	3.8207	1.0000	.0001	1.0000	.0003

$\frac{t_w}{t_0} = 0;\ \frac{t_0}{t_{N_0}} = 1.2$					
η	f	f'	f''	θ	θ'
0	0.0000	0.0000	0.6823	0.0000	0.5130
.2	.0136	.1357	.6708	.1026	.5125
.4	.0540	.2670	.6392	.2048	.5093
.6	.1199	.3903	.5920	.3059	.5007
.8	.2094	.5031	.5338	.4046	.4847
1.0	.3203	.6034	.4688	.4992	.4598
1.2	.4499	.6904	.4010	.5879	.4259
1.4	.5955	.7638	.3339	.6690	.3837
1.6	.7545	.8242	.2704	.7410	.3353
1.8	.9244	.8724	.2128	.8029	.2835
2.0	1.1028	.9098	.1627	.8544	.2315
2.2	1.2877	.9380	.1206	.8957	.1823
2.4	1.4775	.9586	.0866	.9277	.1383
2.6	1.6707	.9731	.0603	.9515	.1009
2.8	1.8664	.9831	.0406	.9685	.0709
3.0	2.0638	.9897	.0264	.9803	.0479
3.2	2.2622	.9940	.0166	.9881	.0311
3.4	2.4612	.9966	.0101	.9931	.0194
3.6	2.6607	.9981	.0059	.9961	.0116
3.8	2.8605	.9990	.0033	.9979	.0067
4.0	3.0603	.9995	.0018	.9989	.0037
4.2	3.2603	.9998	.0010	.9994	.0020
4.4	3.4602	1.0000	.0005	.9997	.0010
4.6	3.6602	1.0000	.0003	.9999	.0005
4.8	3.8603	1.0001	.0002	.9999	.0002
5.0	4.0603	1.0001	.0001	1.0000	.0001
5.2	4.2603	1.0001	.0001	1.0000	.0000
5.4	4.4603	1.0001	.0001	1.0000	.0000
5.6	4.6603	1.0001	.0001	1.0000	.0000
5.8	4.8604	1.0002	.0001	1.0000	.0000
6.0	5.0604	1.0002	.0001	1.0000	.0000

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_O} = 0;\ \frac{t_O}{t_{N_O}} = 1.6$

η	f	f'	f"	θ	θ'
0	0.0000	0.0000	0.7475	0.0000	0.5249
.2	.0149	.1484	.7319	.1049	.5243
.4	.0590	.2910	.6898	.2095	.5207
.6	.1306	.4230	.6282	.3128	.5112
.8	.2273	.5414	.5540	.4134	.4934
1.0	.3461	.6442	.4735	.5095	.4661
1.2	.4839	.7308	.3924	.5992	.4291
1.4	.6374	.8015	.3153	.6806	.3836
1.6	.8035	.8574	.2455	.7523	.3322
1.8	.9795	.9003	.1853	.8133	.2780
2.0	1.1629	.9322	.1355	.8635	.2244
2.2	1.3518	.9552	.0960	.9033	.1745
2.4	1.5445	.9712	.0659	.9337	.1307
2.6	1.7399	.9820	.0438	.9561	.0941
2.8	1.9371	.9891	.0281	.9719	.0651
3.0	2.1354	.9936	.0175	.9826	.0434
3.2	2.3344	.9964	.0106	.9896	.0277
3.4	2.5338	.9980	.0061	.9940	.0171
3.6	2.7335	.9989	.0035	.9967	.0101
3.8	2.9334	.9995	.0019	.9982	.0057
4.0	3.1333	.9997	.0010	.9991	.0031
4.2	3.3333	.9999	.0005	.9995	.0016
4.4	3.5333	.9999	.0002	.9998	.0008
4.6	3.7333	1.0000	.0001	.9999	.0004
4.8	3.9332	1.0000	.0001	1.0000	.0002
5.0	4.1333	1.0000	.0000	1.0000	.0001
5.2	4.3333	1.0000	.0000	1.0000	.0000
5.4	4.5333	1.0000	.0000	1.0000	.0000
5.6	4.7333	1.0000	.0000	1.0000	.0000
5.8	4.9333	1.0000	.0000	1.0000	.0000
6.0	5.1333	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_O} = 0;\ \frac{t_O}{t_{N_O}} = 2.0$

η	f	f'	f"	θ	θ'
0	0.0000	0.0000	0.8105	0.0000	0.5358
.2	.0161	.1608	.7907	.1071	.5353
.4	.0638	.3141	.7379	.2139	.5313
.6	.1409	.4544	.6617	.3192	.5207
.8	.2444	.5778	.5716	.4216	.5013
1.0	.3708	.6826	.4759	.5190	.4715
1.2	.5162	.7683	.3821	.6095	.4316
1.4	.6769	.8359	.2957	.6911	.3832
1.6	.8495	.8874	.2206	.7624	.3290
1.8	1.0309	.9251	.1586	.8226	.2726
2.0	1.2188	.9517	.1099	.8715	.2177
2.2	1.4111	.9699	.0734	.9100	.1674
2.4	1.6063	.9818	.0473	.9389	.1238
2.6	1.8035	.9893	.0294	.9600	.0880
2.8	2.0018	.9939	.0176	.9747	.0602
3.0	2.2009	.9966	.0102	.9845	.0395
3.2	2.4004	.9981	.0057	.9909	.0249
3.4	2.6002	.9990	.0030	.9948	.0151
3.6	2.8000	.9994	.0015	.9972	.0088
3.8	2.9999	.9997	.0007	.9985	.0049
4.0	3.1999	.9998	.0003	.9993	.0027
4.2	3.3998	.9998	.0001	.9997	.0014
4.4	3.5998	.9998	.0000	.9998	.0007
4.6	3.7998	.9998	.0000	.9999	.0003

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 0;\ \frac{t_0}{t_{N_0}} = 2.2$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	0.8413	0.0000	0.5410
.2	.0168	.1668	.8194	.1082	.5404
.4	.0662	.3253	.7611	.2159	.5362
.6	.1459	.4695	.6776	.3222	.5252
.8	.2528	.5954	.5795	.4254	.5049
1.0	.3828	.7010	.4763	.5235	.4740
1.2	.5318	.7862	.3764	.6143	.4327
1.4	.6959	.8522	.2857	.6960	.3828
1.6	.8716	.9013	.2083	.7671	.3273
1.8	1.0555	.9365	.1457	.8268	.2700
2.0	1.2454	.9606	.0978	.8752	.2145
2.2	1.4392	.9765	.0629	.9129	.1640
2.4	1.6356	.9865	.0388	.9412	.1206
2.6	1.8336	.9925	.0230	.9617	.0853
2.8	2.0325	.9960	.0130	.9759	.0579
3.0	2.2319	.9980	.0070	.9853	.0378
3.2	2.4316	.9990	.0036	.9914	.0237
3.4	2.6315	.9996	.0018	.9951	.0143
3.6	2.8314	.9999	.0009	.9973	.0083
3.8	3.0314	.9999	.0004	.9986	.0046
4.0	3.2314	1.0000	.0002	.9993	.0025
4.2	3.4314	1.0000	.0001	.9996	.0013
4.4	3.6314	1.0000	.0000	.9998	.0006
4.6	3.8314	1.0000	.0000	.9999	.0003
4.8	4.0314	1.0000	.0000	1.0000	.0001
5.0	4.2314	1.0000	.0000	1.0000	.0001
5.2	4.4314	1.0000	.0000	1.0000	.0000
5.4	4.6314	1.0000	.0000	1.0000	.0000
5.6	4.8314	1.0000	.0000	1.0000	.0000
5.8	5.0314	1.0000	.0000	1.0000	.0000
6.0	5.2314	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 0;\ \frac{t_0}{t_{N_0}} = 3.0$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	0.9607	0.0000	0.5603
.2	.0191	.1900	.9300	.1120	.5595
.4	.0753	.3687	.8494	.2235	.5546
.6	.1653	.5276	.7361	.3333	.5417
.8	.2847	.6620	.6061	.4395	.5181
1.0	.4283	.7699	.4738	.5398	.4826
1.2	.5909	.8521	.3507	.6318	.4360
1.4	.7676	.9113	.2446	.7136	.3807
1.6	.9542	.9514	.1596	.7838	.3205
1.8	1.1472	.9766	.0963	.8418	.2598
2.0	1.3441	.9912	.0527	.8879	.2025
2.2	1.5432	.9987	.0249	.9232	.1517
2.4	1.7433	1.0019	.0089	.9492	.1092
2.6	1.9438	1.0028	.0008	.9675	.0756
2.8	2.1444	1.0026	-.0025	.9799	.0502
3.0	2.3449	1.0020	-.0032	.9880	.0321
3.2	2.5452	1.0014	-.0028	.9931	.0197
3.4	2.7454	1.0009	-.0021	.9962	.0116
3.6	2.9456	1.0005	-.0014	.9980	.0066
3.8	3.1456	1.0003	-.0009	.9989	.0036
4.0	3.3457	1.0002	-.0005	.9995	.0019
4.2	3.5457	1.0001	-.0003	.9997	.0009
4.4	3.7457	1.0000	-.0001	.9999	.0004
4.6	3.9457	1.0000	-.0001	.9999	.0002
4.8	4.1457	1.0000	.0000	1.0000	.0001
5.0	4.3457	1.0000	.0000	1.0000	.0000
5.2	4.5457	1.0000	.0000	1.0000	.0000
5.4	4.7457	1.0000	.0000	1.0000	.0000
5.6	4.9457	1.0000	.0000	1.0000	.0000
5.8	5.1457	1.0000	.0000	1.0000	.0000
6.0	5.3457	1.0000	.0000	1.0000	.0000

4132

4132

CG-7

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 0;\ \frac{t_0}{t_{N_0}} = 4.0$						$\frac{t_w}{t_0} = 0;\ \frac{t_0}{t_{N_0}} = 6.0$					
η	f	f'	f''	θ	θ'	η	f	f'	f''	θ	θ'
0	0.0000	0.0000	1.1025	0.0000	0.5815	0	0.0000	0.0000	1.3679	0.0000	0.6174
.2	.0219	.2176	1.0603	.1163	.5806	.2	.0271	.2690	1.3014	.1234	.6163
.4	.0860	.4196	.9509	.2319	.5748	.4	.1060	.5137	1.1320	.2461	.6086
.6	.1880	.5952	.7997	.3455	.5596	.6	.2299	.7179	.9038	.3661	.5889
.8	.3219	.7383	.6304	.4549	.5320	.8	.3899	.8740	.6570	.4806	.5538
1.0	.4811	.8475	.4632	.5574	.4911	1.0	.5763	.9817	.4249	.5865	.5030
1.2	.6588	.9248	.3138	.6506	.4383	1.2	.7797	1.0465	.2307	.6810	.4393
1.4	.8492	.9748	.1918	.7322	.3770	1.4	.9926	1.0773	.0861	.7618	.3680
1.6	1.0474	1.0036	.1009	.8011	.3119	1.6	1.2091	1.0843	-.0082	.8281	.2953
1.8	1.2496	1.0172	.0397	.8571	.2479	1.8	1.4254	1.0770	-.0590	.8802	.2269
2.0	1.4536	1.0211	.0032	.9007	.1892	2.0	1.6394	1.0629	-.0776	.9194	.1670
2.2	1.6577	1.0197	-.0149	.9333	.1386	2.2	1.8504	1.0473	-.0759	.9477	.1178
2.4	1.8613	1.0159	-.0210	.9567	.0975	2.4	2.0584	1.0332	-.0638	.9673	.0797
2.6	2.0641	1.0117	-.0203	.9729	.0659	2.6	2.2639	1.0220	-.0484	.9802	.0517
2.8	2.2660	1.0080	-.0165	.9836	.0427	2.8	2.4674	1.0138	-.0340	.9885	.0322
3.0	2.4673	1.0051	-.0121	.9905	.0266	3.0	2.6696	1.0082	-.0223	.9936	.0193
3.2	2.6682	1.0031	-.0082	.9946	.0159	3.2	2.8709	1.0046	-.0137	.9965	.0111
3.4	2.8686	1.0018	-.0052	.9971	.0092	3.4	3.0715	1.0025	-.0080	.9982	.0061
3.6	3.0689	1.0010	-.0031	.9985	.0051	3.6	3.2719	1.0013	-.0044	.9991	.0032
3.8	3.2691	1.0005	-.0017	.9992	.0027	3.8	3.4721	1.0006	-.0021	.9996	.0017
4.0	3.4691	1.0003	-.0009	.9996	.0014	4.0	3.6722	1.0002	-.0005	.9998	.0008
4.2	3.6692	1.0001	-.0005	.9998	.0007	4.2	3.8722	1.0001	.0013	.9999	.0004
4.4	3.8692	1.0001	-.0002	.9999	.0003						
4.6	4.0692	1.0000	-.0001	1.0000	.0001						
4.8	4.2692	1.0000	-.0001	1.0000	.0001						
5.0	4.4692	1.0000	.0000	1.0000	.0000						
5.2	4.6692	1.0000	.0000	1.0000	.0000						
5.4	4.8692	1.0000	.0000	1.0000	.0000						
5.6	5.0692	1.0000	.0000	1.0000	.0000						
5.8	5.2692	1.0000	.0000	1.0000	.0000						
6.0	5.4692	1.0000	.0000	1.0000	.0000						

4132

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 0;\ \frac{t_0}{t_{N_0}} = 6.5$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	1.4313	0.0000	0.6254
.2	.0284	.2813	1.3584	.1250	.6242
.4	.1107	.5359	1.1736	.2492	.6161
.6	.2398	.7465	.9259	.3706	.5953
.8	.4059	.9051	.6601	.4862	.5584
1.0	.5984	1.0118	.4128	.5928	.5052
1.2	.8076	1.0731	.2089	.6874	.4390
1.4	1.0253	1.0990	.0602	.7680	.3655
1.6	1.2456	1.1008	-.0334	.8336	.2913
1.8	1.4648	1.0887	-.0807	.8848	.2221
2.0	1.6808	1.0707	-.0946	.9231	.1622
2.2	1.8930	1.0522	-.0880	.9504	.1134
2.4	2.1018	1.0361	-.0718	.9692	.0761
2.6	2.3077	1.0236	-.0533	.9815	.0490
2.8	2.5115	1.0146	-.0368	.9893	.0302
3.0	2.7138	1.0086	-.0238	.9941	.0179
3.2	2.9151	1.0049	-.0145	.9968	.0102
3.4	3.1158	1.0026	-.0084	.9983	.0056
3.6	3.3162	1.0014	-.0046	.9992	.0029
3.8	3.5164	1.0007	-.0024	.9996	.0015
4.0	3.7165	1.0003	-.0012	.9998	.0007
4.2	3.9166	1.0002	-.0006	.9999	.0003
4.4	4.1166	1.0001	-.0003	1.0000	.0001
4.6	4.3166	1.0000	-.0001	1.0000	.0001
4.8	4.5166	1.0000	.0000	1.0000	.0000
5.0	4.7166	1.0000	.0000	1.0000	.0000
5.2	4.9166	1.0000	.0000	1.0000	.0000
5.4	5.1166	1.0000	.0000	1.0000	.0000
5.6	5.3166	1.0000	.0000	1.0000	.0000
5.8	5.5166	1.0000	.0000	1.0000	.0000
6.0	5.7166	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 0.25;\ \frac{t_0}{t_{N_0}} = 1.2$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	0.8673	0.0000	0.5344
.2	.0169	.1669	.7988	.1068	.5338
.4	.0657	.3187	.7175	.2133	.5297
.6	.1432	.4534	.6292	.3183	.5189
.8	.2459	.5702	.5387	.4203	.4993
1.0	.3701	.6690	.4503	.5173	.4697
1.2	.5124	.7506	.3672	.6075	.4301
1.4	.6693	.8164	.2919	.6888	.3822
1.6	.8380	.8680	.2261	.7600	.3288
1.8	1.0157	.9075	.1703	.8202	.2732
2.0	1.2003	.9368	.1247	.8694	.2189
2.2	1.3899	.9580	.0887	.9081	.1690
2.4	1.5831	.9729	.0612	.9374	.1255
2.6	1.7788	.9830	.0410	.9588	.0897
2.8	1.9761	.9897	.0265	.9738	.0616
3.0	2.1745	.9939	.0166	.9839	.0407
3.2	2.3736	.9965	.0101	.9905	.0258
3.4	2.5730	.9981	.0059	.9945	.0158
3.6	2.7728	.9990	.0034	.9970	.0092
3.8	2.9726	.9995	.0019	.9984	.0052
4.0	3.1725	.9998	.0010	.9992	.0028
4.2	3.3725	.9999	.0005	.9996	.0015
4.4	3.5725	1.0000	.0003	.9998	.0007
4.6	3.7725	1.0001	.0002	.9999	.0004
4.8	3.9725	1.0001	.0001	1.0000	.0002
5.0	4.1726	1.0001	.0001	1.0000	.0001
5.2	4.3726	1.0001	.0001	1.0000	.0000
5.4	4.5726	1.0001	.0001	1.0000	.0000
5.6	4.7726	1.0001	.0001	1.0000	.0000
5.8	4.9727	1.0002	.0001	1.0000	.0000
6.0	5.1727	1.0002	.0001	1.0000	.0000

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 0.25;\ \frac{t_0}{t_{N_0}} = 1.6$					
η	f	f'	f''	θ	θ'
0	0.0000	0.0000	0.9850	0.0000	0.5507
.2	.0191	.1882	.8935	.1101	.5500
.4	.0739	.3563	.7856	.2197	.5452
.6	.1602	.5019	.6699	.3277	.5329
.8	.2732	.6243	.5542	.4322	.5105
1.0	.4084	.7240	.4445	.5312	.4770
1.2	.5614	.8028	.3453	.6223	.4330
1.4	.7283	.8630	.2597	.7038	.3807
1.6	.9056	.9076	.1889	.7743	.3234
1.8	1.0905	.9395	.1328	.8331	.2649
2.0	1.2807	.9616	.0902	.8004	.2090
2.2	1.4746	.9764	.0592	.9171	.1587
2.4	1.6709	.9859	.0375	.9444	.1159
2.6	1.8688	.9919	.0230	.9640	.0813
2.8	2.0675	.9954	.0136	.9774	.0549
3.0	2.2669	.9975	.0078	.9864	.0356
3.2	2.4665	.9987	.0043	.9921	.0222
3.4	2.6663	.9994	.0023	.9955	.0133
3.6	2.8662	.9997	.0012	.9976	.0076
3.8	3.0662	.9999	.0006	.9987	.0042
4.0	3.2662	.9999	.0003	.9994	.0022
4.2	3.4661	1.0000	.0001	.9997	.0011
4.4	3.6661	1.0000	.0001	.9999	.0006
4.6	3.8661	1.0000	.0000	.9999	.0003
4.8	4.0661	1.0000	.0000	1.0000	.0001
5.0	4.2662	1.0000	.0000	1.0000	.0001
5.2	4.4662	1.0000	.0000	1.0000	.0000
5.4	4.6662	1.0000	.0000	1.0000	.0000
5.6	4.8662	1.0000	.0000	1.0000	.0000
5.8	5.0662	1.0000	.0000	1.0000	.0000
6.0	5.2662	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 0.25;\ \frac{t_0}{t_{N_0}} = 2.2$					
η	f	f'	f''	θ	θ'
0	0.0000	0.0000	1.1530	0.0000	0.5724
.2	.0223	.2185	1.0268	.1144	.5716
.4	.0856	.4093	.8787	.2283	.5658
.6	.1839	.5694	.7224	.3402	.5511
.8	.3113	.6985	.5698	.4479	.5247
1.0	.4614	.7982	.4299	.5492	.4858
1.2	.6288	.8717	.3092	.6415	.4358
1.4	.8086	.9233	.2109	.7229	.3775
1.6	.9970	.9576	.1355	.7922	.3152
1.8	1.1908	.9789	.0812	.8490	.2532
2.0	1.3880	.9912	.0446	.8939	.1957
2.2	1.5869	.9977	.0217	.9278	.1453
2.4	1.7868	1.0005	.0086	.9525	.1037
2.6	1.9870	1.0015	.0019	.9699	.0711
2.8	2.1873	1.0015	-.0010	.9815	.0469
3.0	2.3876	1.0012	-.0018	.9891	.0297
3.2	2.5878	1.0009	-.0017	.9938	.0180
3.4	2.7880	1.0006	-.0013	.9966	.0105
3.6	2.9881	1.0003	-.0009	.9982	.0059
3.8	3.1881	1.0002	-.0005	.9991	.0032
4.0	3.3881	1.0001	-.0003	.9995	.0017
4.2	3.5882	1.0001	-.0002	.9998	.0008
4.4	3.7882	1.0000	-.0001	.9999	.0004
4.6	3.9882	1.0000	.0000	1.0000	.0002
4.8	4.1882	1.0000	.0000	1.0000	.0001
5.0	4.3882	1.0000	.0000	1.0000	.0000
5.2	4.5882	1.0000	.0000	1.0000	.0000
5.4	4.7882	1.0000	.0000	1.0000	.0000
5.6	4.9882	1.0000	.0000	1.0000	.0000
5.8	5.1882	1.0000	.0000	1.0000	.0000
6.0	5.3882	1.0000	.0000	1.0000	.0000

4132

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 0.25;\ \frac{t_0}{t_{N_0}} = 3.0$					
η	f	f'	f''	θ	θ'
0	0.0000	0.0000	1.3644	0.0000	0.5976
.2	.0262	.2563	1.1918	.1195	.5965
.4	.1000	.4748	.9898	.2382	.5895
.6	.2134	.6517	.7799	.3545	.5716
.8	.3580	.7874	.5799	.4659	.5401
1.0	.5258	.8852	.4029	.5696	.4946
1.2	.7099	.9905	.2574	.6630	.4372
1.4	.9044	1.0115	.1466	.7440	.3721
1.6	1.1049	1.0200	.0690	.8116	.3044
1.8	1.3082	1.0210	.0200	.8659	.2391
2.0	1.5124	1.0182	-.0070	.9077	.1803
2.2	1.7163	1.0141	-.0187	.9386	.1306
2.4	1.9195	1.0100	-.0211	.9606	.0908
2.6	2.1219	1.0067	-.0187	.9756	.0606
2.8	2.3236	1.0042	-.0145	.9854	.0389
3.0	2.5247	1.0025	-.0103	.9916	.0239
3.2	2.7253	1.0014	-.0068	.9953	.0142
3.4	2.9257	1.0008	-.0042	.9975	.0081
3.6	3.1259	1.0004	-.0024	.9987	.0044
3.8	3.3260	1.0002	-.0013	.9994	.0023
4.0	3.5261	1.0001	-.0007	.9997	.0012
4.2	3.7261	1.0001	-.0004	.9999	.0006
4.4	3.9261	1.0000	-.0002	.9999	.0003
4.6	4.1262	1.0000	.0000	1.0000	.0001
4.8	4.3262	1.0000	.0000	1.0000	.0001
5.0	4.5262	1.0000	.0000	1.0000	.0000
5.2	4.7262	1.0000	.0000	1.0000	.0000
5.4	4.9262	1.0000	.0000	1.0000	.0000
5.6	5.1262	1.0000	.0000	1.0000	.0000
5.8	5.3262	1.0000	.0000	1.0000	.0000
6.0	5.5262	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 0.5;\ \frac{t_0}{t_{N_0}} = 1.2$					
η	f	f'	f''	θ	θ'
0	0.0000	0.0000	1.0409	0.0000	0.5530
.2	.0200	.1958	.9158	.1106	.5522
.4	.0766	.3660	.7859	.2206	.5472
.6	.1647	.5103	.6582	.3289	.5344
.8	.2791	.6298	.5379	.4337	.5114
1.0	.4151	.7262	.4288	.5328	.4773
1.2	.5682	.8022	.3331	.6239	.4327
1.4	.7348	.8605	.2521	.7053	.3799
1.6	.9114	.9040	.1856	.7756	.3223
1.8	1.0956	.9356	.1329	.8341	.2637
2.0	1.2851	.9579	.0925	.8812	.2079
2.2	1.4783	.9733	.0625	.9177	.1577
2.4	1.6740	.9835	.0410	.9448	.1151
2.6	1.8714	.9901	.0260	.9642	.0807
2.8	2.0699	.9942	.0160	.9776	.0544
3.0	2.2690	.9967	.0096	.9865	.0353
3.2	2.4685	.9982	.0055	.9921	.0220
3.4	2.6683	.9990	.0031	.9956	.0131
3.6	2.8681	.9995	.0017	.9976	.0076
3.8	3.0680	.9997	.0009	.9987	.0042
4.0	3.2680	.9999	.0004	.9994	.0022
4.2	3.4680	.9999	.0002	.9997	.0011
4.4	3.6680	.9999	.0001	.9999	.0006
4.6	3.8680	1.0000	.0000	.9999	.0003
4.8	4.0680	1.0000	.0000	1.0000	.0001
5.0	4.2680	1.0000	.0000	1.0000	.0000
5.2	4.4680	1.0000	.0000	1.0000	.0000
5.4	4.6680	1.0000	.0000	1.0000	.0000
5.6	4.8679	1.0000	.0000	1.0000	.0000
5.8	5.0679	1.0000	.0000	1.0000	.0000
6.0	5.2679	1.0000	.0000	1.0000	.0000

4132

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 0.5;\ \frac{t_0}{t_{N_0}} = 1.6$					
η	f	f'	f''	θ	θ'
0	0.0000	0.0000	1.2062	0.0000	0.5728
.2	.0230	.2247	1.0394	.1145	.5719
.4	.0876	.4154	.8973	.2284	.5659
.6	.1869	.5720	.7005	.3403	.5509
.8	.3143	.6965	.5469	.4480	.5242
1.0	.4636	.7920	.4120	.5491	.4851
1.2	.6295	.8627	.2988	.6413	.4350
1.4	.8073	.9130	.2080	.7226	.3768
1.6	.9936	.9473	.1385	.7918	.3148
1.8	1.1855	.9697	.0880	.8485	.2532
2.0	1.3809	.9836	.0531	.8933	.1959
2.2	1.5786	.9917	.0302	.9273	.1460
2.4	1.7774	.9962	.0160	.9522	.1042
2.6	1.9769	.9985	.0078	.9696	.0716
2.8	2.1767	.9996	.0034	.9813	.0472
3.0	2.3767	1.0000	.0012	.9889	.0300
3.2	2.5767	1.0001	.0003	.9937	.0183
3.4	2.7767	1.0002	-.0001	.9965	.0107
3.6	2.9768	1.0001	-.0001	.9982	.0060
3.8	3.1768	1.0001	-.0001	.9991	.0033
4.0	3.3768	1.0001	-.0001	.9995	.0017
4.2	3.5768	1.0001	.0000	.9998	.0008
4.4	3.7768	1.0001	.0000	.9999	.0004
4.6	3.9769	1.0001	.0000	1.0000	.0002
4.8	4.1769	1.0001	.0000	1.0000	.0001
5.0	4.3769	1.0001	.0000	1.0000	.0000
5.2	4.5769	1.0001	.0000	1.0000	.0000
5.4	4.7769	1.0001	.0000	1.0000	.0000
5.6	4.9769	1.0001	.0000	1.0000	.0000
5.8	5.1770	1.0001	.0000	1.0000	.0000
6.0	5.3770	1.0001	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 0.5;\ \frac{t_0}{t_{N_0}} = 2.2$					
η	f	f'	f''	θ	θ'
0	0.0000	0.0000	1.4406	0.0000	0.5986
.2	.0273	.2654	1.2111	.1197	.5975
.4	.1031	.4841	.9760	.2386	.5902
.6	.2179	.6565	.7518	.3550	.5719
.8	.3628	.7863	.5506	.4664	.5398
1.0	.5299	.8788	.3803	.5700	.4939
1.2	.7123	.9407	.2446	.6632	.4363
1.4	.9047	.9790	.1433	.7440	.3712
1.6	1.1028	1.0001	.0730	.8115	.3037
1.8	1.3040	1.0098	.0283	.8657	.2387
2.0	1.5063	1.0127	.0029	.9074	.1803
2.2	1.7088	1.0119	-.0091	.9384	.1307
2.4	1.9110	1.0096	-.0129	.9604	.0910
2.6	2.1126	1.0070	-.0124	.9754	.0609
2.8	2.3138	1.0047	-.0100	.9853	.0391
3.0	2.5146	1.0030	-.0072	.9915	.0241
3.2	2.7150	1.0018	-.0048	.9953	.0143
3.4	2.9153	1.0010	-.0030	.9974	.0082
3.6	3.1155	1.0006	-.0018	.9987	.0045
3.8	3.3155	1.0003	-.0010	.9993	.0023
4.0	3.5156	1.0001	-.0005	.9997	.0012
4.2	3.7156	1.0001	-.0003	.9998	.0006
4.4	3.9156	1.0000	-.0001	.9999	.0003
4.6	4.1156	1.0000	.0000	1.0000	.0001
4.8	4.3156	1.0000	.0000	1.0000	.0000
5.0	4.5156	1.0000	.0000	1.0000	.0000
5.2	4.7156	1.0000	.0000	1.0000	.0000
5.4	4.9156	1.0000	.0000	1.0000	.0000
5.6	5.1157	1.0000	.0000	1.0000	.0000
5.8	5.3157	1.0000	.0000	1.0000	.0000
6.0	5.5157	1.0000	.0000	1.0000	.0000

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 0.5;\ \frac{t_0}{t_{N_0}} = 3.0$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	1.7341	0.0000	0.6280
.2	.0326	.3158	1.4210	.1255	.6266
.4	.1221	.5680	1.1024	.2501	.6175
.6	.2557	.7581	.8035	.3716	.5950
.8	.4216	.8919	.5425	.4870	.5563
1.0	.6094	.9784	.3303	.5931	.5020
1.2	.8105	1.0276	.1706	.6870	.4356
1.4	1.0186	1.0499	.0610	.7669	.3628
1.6	1.2293	1.0548	-.0058	.8321	.2898
1.8	1.4399	1.0498	-.0398	.8832	.2219
2.0	1.6490	1.0403	-.0513	.9215	.1629
2.2	1.8560	1.0301	-.0493	.9490	.1148
2.4	2.0611	1.0210	-.0409	.9681	.0776
2.6	2.2646	1.0138	-.0308	.9807	.0503
2.8	2.4668	1.0086	-.0214	.9887	.0314
3.0	2.6681	1.0086	-.0140	.9937	.0188
3.2	2.8689	1.0051	-.0086	.9966	.0108
3.4	3.0694	1.0029	-.0050	.9982	.0060
3.6	3.2696	1.0016	-.0028	.9991	.0032
3.8	3.4697	1.0008	-.0015	.9996	.0016
4.0	3.6698	1.0004	-.0008	.9998	.0008
4.2	3.8698	1.0002	-.0004	.9999	.0004
4.4	4.0698	1.0001	-.0002	1.0000	.0001
4.6	4.2698	1.0000	-.0001	1.0000	.0001
4.8	4.4698	1.0000	.0000	1.0000	.0000
5.0	4.6698	1.0000	.0000	1.0000	.0000
5.2	4.8698	1.0000	.0000	1.0000	.0000
5.4	5.0698	1.0000	.0000	1.0000	.0000
5.6	5.2698	1.0000	.0000	1.0000	.0000
5.8	5.4698	1.0000	.0000	1.0000	.0000
6.0	5.6698	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 0.5;\ \frac{t_0}{t_{N_0}} = 4.0$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	2.0785	0.0000	0.6593
.2	.0389	.3744	1.6608	.1318	.6576
.4	.1441	.6640	1.2386	.2624	.6463
.6	.2990	.8720	.8491	.3892	.6187
.8	.4881	1.0076	.5184	.5086	.5721
1.0	.6982	1.0842	.2604	.9168	.5083
1.2	.9189	1.1168	.0783	.7111	.4324
1.4	1.1430	1.1200	-.0350	.7895	.3519
1.6	1.3658	1.1065	-.0926	.8520	.2738
1.8	1.5851	1.0856	-.1105	.8995	.2038
2.0	1.8000	1.0638	-.1043	.9342	.1453
2.2	2.0108	1.0446	-.0862	.9585	.0992
2.4	2.2182	1.0295	-.0649	.9747	.0650
2.6	2.4229	1.0185	-.0454	.9852	.0409
2.8	2.6258	1.0111	-.0298	.9916	.0247
3.0	2.8275	1.0063	-.0185	.9954	.0143
3.2	3.0284	1.0035	-.0109	.9976	.0080
3.4	3.2290	1.0018	-.0061	.9988	.0043
3.6	3.4293	1.0009	-.0032	.9994	.0022
3.8	3.6294	1.0004	-.0017	.9997	.0010
4.0	3.8294	1.0001	-.0008	.9999	.0005
4.2	4.0295	1.0001	-.0004	1.0000	.0002
4.4	4.2295	1.0000	-.0002	1.0000	.0001
4.6	4.4295	1.0000	-.0001	1.0000	.0000
4.8	4.6295	1.0000	.0000	1.0000	.0000
5.0	4.8295	1.0000	.0000	1.0000	.0000
5.2	5.0295	1.0000	.0000	1.0000	.0000
5.4	5.2295	1.0000	.0000	1.0000	.0000
5.6	5.4295	1.0000	.0000	1.0000	.0000
5.8	5.6295	1.0000	.0000	1.0000	.0000
6.0	5.8295	1.0000	.0000	1.0000	.0000

4132

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 0.5;\ \frac{t_0}{t_{N_0}} = 6.5$					
η	f	f'	f''	θ	θ'
0	0.0000	0.0000	2.8663	0.0000	0.7213
.2	.0529	.5060	2.1868	.1441	.7187
.4	.1933	.8749	1.5090	.2865	.7021
.6	.3943	1.1145	.9042	.4234	.6626
.8	.6318	1.2445	.4183	.5498	.5982
1.0	.8866	1.2910	.0709	.6613	.5140
1.2	1.1446	1.2817	-.1423	.7548	.4195
1.4	1.3973	1.2414	-.2440	.8292	.3253
1.6	1.6404	1.1893	-.2657	.8855	.2401
1.8	1.8731	1.1382	-.2396	.9261	.1689
2.0	2.0963	1.0948	-.1921	.9541	.1136
2.2	2.3117	1.0615	-.1411	.9725	.0731
2.4	2.5215	1.0379	-.0964	.9842	.0451
2.6	2.7274	1.0223	-.0619	.9912	.0267
2.8	2.9308	1.0125	-.0375	.9953	.0152
3.0	3.1327	1.0067	-.0216	.9976	.0083
3.2	3.3337	1.0034	-.0119	.9988	.0043
3.4	3.5342	1.0017	-.0062	.9994	.0022
3.6	3.7344	1.0008	-.0031	.9997	.0011
3.8	3.9345	1.0003	-.0015	.9999	.0005
4.0	4.1346	1.0001	-.0007	.9999	.0002
4.2	4.3346	1.0000	-.0003	1.0000	.0001
4.4	4.5346	1.0000	-.0001	1.0000	.0000
4.6	4.7346	1.0000	-.0001	1.0000	.0000
4.8	4.9346	1.0000	.0000	1.0000	.0000
5.0	5.1346	1.0000	.0000	1.0000	.0000
5.2	5.3346	1.0000	.0000	1.0000	.0000
5.4	5.5346	1.0000	.0000	1.0000	.0000
5.6	5.7346	1.0000	.0000	1.0000	.0000
5.8	5.9346	1.0000	.0000	1.0000	.0000
6.0	6.1346	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 0.75;\ \frac{t_0}{t_{N_0}} = 1.2$					
η	f	f'	f''	θ	θ'
0	0.0000	0.0000	1.2059	0.0000	0.5995
.2	.0229	.2230	1.0244	.1139	.5686
.4	.0868	.4100	.8469	.2271	.5628
.6	.1846	.5626	.6814	.3384	.5480
.8	.3098	.6837	.5332	.4455	.5218
1.0	.4563	.7772	.4054	.5463	.4834
1.2	.6191	.8473	.2993	.6382	.4342
1.4	.7940	.8983	.2142	.7194	.3771
1.6	.9775	.9343	.1484	.7887	.3159
1.8	1.1669	.9588	.0995	.8458	.2550
2.0	1.3604	.9750	.0645	.8910	.1980
2.2	1.5566	.9853	.0403	.9255	.1479
2.4	1.7543	.9917	.0243	.9507	.1062
2.6	1.9531	.9954	.0142	.9685	.0733
2.8	2.1524	.9976	.0079	.9806	.0487
3.0	2.3520	.9988	.0043	.9885	.0310
3.2	2.5518	.9994	.0022	.9934	.0190
3.4	2.7518	.9997	.0011	.9963	.0112
3.6	2.9517	.9999	.0005	.9980	.0063
3.8	3.1517	.9999	.0002	.9990	.0034
4.0	3.3517	1.0000	.0001	.9995	.0018
4.2	3.5517	1.0000	.0000	.9998	.0009
4.4	3.7517	1.0000	.0000	.9999	.0004
4.6	3.9517	1.0000	.0000	1.0000	.0002
4.8	4.1517	1.0000	.0000	1.0000	.0001
5.0	4.3517	1.0000	.0000	1.0000	.0000
5.2	4.5517	1.0000	.0000	1.0000	.0000
5.4	4.7517	1.0000	.0000	1.0000	.0000
5.6	4.9517	1.0000	.0000	1.0000	.0000
5.8	5.1516	1.0000	.0000	1.0000	.0000
6.0	5.3516	1.0000	.0000	1.0000	.0000

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 0.75;\ \frac{t_0}{t_{N_0}} = 1.6$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	1.4153	0.0000	0.5921
.2	.0267	.2589	1.1735	.1184	.5910
.4	.1004	.4699	.9388	.2360	.5840
.6	.2117	.6357	.7231	.3512	.5663
.8	.3520	.7610	.5347	.4617	.5355
1.0	.5137	.8516	.3777	.5645	.4913
1.2	.6908	.9142	.2532	.6574	.4356
1.4	.8780	.9550	.1597	.7383	.3724
1.6	1.0717	.9798	.0932	.8062	.3065
1.8	1.2692	.9937	.0490	.8610	.2425
2.0	1.4687	1.0006	.0218	.9036	.1844
2.2	1.6692	1.0032	.0065	.9353	.1348
2.4	1.8699	1.0037	-.0009	.9581	.0946
2.6	2.0706	1.0032	-.0037	.9738	.0638
2.8	2.2711	1.0024	-.0041	.9842	.0413
3.0	2.4715	1.0016	-.0034	.9908	.0257
3.2	2.6718	1.0010	-.0025	.9948	.0154
3.4	2.8720	1.0006	-.0016	.9972	.0088
3.6	3.0720	1.0004	-.0010	.9984	.0049
3.8	3.2721	1.0002	-.0006	.9993	.0026
4.0	3.4721	1.0001	-.0003	.9996	.0013
4.2	3.6721	1.0001	-.0002	.9998	.0007
4.4	3.8722	1.0000	-.0001	.9999	.0003
4.6	4.0722	1.0000	.0000	1.0000	.0001
4.8	4.2722	1.0000	.0000	1.0000	.0001
5.0	4.4722	1.0000	.0000	1.0000	.0000
5.2	4.6722	1.0000	.0000	1.0000	.0000
5.4	4.8722	1.0000	.0000	1.0000	.0000
5.6	5.0722	1.0000	.0000	1.0000	.0000
5.8	5.2722	1.0000	.0000	1.0000	.0000
6.0	5.4722	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 0.75;\ \frac{t_0}{t_{N_0}} = 2.2$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	1.7110	0.0000	0.6212
.2	.0320	.3090	1.3790	.1242	.6199
.4	.1192	.5524	1.0592	.2474	.6111
.6	.2489	.7347	.7706	.3677	.5894
.8	.4096	.8636	.5254	.4821	.5520
1.0	.5914	.9482	.3294	.5875	.4996
1.2	.7866	.9986	.1829	.6812	.4354
1.4	.9892	1.0243	.0816	.7612	.3646
1.6	1.1953	1.0337	.0182	.8270	.2930
1.8	1.4021	1.0335	-.0163	.8787	.2260
2.0	1.6084	1.0285	-.0308	.9179	.1673
2.2	1.8134	1.0220	-.0331	.9463	.1188
2.4	2.0172	1.0157	-.0290	.9661	.0810
2.6	2.2198	1.0105	-.0225	.9794	.0530
2.8	2.4215	1.0067	-.0161	.9879	.0333
3.0	2.6226	1.0040	-.0107	.9931	.0201
3.2	2.8232	1.0023	-.0067	.9963	.0117
3.4	3.0235	1.0013	-.0040	.9980	.0065
3.6	3.2237	1.0007	-.0022	.9990	.0035
3.8	3.4238	1.0003	-.0012	.9995	.0018
4.0	3.6239	1.0002	-.0006	.9998	.0009
4.2	3.8239	1.0001	-.0003	.9999	.0004
4.4	4.0239	1.0000	-.0001	1.0000	.0002
4.6	4.2239	1.0000	-.0001	1.0000	.0001
4.8	4.4239	1.0000	.0000	1.0000	.0000
5.0	4.6239	1.0000	.0000	1.0000	.0000
5.2	4.8239	1.0000	.0000	1.0000	.0000
5.4	5.0239	1.0000	.0000	1.0000	.0000
5.6	5.2239	1.0000	.0000	1.0000	.0000
5.8	5.4239	1.0000	.0000	1.0000	.0000
6.0	5.6239	1.0000	.0000	1.0000	.0000

4152

4132

CG-8

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 0.75$; $\frac{t_0}{t_{N_0}} = 3.0$						$\frac{t_w}{t_0} = 1.0$; $\frac{t_0}{t_{N_0}} = 1.1$					
η	f	f'	f''	θ	θ'	η	f	f'	f''	θ	θ'
0	0.0000	0.0000	2.0802	0.0000	0.6541	0	0.0000	0.0000	1.2989	0.0000	0.5776
.2	.0386	.3708	1.6278	.1307	.6524	.2	.0245	.2379	1.0810	.1155	.5767
.4	.1424	.6525	1.1961	.2603	.6413	.4	.0923	.4332	.8747	.2303	.5703
.6	.2942	.8525	.8139	.3862	.6143	.6	.1952	.5891	.6880	.3430	.5545
.8	.4788	.9825	.4987	.5048	.5688	.8	.3256	.7100	.5256	.4513	.5265
1.0	.6835	1.0569	.2579	.6126	.5066	1.0	.4772	.8011	.3896	.5527	.4861
1.2	.8988	1.0905	.0896	.7066	.4325	1.2	.6444	.8676	.2798	.6450	.4346
1.4	1.1179	1.0969	-.0150	.7852	.3535	1.4	.8229	.9146	.1944	.7261	.3753
1.6	1.3366	1.0878	-.0694	.8481	.2766	1.6	1.0093	.9468	.1305	.7949	.3125
1.8	1.5526	1.0715	-.0884	.8963	.2072	1.8	1.2009	.9680	.0844	.8511	.2506
2.0	1.7651	1.0538	-.0855	.9317	.1487	2.0	1.3960	.9815	.0525	.8954	.1933
2.2	1.9743	1.0380	-.0718	.9566	.1023	2.2	1.5932	.9897	.0314	.9289	.1434
2.4	2.1805	1.0253	-.0547	.9734	.0675	2.4	1.7916	.9945	.0180	.9533	.1022
2.6	2.3846	1.0160	-.0386	.9843	.0428	2.6	1.9909	.9972	.0098	.9704	.0700
2.8	2.5871	1.0097	-.0255	.9910	.0260	2.8	2.1905	.9987	.0051	.9819	.0461
3.0	2.7886	1.0056	-.0159	.9951	.0152	3.0	2.3903	.9994	.0025	.9893	.0292
3.2	2.9895	1.0031	-.0094	.9974	.0085	3.2	2.5902	.9997	.0012	.9939	.0177
3.4	3.1899	1.0016	-.0053	.9987	.0046	3.4	2.7902	.9999	.0005	.9967	.0104
3.6	3.3902	1.0008	-.0029	.9993	.0024	3.6	2.9901	1.0000	.0002	.9982	.0058
3.8	3.5903	1.0004	-.0015	.9997	.0012	3.8	3.1901	1.0000	.0001	.9991	.0031
4.0	3.7904	1.0002	-.0007	.9999	.0006	4.0	3.3901	1.0000	.0000	.9996	.0016
4.2	3.9904	1.0001	-.0003	.9999	.0003	4.2	3.5901	1.0000	.0000	.9998	.0008
4.4	4.1904	1.0001	-.0001	1.0000	.0001	4.4	3.7901	1.0000	.0000	.9999	.0004
4.6	4.3904	1.0001	.0000	1.0000	.0001	4.6	3.9901	1.0000	.0000	1.0000	.0002
4.8	4.5904	1.0001	.0000	1.0000	.0000	4.8	4.1901	1.0000	.0000	1.0000	.0001
5.0	4.7905	1.0001	.0000	1.0000	.0000	5.0	4.3901	1.0000	.0000	1.0000	.0000
5.2	4.9905	1.0001	.0000	1.0000	.0000	5.2	4.5901	1.0000	.0000	1.0000	.0000
5.4	5.1905	1.0001	.0000	1.0000	.0000	5.4	4.7901	1.0000	.0000	1.0000	.0000
5.6	5.3905	1.0001	.0000	1.0000	.0000	5.6	4.9901	1.0000	.0000	1.0000	.0000
5.8	5.5905	1.0001	.0000	1.0000	.0000	5.8	5.1901	1.0000	.0000	1.0000	.0000
6.0	5.7905	1.0001	.0000	1.0000	.0000	6.0	5.3901	1.0000	.0000	1.0000	.0000

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 1.0;\ \frac{t_0}{t_{N_0}} = 1.2$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	1.3640	0.0000	0.5845
.2	.0257	.2489	1.1265	.1168	.5834
.4	.0965	.4515	.9020	.2330	.5768
.6	.2034	.6112	.6999	.3469	.5600
.8	.3385	.7333	.5254	.4561	.5307
1.0	.4946	.8234	.3808	.5583	.4884
1.2	.6661	.8875	.2658	.6508	.4350
1.4	.8483	.9315	.1780	.7317	.3739
1.6	1.0377	.9603	.1140	.8001	.3097
1.8	1.2317	.9784	.0694	.8557	.2468
2.0	1.4286	.9891	.0399	.8992	.1892
2.2	1.6271	.9950	.0214	.9319	.1394
2.4	1.8264	.9981	.0105	.9555	.0987
2.6	2.0262	.9995	.0045	.9720	.0671
2.8	2.2262	1.0001	.0015	.9829	.0439
3.0	2.4262	1.0002	.0002	.9900	.0276
3.2	2.6263	1.0002	-.0003	.9943	.0166
3.4	2.8263	1.0002	-.0003	.9969	.0096
3.6	3.0263	1.0001	-.0003	.9984	.0054
3.8	3.2263	1.0001	-.0002	.9992	.0029
4.0	3.4263	1.0000	-.0001	.9996	.0015
4.2	3.6264	1.0000	-.0001	.9998	.0007
4.4	3.8264	1.0000	.0000	.9999	.0003
4.6	4.0264	1.0000	.0000	1.0000	.0002
4.8	4.2264	1.0000	.0000	1.0000	.0001
5.0	4.4263	1.0000	.0000	1.0000	.0000
5.2	4.6263	1.0000	.0000	1.0000	.0000
5.4	4.8263	1.0000	.0000	1.0000	.0000
5.6	5.0263	1.0000	.0000	1.0000	.0000
5.8	5.2263	1.0000	.0000	1.0000	.0000
6.0	5.4263	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 1.0;\ \frac{t_0}{t_{N_0}} = 1.5$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	1.5535	0.0000	0.6035
.2	.0291	.2809	1.2569	.1206	.6023
.4	.1085	.5040	.9785	.2405	.5945
.6	.2272	.6743	.7309	.3577	.5752
.8	.3752	.7989	.5152	.4696	.5418
1.0	.5442	.8855	.3523	.5735	.4944
1.2	.7274	.9424	.2231	.6666	.4354
1.4	.9197	.9772	.1299	.7472	.3694
1.6	1.1173	.9964	.0668	.8142	.3013
1.8	1.3176	1.0055	.0275	.8679	.2362
2.0	1.5191	1.0085	.0053	.9091	.1779
2.2	1.7208	1.0084	-.0053	.9396	.1286
2.4	1.9223	1.0069	-.0090	.9613	.0894
2.6	2.1235	1.0050	-.0090	.9760	.0596
2.8	2.3244	1.0034	-.0073	.9857	.0382
3.0	2.5249	1.0021	-.0054	.9917	.0235
3.2	2.7252	1.0012	-.0036	.9954	.0139
3.4	2.9254	1.0007	-.0023	.9975	.0079
3.6	3.1255	1.0003	-.0014	.9987	.0043
3.8	3.3255	1.0001	-.0008	.9994	.0023
4.0	3.5255	1.0000	-.0005	.9997	.0011
4.2	3.7255	.9999	-.0003	.9999	.0006

4132

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 1.0;\ \frac{t_0}{t_{N_0}} = 1.6$

η	f	f'	f''	θ	θ'
0	0.0000	0.0000	1.6149	0.0000	0.6094
.2	.0302	.2912	1.2987	.1218	.6082
.4	.1124	.5208	1.0024	.2428	.6000
.6	.2348	.6944	.7398	.3610	.5799
.8	.3869	.8195	.5188	.4738	.5452
1.0	.5599	.9049	.3423	.5781	.4961
1.2	.7468	.9593	.2089	.6714	.4354
1.4	.9422	.9910	.1143	.7518	.3678
1.6	1.1422	1.0071	.0520	.8184	.2986
1.8	1.3444	1.0134	.0146	.8714	.2329
2.0	1.5472	1.0141	-.0050	.9120	.1744
2.2	1.7499	1.0127	-.0131	.9418	.1254
2.4	1.9520	1.0093	-.0145	.9629	.0866
2.6	2.1536	1.0066	-.0126	.9771	.0575
2.8	2.3547	1.0043	-.0097	.9864	.0366
3.0	2.5554	1.0027	-.0068	.9922	.0224
3.2	2.7558	1.0016	-.0044	.9957	.0132
3.4	2.9560	1.0009	-.0027	.9977	.0075
3.6	3.1562	1.0005	-.0016	.9988	.0041
3.8	3.3562	1.0002	-.0009	.9994	.0021
4.0	3.5563	1.0001	-.0005	.9997	.0011
4.2	3.7563	1.0000	-.0002	.9999	.0005
4.4	3.9563	1.0000	-.0001	1.0000	.0002
4.6	4.1563	1.0000	-.0001	1.0000	.0001
4.8	4.3563	1.0000	.0000	1.0000	.0000
5.0	4.5563	1.0000	.0000	1.0000	.0000
5.2	4.7563	1.0000	.0000	1.0000	.0000
5.4	4.9563	1.0000	.0000	1.0000	.0000
5.6	5.1563	1.0000	.0000	1.0000	.0000
5.8	5.3563	1.0000	.0000	1.0000	.0000
6.0	5.5563	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 1.0;\ \frac{t_0}{t_{N_0}} = 2.0$

η	f	f'	f''	θ	θ'
0	0.0000	0.0000	1.8532	0.0000	0.6313
.2	.0344	.3309	1.4583	.1262	.6298
.4	.1272	.5852	1.0910	.2514	.6202
.6	.2639	.7704	.7698	.3733	.5968
.8	.4315	.8969	.5051	.4890	.5569
1.0	.6195	.9764	.3000	.5951	.5015
1.2	.8197	1.0207	.1520	.6888	.4344
1.4	1.0261	1.0405	.0538	.7684	.3612
1.6	1.2349	1.0449	-.0044	.8333	.2881
1.8	1.4435	1.0407	-.0331	.8840	.2204
2.0	1.6509	1.0329	-.0425	.9221	.1617
2.2	1.8567	1.0245	-.0406	.9494	.1139
2.4	2.0608	1.0170	-.0335	.9683	.0770
2.6	2.2636	1.0112	-.0251	.9809	.0499
2.8	2.4654	1.0069	-.0174	.9889	.0311
3.0	2.6664	1.0041	-.0114	.9937	.0186
3.2	2.8671	1.0023	-.0070	.9966	.0107
3.4	3.0674	1.0012	-.0041	.9982	.0059
3.6	3.2676	1.0006	-.0023	.9991	.0031
3.8	3.4676	1.0002	-.0012	.9996	.0016
4.0	3.6677	1.0000	-.0007	.9998	.0008
4.2	3.8677	.9999	-.0004	.9999	.0004
4.4	4.0676	.9999	-.0002	1.0000	.0002

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_O} = 1.0;\ \frac{t_O}{t_{N_O}} = 2.2$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	1.9684	0.0000	0.6413
.2	.0365	.3500	1.5343	.1282	.6397
.4	.1344	.6158	1.1317	.2553	.6295
.6	.2778	.8062	.7819	.3790	.6044
.8	.4526	.9328	.4962	.4959	.5621
1.0	.6476	1.0092	.2781	.6027	.5037
1.2	.8539	1.0483	.1239	.6966	.4335
1.4	1.0653	1.0623	.0249	.7757	.3578
1.6	1.2778	1.0611	-.0305	.8398	.2831
1.8	1.4892	1.0522	-.0546	.8894	.2146
2.0	1.6985	1.0406	-.0588	.9263	.1561
2.2	1.9055	1.0294	-.0522	.9526	.1088
2.4	2.1104	1.0200	-.0412	.9706	.0728
2.6	2.3137	1.0129	-.0299	.9824	.0468
2.8	2.5157	1.0079	-.0203	.9898	.0289
3.0	2.7170	1.0046	-.0129	.9943	.0171
3.2	2.9177	1.0026	-.0078	.9970	.0098
3.4	3.1181	1.0014	-.0045	.9984	.0053
3.6	3.3183	1.0007	-.0025	.9992	.0028
3.8	3.5184	1.0003	-.0013	.9996	.0014
4.0	3.7184	1.0002	-.0006	.9998	.0007
4.2	3.9184	1.0001	-.0003	.9999	.0003
4.4	4.1184	1.0000	-.0001	1.0000	.0001
4.6	4.3184	1.0000	-.0001	1.0000	.0001
4.8	4.5184	1.0000	.0000	1.0000	.0000
5.0	4.7184	1.0000	.0000	1.0000	.0000
5.2	4.9184	1.0000	.0000	1.0000	.0000
5.4	5.1184	1.0000	.0000	1.0000	.0000
5.6	5.3184	1.0000	.0000	1.0000	.0000
5.8	5.5184	1.0000	.0000	1.0000	.0000
6.0	5.7184	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_O} = 1.0;\ \frac{t_O}{t_{N_O}} = 3.0$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	2.4086	0.0000	0.6770
.2	.0442	.4222	1.8178	.1353	.6750
.4	.1613	.7304	1.2760	.2692	.6619
.6	.3297	.9380	.8149	.3988	.6306
.8	.5310	1.0628	.4508	.5201	.5789
1.0	.7507	1.1249	.1865	.6292	.5093
1.2	.9781	1.1435	.0136	.7231	.4285
1.4	1.2063	1.1353	-.0836	.8003	.3444
1.6	1.4314	1.1137	-.1246	.8611	.2645
1.8	1.6516	1.0879	-.1288	.9068	.1943
2.0	1.8667	1.0635	-.1129	.9397	.1367
2.2	2.0773	1.0433	-.0889	.9624	.0921
2.4	2.2843	1.0279	-.0645	.9774	.0596
2.6	2.4888	1.0172	-.0438	.9869	.0370
2.8	2.6914	1.0101	-.0280	.9926	.0220
3.0	2.8930	1.0059	-.0170	.9960	.0126
3.2	3.0938	1.0030	-.0980	.9979	.0069
3.4	3.2943	1.0016	-.0054	.9990	.0037
3.6	3.4945	1.0008	-.0028	.9995	.0019
3.8	3.6946	1.0004	-.0014	.9998	.0009
4.0	3.8947	1.0001	-.0007	.9999	.0004
4.2	4.0947	1.0001	-.0003	.9999	.0002
4.4	4.2947	1.0000	-.0001	1.0000	.0001
4.6	4.4947	1.0000	-.0001	1.0000	.0000
4.8	4.6947	1.0000	.0000	1.0000	.0000
5.0	4.8947	1.0000	.0000	1.0000	.0000
5.2	5.0947	1.0000	.0000	1.0000	.0000
5.4	5.2947	1.0000	.0000	1.0000	.0000
5.6	5.4947	1.0000	.0000	1.0000	.0000
5.8	5.6947	1.0000	.0000	1.0000	.0000
6.0	5.8947	1.0000	.0000	1.0000	.0000

4132

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 1.0;\ \frac{t_0}{t_{N_0}} = 4.0$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	2.9230	0.0000	0.7143
.2	.0532	.5053	2.1371	.1427	.7117
.4	.1921	.8597	1.4243	.2837	.6953
.6	.3884	1.0830	.8312	.4193	.6566
.8	.6184	1.2016	.3790	.5448	.5940
1.0	.8640	1.2440	.0684	.6556	.5122
1.2	1.1128	1.2372	-.1170	.7490	.4203
1.4	1.3572	1.2037	-.2038	.8238	.3283
1.6	1.5936	1.1601	-.2224	.8808	.2444
1.8	1.8213	1.1173	-.2010	.9224	.1737
2.0	2.0410	1.0808	-.1617	.9513	.1180
2.2	2.2542	1.0528	-.1193	.9706	.0768
2.4	2.4627	1.0328	-.0820	.9828	.0479
2.6	2.6678	1.0194	-.0531	.9904	.0287
2.8	2.8707	1.0110	-.0325	.9948	.0165
3.0	3.0724	1.0059	-.0189	.9973	.0091
3.2	3.2733	1.0031	-.0104	.9986	.0048
3.4	3.4737	1.0015	-.0055	.9993	.0025
3.6	3.6739	1.0007	-.0028	.9997	.0012
3.8	3.8740	1.0003	-.0014	.9999	.0006
4.0	4.0741	1.0001	-.0006	.9999	.0003
4.2	4.2741	1.0001	-.0002	1.0000	.0001
4.4	4.4741	1.0000	-.0001	1.0000	.0000
4.6	4.6741	1.0000	-.0001	1.0000	.0000
4.8	4.8741	1.0000	.0000	1.0000	.0000
5.0	5.0741	1.0000	.0000	1.0000	.0000
5.2	5.2741	1.0000	.0000	1.0000	.0000
5.4	5.4741	1.0000	.0000	1.0000	.0000
5.6	5.6741	1.0000	.0000	1.0000	.0000
5.8	5.8741	1.0000	.0000	1.0000	.0000
6.0	6.0741	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 1.0;\ \frac{t_0}{t_{N_0}} = 6.0$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	3.8711	0.0000	0.7742
.2	.0695	.6555	2.6962	.1546	.7705
.4	.2472	1.0872	1.6505	.3069	.7476
.6	.4917	1.3296	.8114	.4517	.6949
.8	.7694	1.4276	.2088	.5829	.6127
1.0	1.0563	1.4283	-.1669	.6954	.5105
1.2	1.3371	1.3735	-.3537	.7866	.4018
1.4	1.6042	1.2959	-.4042	.8565	.2993
1.6	1.8554	1.2173	-.3719	.9073	.2117
1.8	2.0919	1.1497	-.3012	.9425	.1426
2.0	2.3163	1.0974	-.2224	.9656	.0917
2.2	2.5318	1.0601	-.1524	.9802	.0565
2.4	2.7412	1.0354	-.0979	.9890	.0333
2.6	2.9466	1.0199	-.0594	.9941	.0189
2.8	3.1496	1.0107	-.0342	.9969	.0103
3.0	3.3511	1.0055	-.0188	.9985	.0053
3.2	3.5519	1.0028	-.0098	.9992	.0027
3.4	3.7523	1.0013	-.0050	.9996	.0012
3.6	3.9525	1.0006	-.0025	.9998	.0004
3.8	4.1526	1.0003	-.0014	.9999	.0003
4.0	4.3527	1.0001	-.0001	.9999	.0002

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 1.0;\ \frac{t_0}{t_{N_0}} = 6.5$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	4.0951	0.0000	0.7871
.2	.0734	.6904	2.8234	.1572	.7832
.4	.2602	1.1390	1.6963	.3118	.7586
.6	.5155	1.3843	.7992	.4585	.7026
.8	.8038	1.4761	.1635	.5908	.6160
1.0	1.0993	1.4661	-.2239	.7035	.5092
1.2	1.3866	1.3999	-.4073	.7941	.3971
1.4	1.6580	1.3125	-.4468	.8629	.2928
1.6	1.9118	1.2266	-.4016	.9123	.2048
1.8	2.1496	1.1542	-.3195	.9461	.1364
2.0	2.3747	1.0991	-.2323	.9681	.0868
2.2	2.5904	1.0604	-.1569	.9819	.0528
2.4	2.7997	1.0351	-.0995	.9901	.0308
2.6	3.0050	1.0194	-.0596	.9947	.0173
2.8	3.2079	1.0103	-.0339	.9973	.0093
3.0	3.4094	1.0052	-.0183	.9987	.0048
3.2	3.6101	1.0025	-.0095	.9994	.0024
3.4	3.8105	1.0012	-.0047	.9997	.0011
3.6	4.0106	1.0005	-.0022	.9999	.0005
3.8	4.2107	1.0002	-.0010	.9999	.0002
4.0	4.4107	1.0001	-.0005	1.0000	.0001
4.2	4.6107	1.0000	-.0002	1.0000	.0000
4.4	4.8107	1.0000	-.0001	1.0000	.0000
4.6	5.0107	1.0000	.0000	1.0000	.0000
4.8	5.2107	1.0000	.0000	1.0000	.0000
5.0	5.4107	1.0000	.0000	1.0000	.0000
5.2	5.6107	1.0000	.0000	1.0000	.0000
5.4	5.8107	1.0000	.0000	1.0000	.0000
5.6	6.0107	1.0000	.0000	1.0000	.0000
5.8	6.2107	1.0000	.0000	1.0000	.0000
6.0	6.4106	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 1.0\ \ \frac{t_0}{t_{N_0}} = 11.0$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	5.9629	0.0000	0.8808
.2	.1047	.9757	3.8229	.1758	.8744
.4	.3634	1.5496	1.9846	.3476	.8360
.6	.7030	1.8006	.6093	.5072	.7521
.8	1.0687	1.8268	-.2673	.6458	.6300
1.0	1.4251	1.7230	-.7058	.7580	.4908
1.2	1.7544	1.5659	-.8231	.8425	.3569
1.4	2.0514	1.4065	-.7489	.9022	.2437
1.6	2.3187	1.2718	-.5914	.9418	.1573
1.8	2.5623	1.1706	-.4223	.9668	.0956
2.0	2.7890	1.1011	-.2784	.9818	.0565
2.2	3.0045	1.0567	-.1715	.9905	.0317
2.4	3.2129	1.0302	-.0995	.9952	.0170
2.6	3.4173	1.0151	-.0545	.9977	.0087
2.8	3.6194	1.0071	-.0282	.9990	.0042
3.0	3.8204	1.0029	-.0135	.9996	.0017
3.2	4.0207	1.0009	-.0051	.9999	.0000

4132

4132

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 1.5;\ \frac{t_0}{t_{N_0}} = 1.2$

η	f	f'	f''	θ	θ'
0	0.0000	0.0000	1.6641	0.0000	0.6109
.2	.0309	.2975	1.3149	.1221	.6096
.4	.1146	.5282	.9987	.2434	.6012
.6	.2383	.6999	.7266	.3618	.5807
.8	.3912	.8221	.5035	.4747	.5455
1.0	.5645	.9045	.3294	.5990	.4959
1.2	.7511	.9568	.2005	.6723	.4349
1.4	.9458	.9873	.1105	.7525	.3671
1.6	1.1450	1.0031	.0519	.8190	.2978
1.8	1.3464	1.0096	.0169	.8719	.2322
2.0	1.5485	1.0109	-.0016	.9123	.1738
2.2	1.7506	1.0097	-.0095	.9420	.1250
2.4	1.9523	1.0075	-.0113	.9630	.0863
2.6	2.1536	1.0053	-.0101	.9772	.0572
2.8	2.3545	1.0035	-.0078	.9864	.0365
3.0	2.5551	1.0022	-.0055	.9922	.0223
3.2	2.7554	1.0013	-.0036	.9957	.0131
3.4	2.9556	1.0007	-.0022	.9977	.0074
3.6	3.1557	1.0004	-.0013	.9988	.0040
3.8	3.3558	1.0002	-.0007	.9994	.0021
4.0	3.5556	1.0001	-.0003	.9997	.0011
4.2	3.7558	1.0000	-.0002	.9999	.0005
4.4	3.9558	1.0000	-.0001	.9999	.0002
4.6	4.1558	1.0000	.0000	1.0000	.0001
4.8	4.3558	1.0000	.0000	1.0000	.0000
5.0	4.5558	1.0000	.0000	1.0000	.0000
5.2	4.7558	1.0000	.0000	1.0000	.0000
5.4	4.9558	1.0000	.0000	1.0000	.0000
5.6	5.1558	1.0000	.0000	1.0000	.0000
5.8	5.3558	1.0000	.0000	1.0000	.0000
6.0	5.5558	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 1.5;\ \frac{t_0}{t_{N_0}} = 1.6$

η	f	f'	f''	θ	θ'
0	0.0000	0.0000	1.9924	0.0000	0.6397
.2	.0367	.3514	1.5280	.1278	.6381
.4	.1347	.6144	1.1117	.2546	.6278
.6	.2774	.8004	.7600	.3780	.6028
.8	.4507	.9232	.4798	.4946	.5607
1.0	.6434	.9970	.2701	.6012	.5027
1.2	.8472	1.0354	.1241	.6949	.4332
1.4	1.0560	1.0502	.0313	.7741	.3582
1.6	1.2663	1.0506	-.0206	.8382	.2839
1.8	1.4758	1.0438	-.0437	.8880	.2158
2.0	1.6836	1.0343	-.0486	.9252	.1574
2.2	1.8896	1.2498	-.0438	.9517	.1101
2.4	2.0937	1.0171	-.0349	.9699	.0739
2.6	2.2965	1.0111	-.0254	.9819	.0747
2.8	2.4983	1.0068	-.0173	.9895	.0295
3.0	2.6994	1.0040	-.0111	.9942	.0176
3.2	2.9000	1.0022	-.0067	.9969	.0100
3.4	3.1003	1.0012	-.0039	.9984	.0055
3.6	3.3005	1.0006	-.0021	.9992	.0029
3.8	3.5006	1.0003	-.0011	.9996	.0015
4.0	3.7006	1.0002	-.0006	.9998	.0007
4.2	3.9006	1.0001	-.0002	.9999	.0003
4.4	4.1007	1.0000	-.0001	1.0000	.0001
4.6	4.3007	1.0000	.0000	1.0000	.0001
4.8	4.5007	1.0000	.0000	1.0000	.0000
5.0	4.7007	1.0000	.0000	1.0000	.0000
5.2	4.9007	1.0000	.0000	1.0000	.0000
5.4	5.1007	1.0000	.0000	1.0000	.0000
5.6	5.3007	1.0000	.0000	1.0000	.0000
5.8	5.5007	1.0000	.0000	1.0000	.0000
6.0	5.7007	1.0000	.0000	1.0000	.0000

4132

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 1.5;\ \frac{t_0}{t_{N_0}} = 2.2$					
η	f	f'	f''	θ	θ'
0	0.0000	0.0000	2.4534	0.0000	0.6761
.2	.0448	.4261	1.8168	.1351	.6740
.4	.1624	.7316	1.2532	.2688	.6609
.6	.3306	.9339	.7880	.3982	.6295
.8	.5306	1.0539	.4301	.5193	.5778
1.0	.7481	1.1129	.1762	.6281	.5085
1.2	.9730	1.1304	.0134	.7219	.4282
1.4	1.1187	1.1230	-.0766	.7992	.3446
1.6	1.4214	1.1033	-.1138	.8600	.2651
1.8	1.6397	1.0797	-.1172	.9059	.1952
2.0	1.8534	1.0575	-.1024	.9389	.1377
2.2	2.0630	1.0392	-.0805	.9618	.0931
2.4	2.2694	1.0253	-.0584	.9770	.0603
2.6	2.4734	1.0156	-.0397	.9866	.0376
2.8	2.6759	1.0092	-.0254	.9925	.0225
3.0	2.8773	1.0051	-.0154	.9959	.0129
3.2	3.0780	1.0028	-.0089	.9979	.0071
3.4	3.2784	1.0014	-.0049	.9989	.0038
3.6	3.4786	1.0007	-.0026	.9995	.0019
3.8	3.6787	1.0003	-.0013	.9998	.0009
4.0	3.8788	1.0001	-.0006	.9999	.0004
4.2	4.0788	1.0001	-.0002	1.0000	.0002
4.4	4.2788	1.0000	-.0001	1.0000	.0001
4.6	4.4788	1.0000	-.0001	1.0000	.0000
4.8	4.6788	1.0000	.0000	1.0000	.0000
5.0	4.8788	1.0000	.0000	1.0000	.0000
5.2	5.0788	1.0000	.0000	1.0000	.0000
5.4	5.2788	1.0000	.0000	1.0000	.0000
5.6	5.4788	1.0000	.0000	1.0000	.0000
5.8	5.6788	1.0000	.0000	1.0000	.0000
6.0	5.8788	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 1.5;\ \frac{t_0}{t_{N_0}} = 3.0$					
η	f	f'	f''	θ	θ'
0	0.0000	0.0000	3.0259	0.0000	0.7163
.2	.0547	.5173	2.1607	.1431	.7136
.4	.1961	.8716	1.4056	.2845	.6968
.6	.3943	1.0893	.7977	.4203	.6573
.8	.6249	1.2012	.3482	.5458	.5939
1.0	.8699	1.2385	.0481	.6566	.5115
1.2	1.1172	1.2289	-.1253	.7497	.4193
1.4	1.3598	1.1947	-.2028	.8243	.3273
1.6	1.5946	1.1520	-.2159	.8812	.2435
1.8	1.8208	1.1107	-.1924	.9226	.1731
2.0	2.0393	1.0760	-.1534	.9514	.1176
2.2	2.2517	1.0414	-.1125	.9706	.0769
2.4	2.4596	1.0306	-.0770	.9829	.0478
2.6	2.6644	1.0181	-.0496	.9904	.0287
2.8	2.8671	1.0102	-.0303	.9948	.0165
3.0	3.0687	1.0055	-.0176	.9973	.0091
3.2	3.2695	1.0029	-.0097	.9986	.0048
3.4	3.4699	1.0014	-.0051	.9993	.0025
3.6	3.6701	1.0007	-.0026	.9997	.0012
3.8	3.8702	1.0003	-.0012	.9999	.0006
4.0	4.0703	1.0001	-.0006	.9999	.0003
4.2	4.2703	1.0001	-.0002	1.0000	.0001
4.4	4.4703	1.0001	-.0001	1.0000	.0000
4.6	4.6703	1.0000	.0000	1.0000	.0000
4.8	4.8703	1.0000	.0000	1.0000	.0000
5.0	5.0703	1.0000	.0000	1.0000	.0000
5.2	5.2703	1.0000	.0000	1.0000	.0000
5.4	5.4703	1.0000	.0000	1.0000	.0000
5.6	5.6703	1.0000	.0000	1.0000	.0000
5.8	5.8703	1.0000	.0000	1.0000	.0000
6.0	6.0704	1.0000	.0000	1.0000	.0000

TABLE I. - Continued. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_0} = 2.0;\ \frac{t_0}{t_{N_0}} = 1.0$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	1.7638	0.0000	0.6154
.2	.0321	.3084	1.3526	.1230	.6140
.4	.1185	.5439	1.0114	.2451	.6053
.6	.2455	.7165	.7232	.3643	.5840
.8	.4016	.8370	.4915	.4777	.5476
1.0	.5776	.9167	.3142	.5824	.4967
1.2	.7663	.9659	.1857	.6757	.4343
1.4	.9625	.9936	.0979	.7556	.3654
1.6	1.1628	1.0073	.0422	.8217	.2954
1.8	1.3648	1.0122	.0101	.8741	.2294
2.0	1.5673	1.0123	-.0061	.9140	.1711
2.2	1.7696	1.0104	-.0123	.9432	.1226
2.4	1.9714	1.0078	-.0130	.9637	.0843
2.6	2.1728	1.0053	-.0111	.9776	.0557
2.8	2.3736	1.0034	-.0085	.9866	.0354
3.0	2.5741	1.0020	-.0059	.9922	.0216
3.2	2.7744	1.0010	-.0040	.9955	.0126
3.4	2.9746	1.0003	-.0026	.9974	.0071
3.6	3.1746	.9999	-.0016	.9985	.0038

$\frac{t_w}{t_0} = 2.0;\ \frac{t_0}{t_{N_0}} = 2.0$					
η	f	f'	f"	θ	θ'
0	0.0000	0.0000	2.7262	0.0000	0.6931
.2	.0493	.4676	1.9638	.1385	.6908
.4	.1775	.7925	1.3058	.2755	.6760
.6	.3584	.9986	.7777	.4076	.6412
.8	.5708	1.1127	.3846	.5305	.5845
1.0	.7991	1.1609	.1168	.6401	.5098
1.2	1.0323	1.1665	-.0453	.7337	.4245
1.4	1.2641	1.1481	-.1265	.8098	.3373
1.6	1.4909	1.1196	-.1520	.8690	.2561
1.8	1.7118	1.0896	-.1439	.9130	.1859
2.0	1.9270	1.0631	-.1196	.9443	.1292
2.2	2.1374	1.0420	-.0906	.9656	.0860
2.4	2.3442	1.0267	-.0639	.9795	.0549
2.6	2.5483	1.0161	-.0423	.9882	.0337
2.8	2.7509	1.0093	-.0265	.9934	.0198
3.0	2.9523	1.0052	-.0158	.9965	.0112
3.2	3.1531	1.0028	-.0090	.9982	.0061
3.4	3.3535	1.0014	-.0049	.9991	.0032
3.6	3.5537	1.0007	-.0025	.9995	.0016
3.8	3.7538	1.0003	-.0013	.9997	.0008
4.0	3.9538	1.0002	-.0007	.9998	.0003
4.2	4.1539	1.0001	-.0004	.9999	.0000

4132

TABLE I. - Concluded. STAGNATION-LINE FLOW SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 1

$\frac{t_w}{t_O} = 2.0;\ \frac{t_O}{t_{N_O}} = 6.0$					
η	f	f'	f''	θ	θ'
0	0.0000	0.0000	5.9032	0.0000	0.8666
.2	.1025	.9500	3.6549	.1730	.8605
.4	.3527	1:4913	1.8409	.3421	.8236
.6	.6783	1.7214	.5479	.4995	.7435
.8	1.0274	1.7438	-.2461	.6370	.6270
1.0	1.3681	1.6502	-.6321	.7492	.4933
1.2	1.6845	1.5100	-.7325	.8346	.3633
1.4	1.9721	1.3682	-.6667	.8957	.2519
1.6	2.2332	1.2480	-.5290	.9370	.1653
1.8	2.4732	1.1572	-.3809	.9635	.1032
2.0	2.6980	1.0943	-.2537	.9797	.0615
2.2	2.9124	1.0536	-.1583	.9891	.0351
2.4	3.1205	1.0289	-.0931	.9944	.0192
2.6	3.3247	1.0148	-.0519	.9973	.0101
2.8	3.5268	1.0071	-.0275	.9987	.0050
3.0	3.7278	1.0031	-.0140	.9995	.0023
3.2	3.9282	1.0011	-.0071	.9998	.0007

TABLE II. - STAGNATION-LINE SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 0.7

$\frac{t_w}{t_0} = 0.5;\ \frac{t_0}{t_{N_0}} = 1.6$

η	f	f'	f"	g	g'	θ	θ'
0	0.0000	0.0000	1.1824	0.0000	0.5692	0.0000	0.4386
.2	.0226	.2201	1.0175	.1138	.5683	.0906	.4672
.4	.0858	.4068	.8502	.2270	.5625	.1866	.4922
.6	.1831	.5606	.6898	.3382	.5479	.2869	.5088
.8	.3080	.6836	.5429	.4454	.5218	.3893	.5125
1.0	.4547	.7790	.4140	.5461	.4837	.4908	.4999
1.2	.6181	.8506	.3053	.6381	.4346	.5881	.4694
1.4	.7937	.9025	.2173	.7194	.3774	.6775	.4228
1.6	.9780	.9388	.1490	.7888	.3162	.7564	.3641
1.8	1.1684	.9632	.0981	.8459	.2551	.8227	.2993
2.0	1.3628	.9790	.0618	.8911	.1981	.8761	.2345
2.2	1.5596	.9887	.0371	.9256	.1479	.9169	.1750
2.4	1.7580	.9944	.0210	.9509	.1061	.9467	.1244
2.6	1.9572	.9975	.0111	.9686	.0732	.9673	.0841
2.8	2.1569	.9991	.0054	.9807	.0485	.9810	.0540
3.0	2.3568	.9999	.0023	.9885	.0309	.9895	.0329
3.2	2.5568	1.0001	.0007	.9934	.0189	.9946	.0189
3.4	2.7569	1.0002	.0000	.9964	.0111	.9975	.0102
3.6	2.9569	1.0002	-.0002	.9981	.0063	.9989	.0051
3.8	3.1569	1.0002	-.0002	.9990	.0034	.9996	.0023
4.0	3.3570	1.0001	-.0002	.9995	.0018	.9999	.0009
4.2	3.5570	1.0001	-.0001	.9998	.0009	1.0000	.0002
4.4	3.7570	1.0001	-.0001	.9999	.0004	1.0001	.0000
4.6	3.9570	1.0001	.0000	.9999	.0002	1.0001	-.0001
4.8	4.1570	1.0001	.0000	1.0000	.0001	1.0000	-.0001
5.0	4.3570	1.0001	.0000	1.0000	.0000	1.0000	-.0001
5.2	4.5571	1.0001	.0000	1.0000	.0000	1.0000	.0000
5.4	4.7571	1.0001	.0000	1.0000	.0000	1.0000	.0000
5.6	4.9571	1.0001	.0000	1.0000	.0000	1.0000	.0000
5.8	5.1571	1.0001	.0000	1.0000	.0000	1.0000	.0000
6.0	5.3571	1.0001	.0000	1.0000	.0000	1.0000	.0000

$\frac{t_w}{t_0} = 0.5;\ \frac{t_0}{t_{N_0}} = 3.0$

η	f	f'	f"	g	g'	θ	θ'
0	0.0000	0.0000	1.7009	0.0000	0.6252	0.0000	0.4350
.2	.0320	.3096	1.3928	.1250	.6238	.0932	.4966
.4	.1197	.5572	1.0861	.2490	.6150	.1982	.5515
.6	.2509	.7465	.8016	.3701	.5930	.3127	.5898
.8	.4144	.8803	.5537	.4851	.5550	.4324	.6020
1.0	.6001	.9699	.3505	.5901	.5017	.5513	.5817
1.2	.8000	1.0236	.1946	.6850	.4362	.6629	.5291
1.4	1.0078	1.0507	.0836	.7651	.3641	.7612	.4509
1.6	1.2191	1.0597	.0117	.8306	.2914	.8423	.3587
1.8	1.4309	1.0575	-.0292	.8820	.2236	.9046	.2653
2.0	1.6417	1.0495	-.0475	.9206	.1644	.9490	.1811
2.2	1.8506	1.0394	-.0511	.9484	.1160	.9781	.1126
2.4	2.0575	1.0295	-.0465	.9677	.0785	.9953	.0620
2.6	2.2625	1.0210	-.0381	.9805	.0509	1.0040	.0281
2.8	2.4660	1.0143	-.0290	.9886	.0318	1.0074	.0077
3.0	2.6684	1.0094	-.0208	.9936	.0190	1.0077	-.0029
3.2	2.8699	1.0059	-.0142	.9965	.0109	1.0066	-.0072
3.4	3.0708	1.0036	-.0092	.9982	.0060	1.0051	-.0078
3.6	3.2714	1.0021	-.0058	.9991	.0032	1.0036	-.0068
3.8	3.4717	1.0012	-.0035	.9996	.0016	1.0024	-.0052
4.0	3.6719	1.0007	-.0020	.9998	.0008	1.0015	-.0037
4.2	3.8720	1.0004	-.0011	.9999	.0004	1.0009	-.0024
4.4	4.0720	1.0002	-.0006	1.0000	.0002	1.0005	-.0015
4.6	4.2721	1.0001	-.0003	1.0000	.0001	1.0003	-.0009
4.8	4.4721	1.0001	-.0002	1.0000	.0000	1.0002	-.0005
5.0	4.6721	1.0000	-.0001	1.0000	.0000	1.0001	-.0003
5.2	4.8721	1.0000	.0000	1.0000	.0000	1.0000	-.0001
5.4	5.0721	1.0000	.0000	1.0000	.0000	1.0000	-.0001
5.6	5.2721	1.0000	.0000	1.0000	.0000	1.0000	.0000
5.8	5.4721	1.0000	.0000	1.0000	.0000	1.0000	.0000
6.0	5.6721	1.0000	.0000	1.0000	.0000	1.0000	.0000

TABLE II. - Continued. STAGNATION-LINE SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 0.7

$\frac{t_w}{t_0} = 0.5$; $\frac{t_0}{t_{N_0}} = 6.5$

η	f	f'	f"	g	g'	θ	θ'
0	0.0000	0.0000	2.8164	0.0000	0.7200	0.0000	0.4717
.2	.0520	.4970	2.1505	.1439	.7175	.1048	.5752
.4	.1900	.8615	1.5030	.2860	.7012	.2291	.6639
.6	.3884	1.1032	.9307	.4228	.6623	.3679	.7167
.8	.6244	1.2410	.4683	.5493	.5988	.5121	.7155
1.0	.8796	1.2987	.1294	.6610	.5153	.6501	.6550
1.2	1.1403	1.3006	-.0904	.7547	.4210	.7709	.5468
1.4	1.3977	1.2691	-.2091	.8294	.3266	.8672	.4140
1.6	1.6469	1.2220	-.2519	.8859	.2409	.9366	.2820
1.8	1.8863	1.1716	-.2449	.9267	.1692	.9813	.1695
2.0	2.1159	1.1257	-.2110	.9546	.1134	1.0063	.0855
2.2	2.3371	1.0878	-.1671	.9730	.0726	1.0174	.0302
2.4	2.5516	1.0588	-.1239	.9845	.0446	1.0199	-.0013
2.6	2.7612	1.0378	-.0869	.9914	.0262	1.0180	-.0158
2.8	2.9672	1.0235	-.0581	.9954	.0148	1.0143	-.0198
3.0	3.1709	1.0141	-.0372	.9977	.0080	1.0104	-.0183
3.2	3.3731	1.0082	-.0229	.9988	.0042	1.0071	-.0146
3.4	3.5743	1.0046	-.0136	.9994	.0021	1.0046	-.0106
3.6	3.7750	1.0025	-.0078	.9997	.0010	1.0028	-.0072
3.8	3.9754	1.0013	-.0043	.9999	.0005	1.0017	-.0046
4.0	4.1756	1.0007	-.0023	.9999	.0002	1.0009	-.0028
4.2	4.3757	1.0004	-.0012	1.0000	.0001	1.0005	-.0016
4.4	4.5757	1.0002	-.0006	1.0000	.0000	1.0003	-.0009
4.6	4.7757	1.0001	-.0003	1.0000	.0000	1.0001	-.0005
4.8	4.9758	1.0000	-.0001	1.0000	.0000	1.0001	-.0002
5.0	5.1758	1.0000	-.0001	1.0000	.0000	1.0000	-.0001
5.2	5.3758	1.0000	.0000	1.0000	.0000	1.0000	-.0001
5.4	5.5758	1.0000	.0000	1.0000	.0000	1.0000	.0000
5.6	5.7758	1.0000	.0000	1.0000	.0000	1.0000	.0000
5.8	5.9758	1.0000	.0000	1.0000	.0000	1.0000	.0000
6.0	6.1758	1.0000	.0000	1.0000	.0000	1.0000	.0000

Insulated surface; $\frac{t_{aw}}{t_0} = 0.9444$; $\frac{t_0}{t_{N_0}} = 1.6$; $\zeta_w = 0.8518$

η	f	f'	f"	g	g'	θ	θ'
0	0.0000	0.0000	1.5724	0.0000	0.6067	0.0000	0.0000
.2	.0294	.2844	1.2736	.1213	.6055	.0298	.2971
.4	.1099	.5107	.9930	.2418	.5976	.1180	.5804
.6	.2302	.6836	.7429	.3595	.5780	.2591	.8200
.8	.3803	.8103	.5305	.4720	.5440	.4406	.9794
1.0	.5518	.8985	.3585	.5762	.4957	.6435	1.0302
1.2	.7377	.9563	.2259	.6695	.4358	.8448	.9646
1.4	.9328	.9913	.1292	.7500	.3688	1.0227	.7997
1.6	1.1331	1.0100	.0630	.8169	.3000	1.1606	.5728
1.8	1.3361	1.0181	.0211	.8702	.2344	1.2506	.3290
2.0	1.5400	1.0197	-.0027	.9111	.1758	1.2938	.1089
2.2	1.7438	1.0178	-.0142	.9412	.1266	1.2975	-.0612
2.4	1.9470	1.0145	-.0178	.9624	.0875	1.2733	-.1709
2.6	2.1496	1.0110	-.0170	.9768	.0581	1.2329	-.2241
2.8	2.3514	1.0078	-.0142	.9862	.0371	1.1866	-.2329
3.0	2.5527	1.0053	-.0109	.9921	.0227	1.1416	-.2126
3.2	2.7536	1.0035	-.0078	.9956	.0134	1.1024	-.1773
3.4	2.9542	1.0022	-.0053	.9977	.0076	1.0709	-.1377
3.6	3.1545	1.0013	-.0034	.9988	.0041	1.0471	-.1009
3.8	3.3547	1.0008	-.0021	.9994	.0021	1.0301	-.0702
4.0	3.5548	1.0004	-.0013	.9997	.0011	1.0186	-.0466
4.2	3.7549	1.0002	-.0007	.9999	.0005	1.0111	-.0296
4.4	3.9549	1.0001	-.0004	.9999	.0002	1.0064	-.0181
4.6	4.1550	1.0001	-.0002	1.0000	.0001	1.0035	-.0107
4.8	4.3550	1.0000	-.0001	1.0000	.0000	1.0019	-.0061
5.0	4.5550	1.0000	.0000	1.0000	.0000	1.0010	-.0033
5.2	4.7550	1.0000	.0000	1.0000	.0000	1.0005	-.0018
5.4	4.9550	1.0000	.0000	1.0000	.0000	1.0002	-.0009
5.6	5.1550	1.0000	.0000	1.0000	.0000	1.0001	-.0005
5.8	5.3550	1.0000	.0000	1.0000	.0000	1.0000	-.0002
6.0	5.5550	1.0000	.0000	1.0000	.0000	1.0000	-.0001

TABLE II. - Concluded. STAGNATION-LINE SOLUTIONS FOR YAWED INFINITE CYLINDER WITH PRANDTL NUMBER OF 0.7

Insulated surface; $\frac{t_{aw}}{t_0} = 0.9045$; $\frac{t_0}{t_{N_0}} = 3.0$; $\zeta_w = 0.8567$

η	f	f'	f"	g	g'	θ	θ'
0	0.0000	0.0000	2.2902	0.0000	0.6716	0.0000	0.0000
.2	.0422	.4042	1.7554	.1342	.6696	.0377	.3758
.4	.1548	.7049	1.2622	.2671	.6572	.1488	.7269
.6	.3181	.9136	.8375	.3959	.6273	.3235	1.0028
.8	.5152	1.0454	.4952	.5167	.5774	.5411	1.1487
1.0	.7323	1.1174	.2384	.6257	.5098	.7721	1.1345
1.2	.9593	1.1460	.0612	.7199	.4305	.9849	.9710
1.4	1.1889	1.1463	-.0479	.7976	.3473	1.1538	.7070
1.6	1.4168	1.1304	-.1041	.8590	.2676	1.2654	.4087
1.8	1.6406	1.1071	-.1228	.9053	.1971	1.3190	.1365
2.0	1.8596	1.0827	-.1182	.9387	.1389	1.3243	-.0707
2.2	2.0738	1.0607	-.1013	.9617	.0937	1.2960	-.1998
2.4	2.2841	1.0425	-.0801	.9770	.0606	1.2491	-.2576
2.6	2.4911	1.0285	-.0595	.9867	.0376	1.1964	-.2620
2.8	2.6958	1.0185	-.0419	.9925	.0224	1.1464	-.2336
3.0	2.8987	1.0115	-.0281	.9960	.0128	1.1038	-.1901
3.2	3.1005	1.0070	-.0181	.9979	.0070	1.0704	-.1441
3.4	3.3016	1.0041	-.0112	.9990	.0037	1.0458	-.1029
3.6	3.5022	1.0023	-.0067	.9995	.0019	1.0287	-.0698
3.8	3.7026	1.0013	-.0039	.9998	.0009	1.0173	-.0453
4.0	3.9028	1.0007	-.0021	.9999	.0004	1.0101	-.0281
4.2	4.1029	1.0004	-.0012	.9999	.0002	1.0057	-.0168
4.4	4.3030	1.0002	-.0006	1.0000	.0001	1.0031	-.0097
4.6	4.5030	1.0001	-.0003	1.0000	.0000	1.0016	-.0054
4.8	4.7030	1.0001	-.0001	1.0000	.0000	1.0008	-.0029
5.0	4.9030	1.0001	-.0001	1.0000	.0000	1.0004	-.0015
5.2	5.1030	1.0001	.0000	1.0000	.0000	1.0002	-.0007
5.4	5.3030	1.0001	.0000	1.0000	.0000	1.0001	-.0004
5.6	5.5031	1.0001	.0000	1.0000	.0000	1.0000	-.0002
5.8	5.7031	1.0001	.0000	1.0000	.0000	1.0000	-.0001
6.0	5.9031	1.0001	.0000	1.0000	.0000	1.0000	.0000

Insulated surface; $\frac{t_{aw}}{t_0} = 0.8838$; $\frac{t_0}{t_{N_0}} = 6.5$; $\zeta_w = 0.8627$

η	f	f'	f"	g	g'	θ	θ'
0	0.0000	0.0000	3.8392	0.0000	0.7797	0.0000	0.0000
.2	.0692	.6541	2.7135	.1557	.7760	.0530	.5270
.4	.2474	1.0934	1.7066	.3091	.7530	.2073	.9987
.6	.4945	1.3493	.8885	.4549	.6998	.4419	1.3117
.8	.7778	1.4631	.2863	.5869	.6164	.7154	1.3802
1.0	1.0732	1.4776	-.1068	.7000	.5123	.9769	1.1976
1.2	1.3649	1.4320	-.3220	.7914	.4014	1.1829	.8438
1.4	1.6442	1.3576	-.4032	.8610	.2970	1.3111	.4394
1.6	1.9076	1.2764	-.3968	.9112	.2082	1.3623	.0882
1.8	2.1553	1.2019	-.3428	.9456	.1386	1.3536	-.1548
2.0	2.3893	1.1404	-.2709	.9679	.0880	1.3080	-.2825
2.2	2.6124	1.0934	-.1999	.9818	.0534	1.2466	-.3181
2.4	2.8275	1.0597	-.1393	.9901	.0310	1.1845	-.2949
2.6	3.0370	1.0367	-.0924	.9948	.0173	1.1304	-.2430
2.8	3.2428	1.0218	-.0587	.9974	.0092	1.0877	-.1840
3.0	3.4461	1.0126	-.0358	.9987	.0047	1.0564	-.1304
3.2	3.6480	1.0070	-.0210	.9994	.0023	1.0348	-.0873
3.4	3.8491	1.0038	-.0119	.9997	.0011	1.0207	-.0557
3.6	4.0496	1.0020	-.0065	.9999	.0005	1.0118	-.0340
3.8	4.2499	1.0010	-.0035	.9999	.0002	1.0065	-.0199
4.0	4.4501	1.0005	-.0018	1.0000	.0001	1.0035	-.0112
4.2	4.6501	1.0003	-.0009	1.0000	.0000	1.0018	-.0061
4.4	4.8502	1.0001	-.0004	1.0000	.0000	1.0009	-.0032
4.6	5.0502	1.0001	-.0002	1.0000	.0000	1.0004	-.0016
4.8	5.2502	1.0000	-.0001	1.0000	.0000	1.0002	-.0008
5.0	5.4502	1.0000	.0000	1.0000	.0000	1.0001	-.0004
5.2	5.6502	1.0000	.0000	1.0000	.0000	1.0000	-.0002
5.4	5.8502	1.0000	.0000	1.0000	.0000	1.0000	-.0001
5.6	6.0502	1.0000	.0000	1.0000	.0000	1.0000	.0000
5.8	6.2502	1.0000	.0000	1.0000	.0000	1.0000	.0000
6.0	6.4502	1.0000	.0000	1.0000	.0000	1.0000	.0000

4132

TABLE III. - SUMMARY OF HEAT-TRANSFER AND SKIN-FRICTION PARAMETERS FOR YAWED STAGNATION LINE

(a) Prandtl number, 1.

$\frac{t_w}{t_0}$	$\frac{t_0}{t_{N_0}}$	f_w''	θ_w' or g_w'	$\frac{f_w''}{\theta_w'}$
0	1.0	0.6489	0.5067	1.2807
	1.2	.6823	.5130	1.3300
	1.6	.7475	.5249	1.4241
	2.0	.8105	.5358	1.5127
	2.2	.8413	.5410	1.5551
	3.0	.9607	.5603	1.7146
	4.0	1.1025	.5815	1.8960
	6.0	1.3679	.6174	2.2156
	6.5	1.4313	.6254	2.2886
0.25	1.2	0.8673	0.5344	1.6229
	1.6	.9850	.5507	1.7886
	2.2	1.1530	.5724	2.0143
	3.0	1.3644	.5976	2.2831
0.50	1.2	1.0409	0.5530	1.8823
	1.6	1.2062	.5728	2.1058
	2.2	1.4406	.5986	2.4066
	3.0	1.7341	.6280	2.7613
	4.0	2.0785	.6593	3.1526
	6.5	2.8663	.7213	3.9738
0.75	1.2	1.2059	0.5695	2.1175
	1.6	1.4153	.5921	2.3903
	2.2	1.7110	.6212	2.7543
	3.0	2.0802	.6541	3.1802
1.00	1.0	1.2326	0.5704	2.1610
	1.1	1.2989	.5776	2.2488
	1.2	1.3640	.5845	2.3336
	1.5	1.5535	.6035	2.5742
	1.6	1.6149	.6094	2.6500
	2.0	1.8532	.6313	2.9355
	2.2	1.9684	.6413	3.0694
	3.0	2.4086	.6770	3.5578
	4.0	2.9230	.7143	4.0921
	6.0	3.8711	.7742	5.0001
	6.5	4.0951	.7871	5.2028
	11.0	5.9630	.8808	6.7700
1.50	1.2	1.6641	0.6109	2.7240
	1.6	1.9924	.6397	3.1146
	2.2	2.4534	.6761	3.6288
	3.0	3.0259	.7163	4.2243
2.00	1.0	1.7368	0.6154	2.8223
	2.0	2.7262	.6931	3.9334
	6.0	5.9032	.8666	6.8119

(b) Prandtl number, 0.7.

$\frac{t_w}{t_0}$	$\frac{t_0}{t_{N_0}}$	f_w''	g_w'	θ_w'	$\frac{f_w''}{g_w'}$	$\left(\frac{t_w - t_0}{t_w - t_{aw}}\right)\theta_w'$
0.50	1.6	1.1824	0.5692	0.4386	2.0773	0.4935
	3.0	1.7009	.6252	.4350	2.7206	.5377
	6.5	2.8164	.7200	.4717	3.9117	.6145
0.9444	1.6	1.5724	0.6067	0	2.5917	
.9045	3.0	2.2902	.6716	0	3.4101	
.8838	6.5	3.8392	.7797	0	4.9239	

4132

TABLE IV. - LOCAL RECOVERY FACTORS

FOR YAWED STAGNATION LINE

Yaw parameter, $\frac{t_0}{t_{N_0}}$	Local recovery factor, ζ_w			
	Prandtl number			
	0.7	0.8	0.9	1.0
1.0	0.849	0.903	0.953	1.000
1.6	.8518	-----	-----	1.000
3.0	.8567	-----	-----	1.000
6.5	.8627	-----	-----	1.000

4132

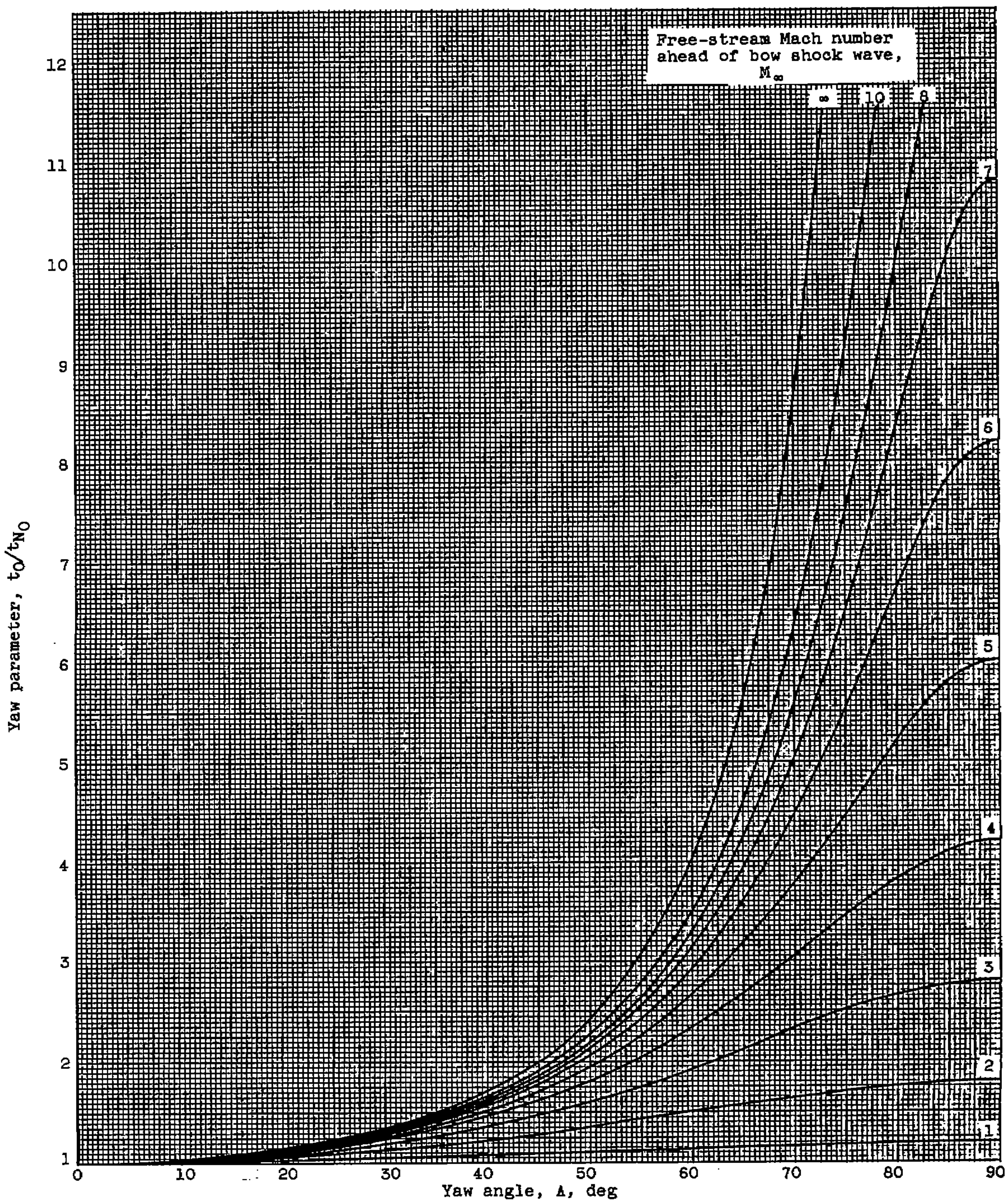
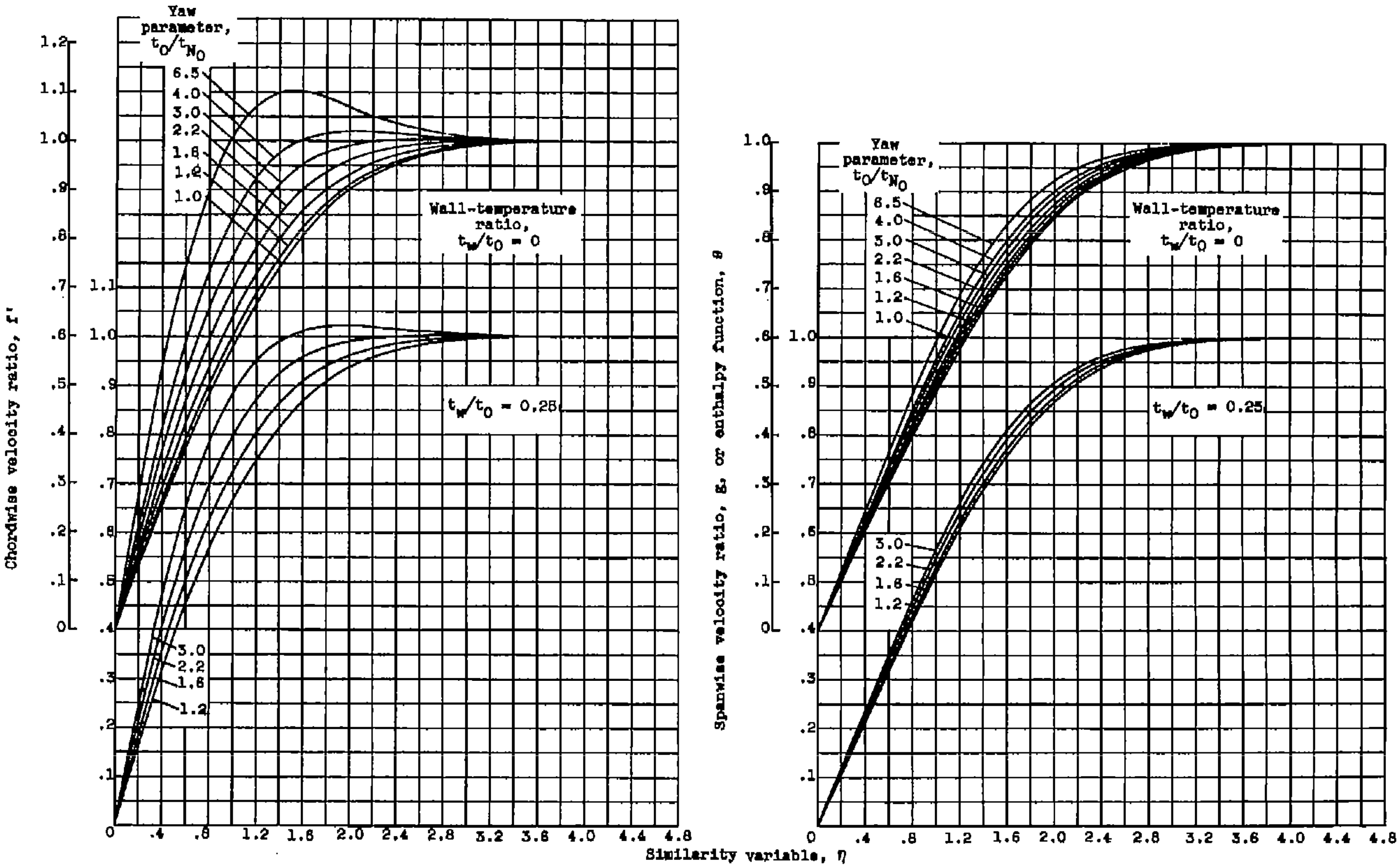
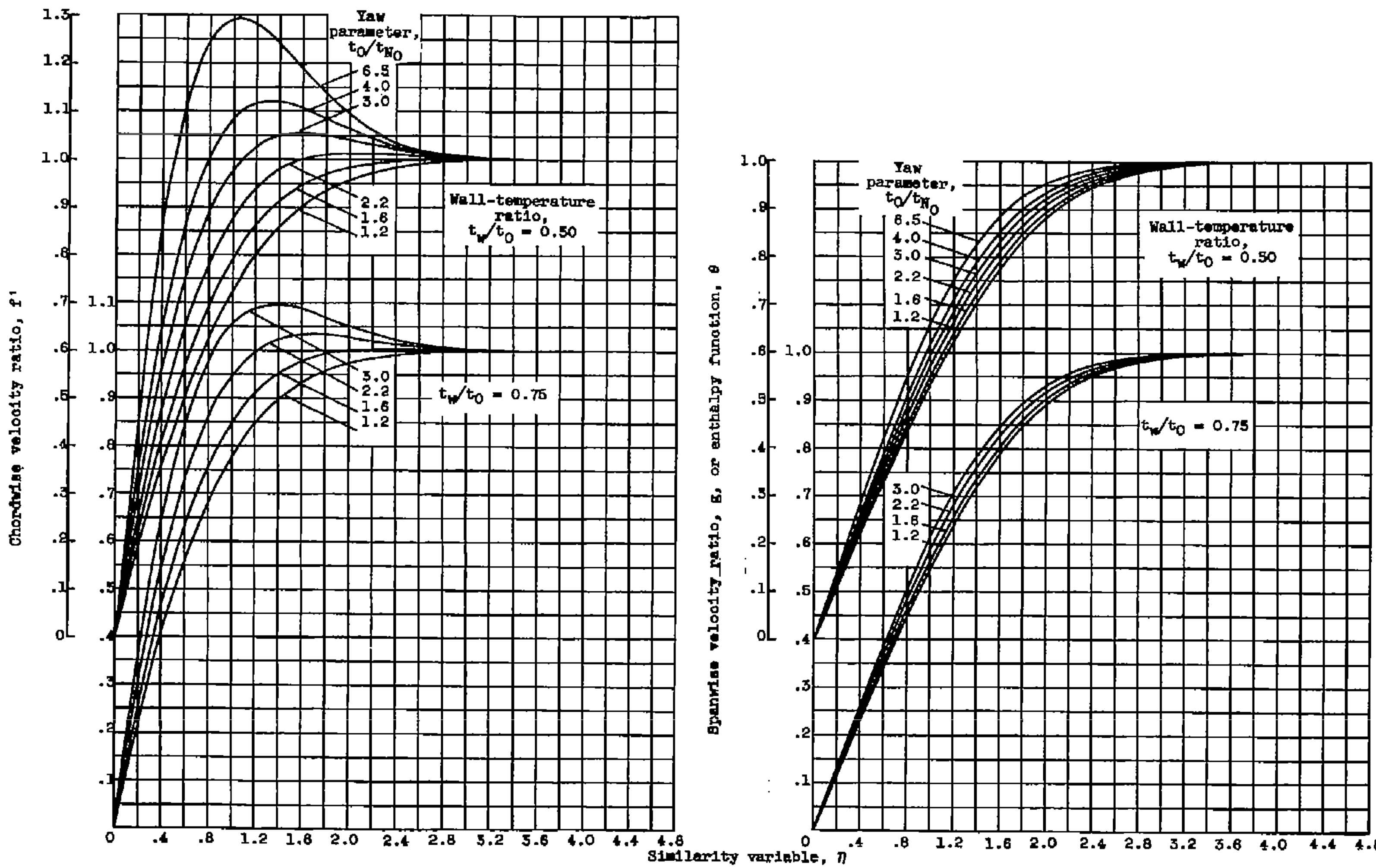


Figure 1. - Effect of yaw angle on yaw parameter. Ratio of specific heats, 1.4.



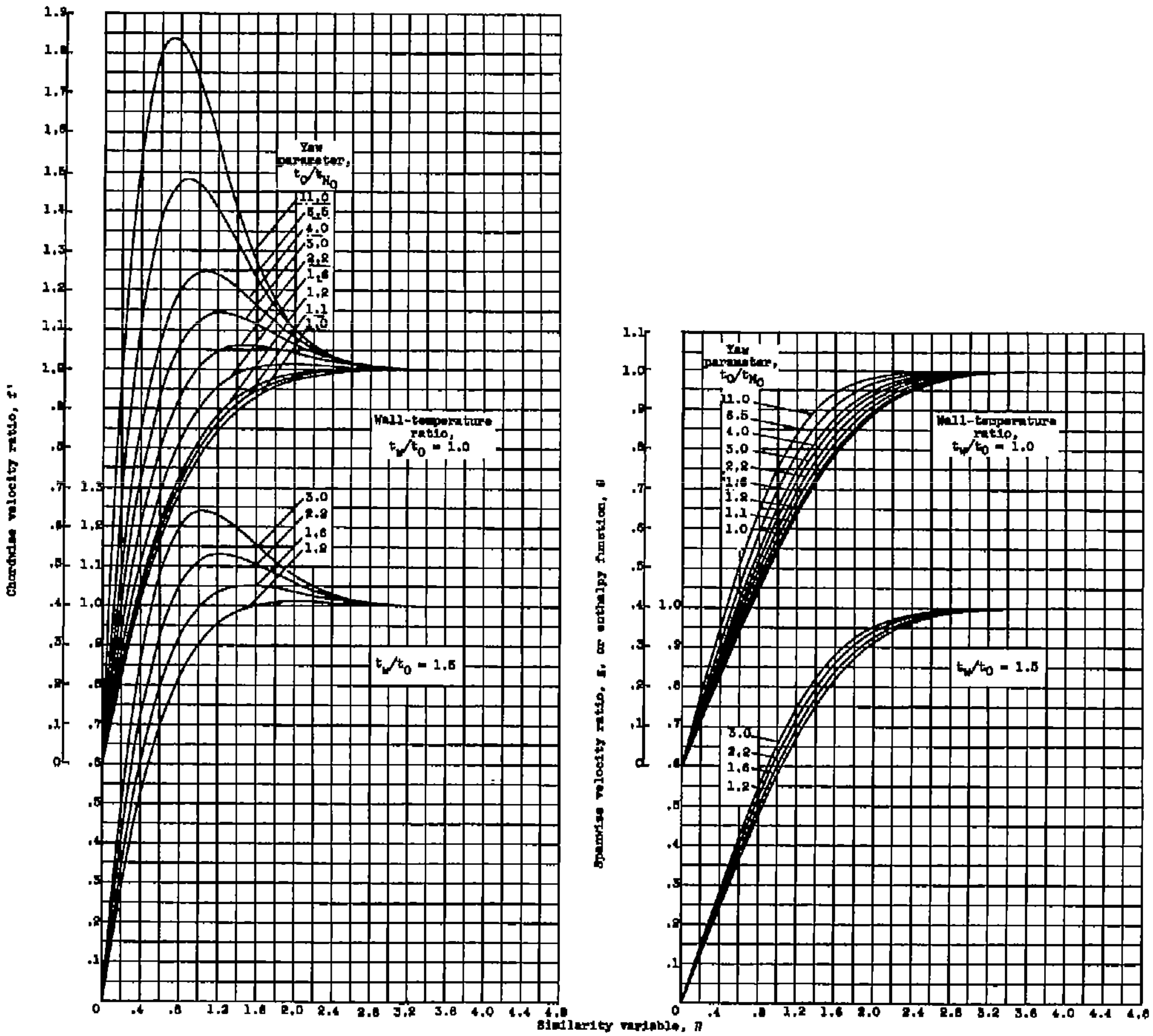
(a) Wall-temperature ratio, 0 and 0.25.

Figure 2. - Velocity and enthalpy profiles for Prandtl number of 1.



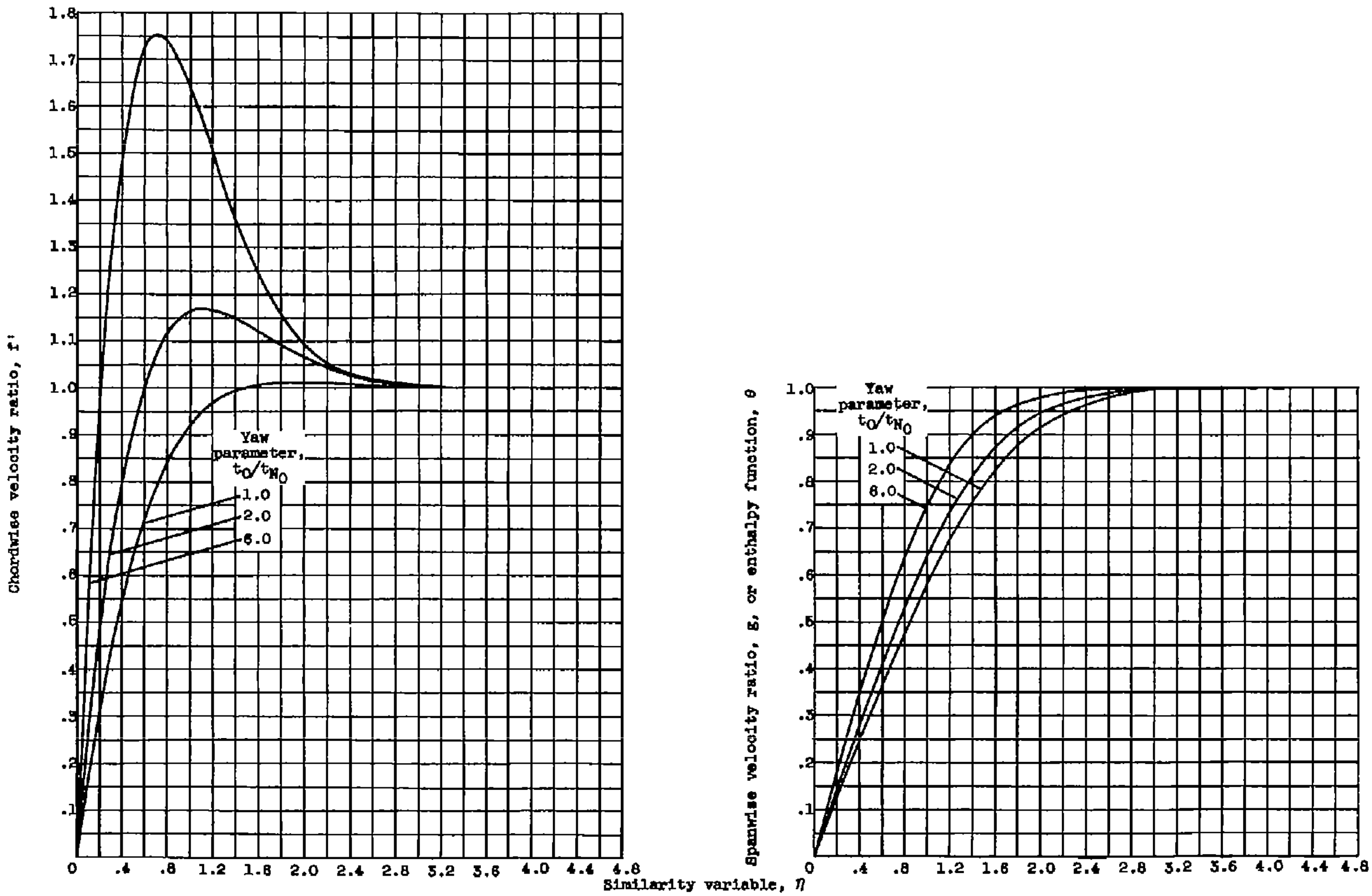
(b) Wall-temperature ratio, 0.50 and 0.75.

Figure 2. - Continued. Velocity and enthalpy profiles for Prandtl number of 1.



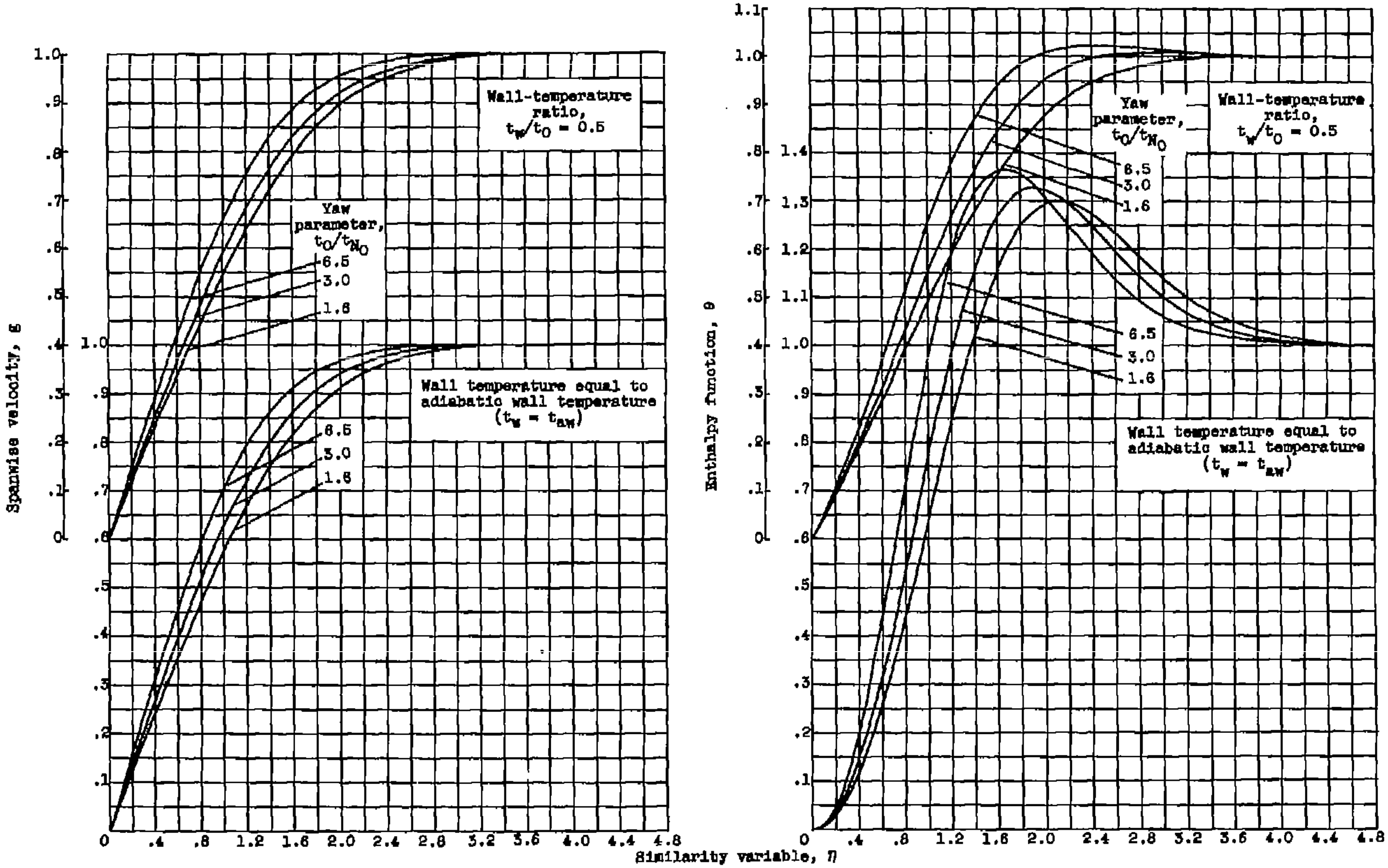
(c) Wall-temperature ratio, 1.0 and 1.5.

Figure 2. - Continued. Velocity and enthalpy profiles for Prandtl number of 1.



(d) Wall-temperature ratio, 2.0.

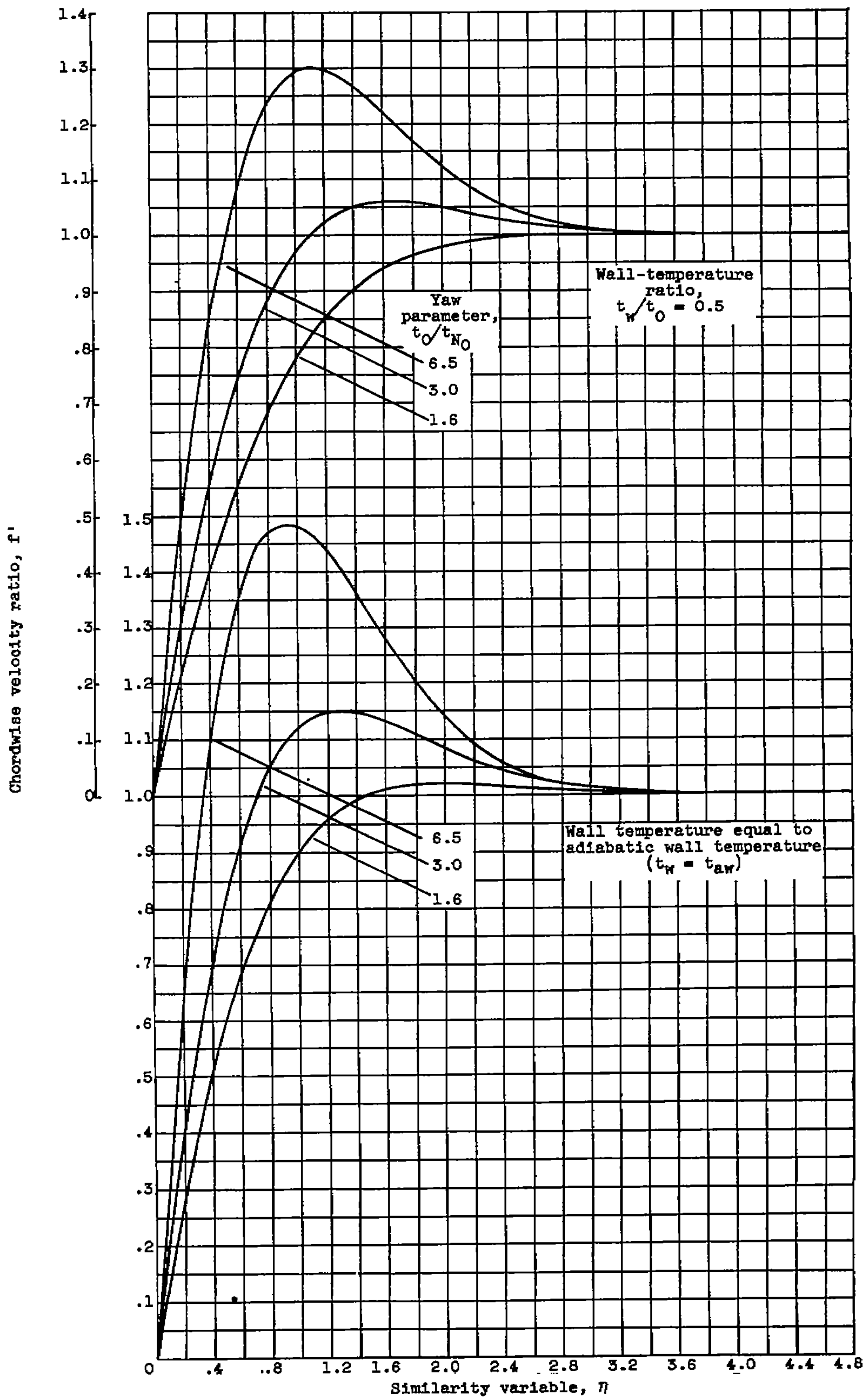
Figure 2. - Concluded. Velocity and enthalpy profiles for Prandtl number of 1.



(a) Spanwise velocity and enthalpy function.

Figure 5. - Velocity and enthalpy profiles for Prandtl number of 0.7.

4132



(b) Chordwise velocity.

Figure 3. - Concluded. Velocity and enthalpy profiles for Prandtl number of 0.7.

4132

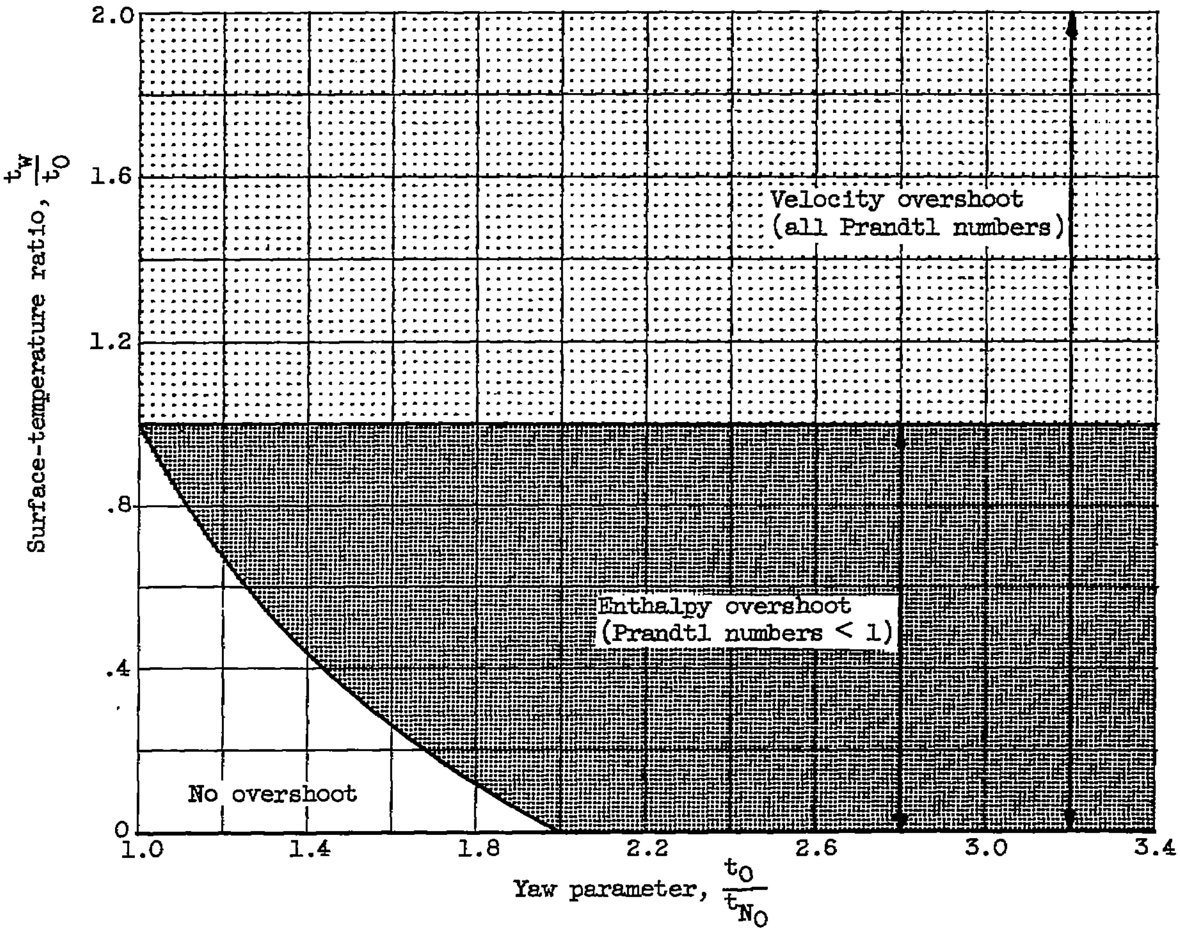


Figure 4. - Domains of velocity and enthalpy overshoot for stagnation-line flow over yawed cylinder.

4132

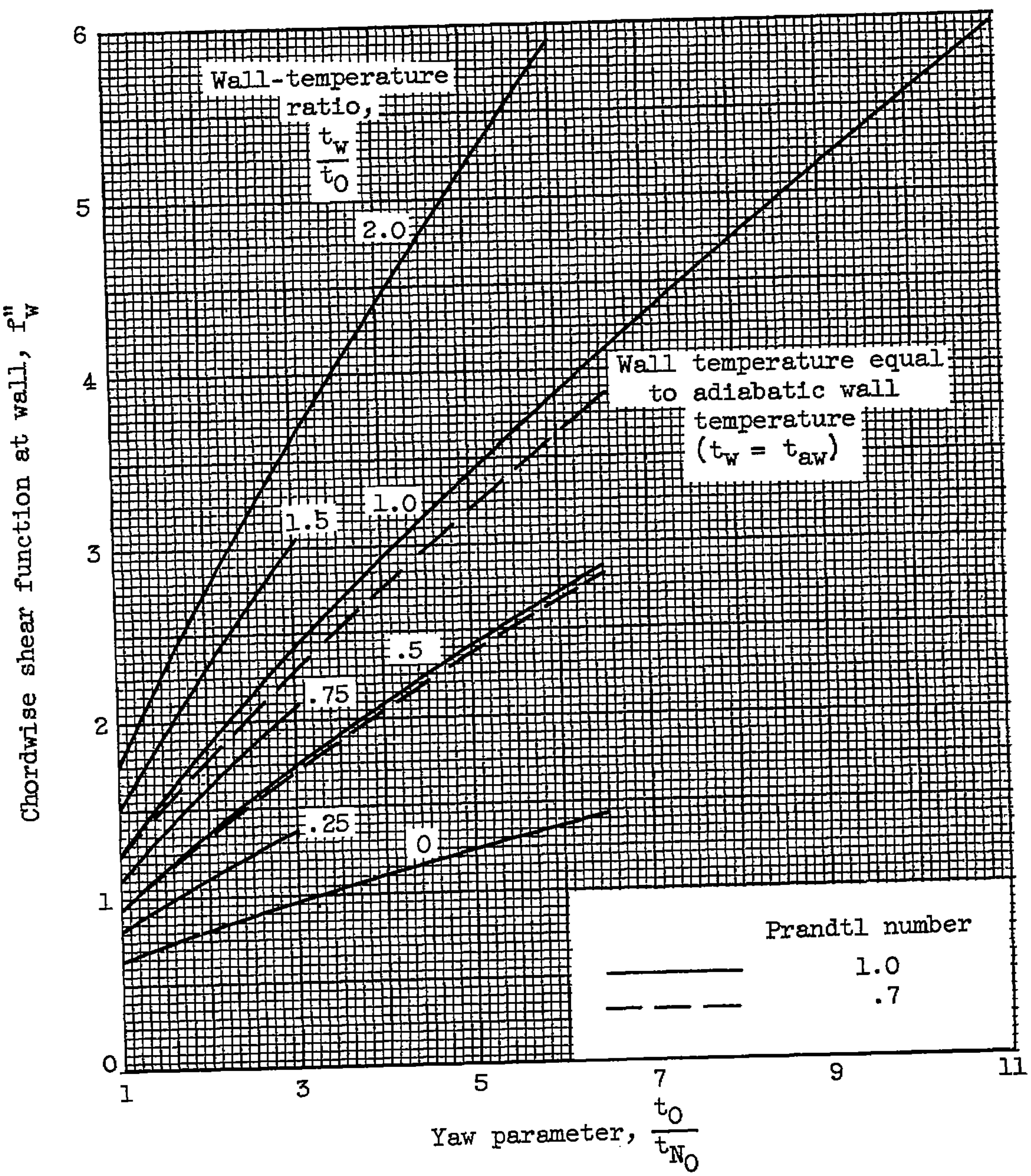


Figure 5. - Effect of yaw on wall-shear function for stagnation-line flow.

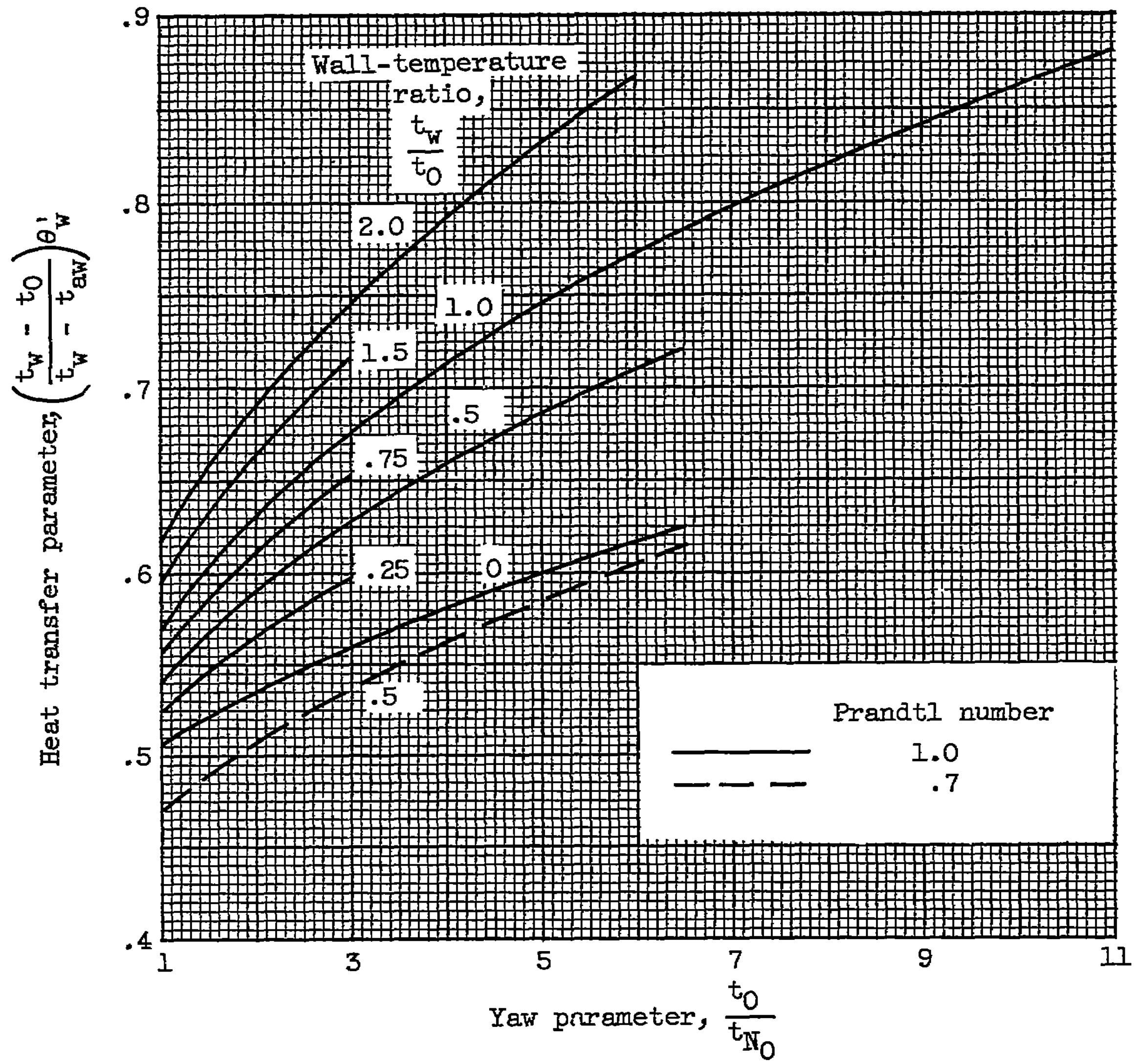


Figure 6. - Effect of yaw on heat-transfer parameter for stagnation-line flow. (For Prandtl number of 1 spanwise shear parameter g_w' is equal to heat-transfer parameter θ_w'.)

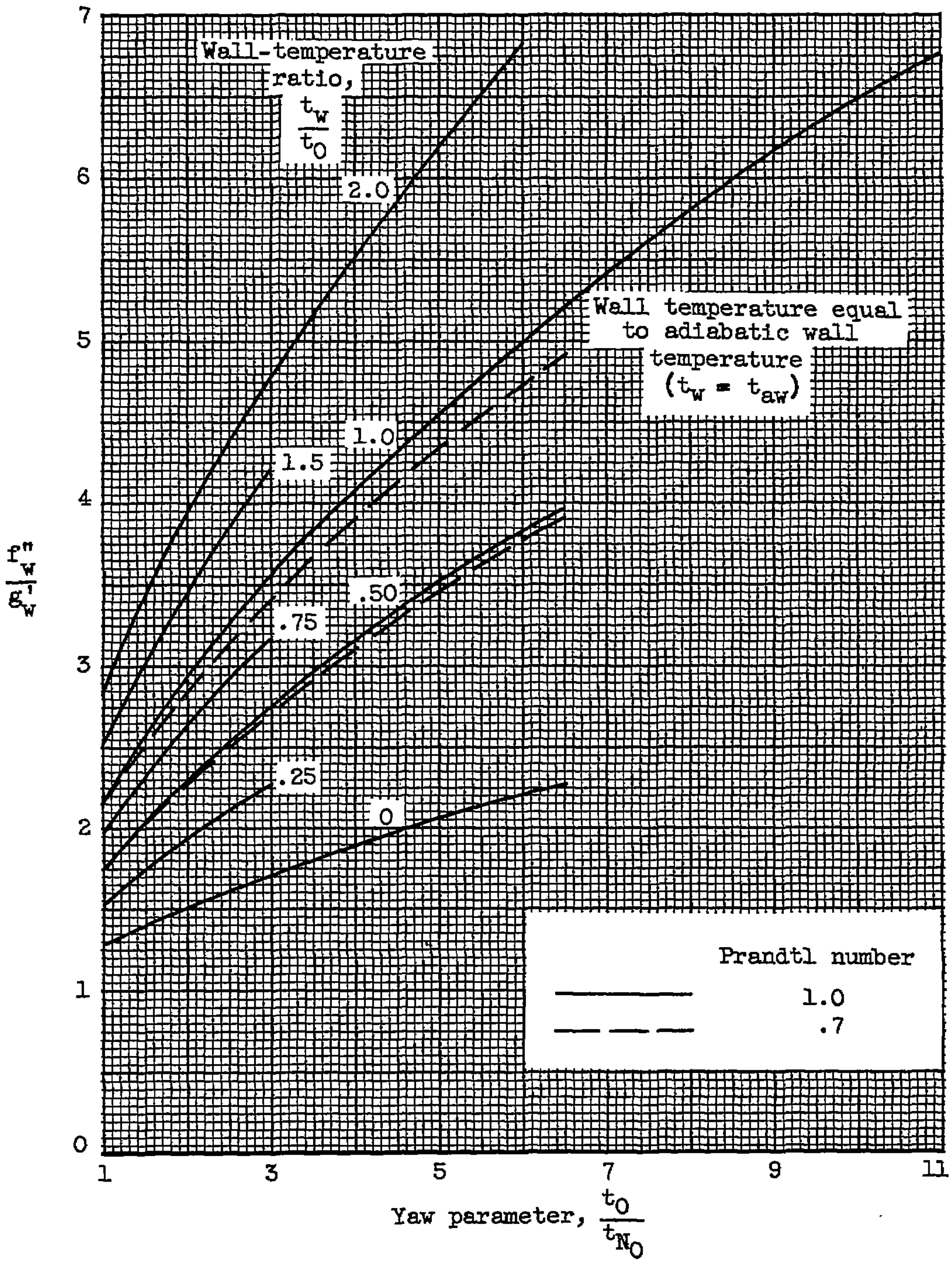


Figure 7. - Ratio of chordwise to spanwise surface-shear parameters for stagnation-line flow. (For Prandtl number of 1 $\frac{f''_w}{g'_w} = \frac{f''_w}{\theta'_w}$.)

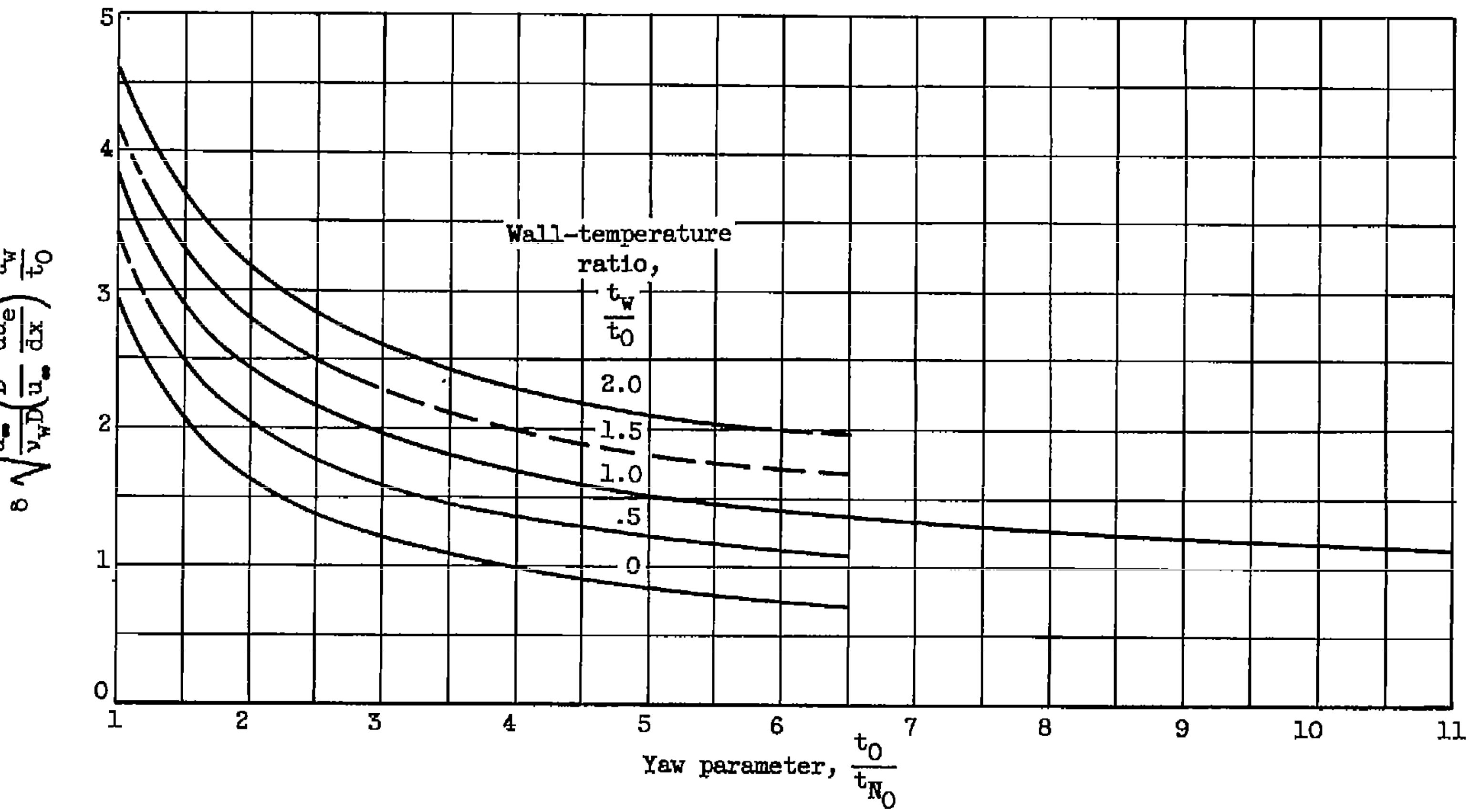


Figure 8. - Boundary-layer thickness at stagnation line of yawed cylinder. Prandtl number, 1.

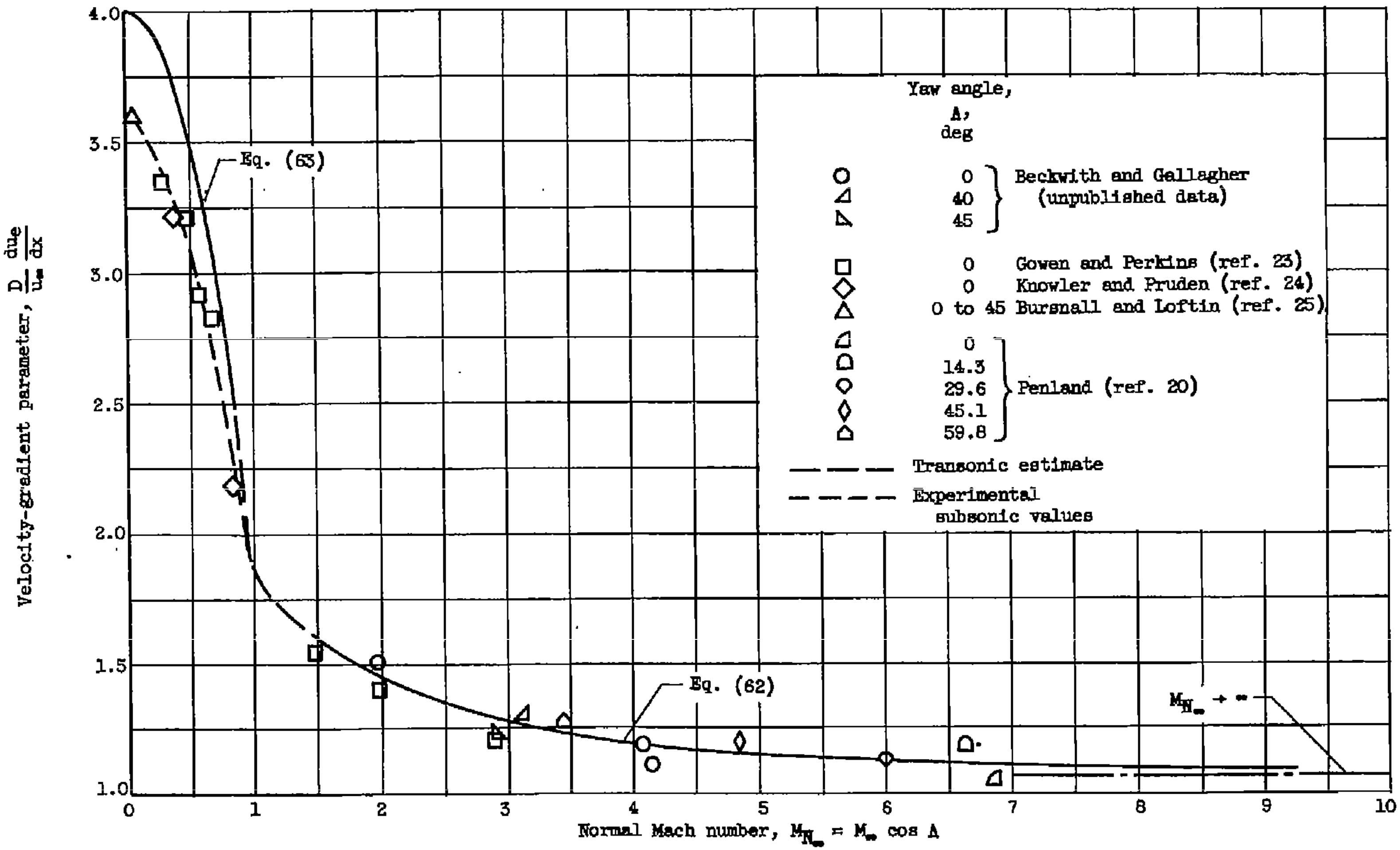


Figure 9. - Chordwise-velocity-gradient parameter as function of normal Mach number component for flow at stagnation line of yawed circular cylinder.

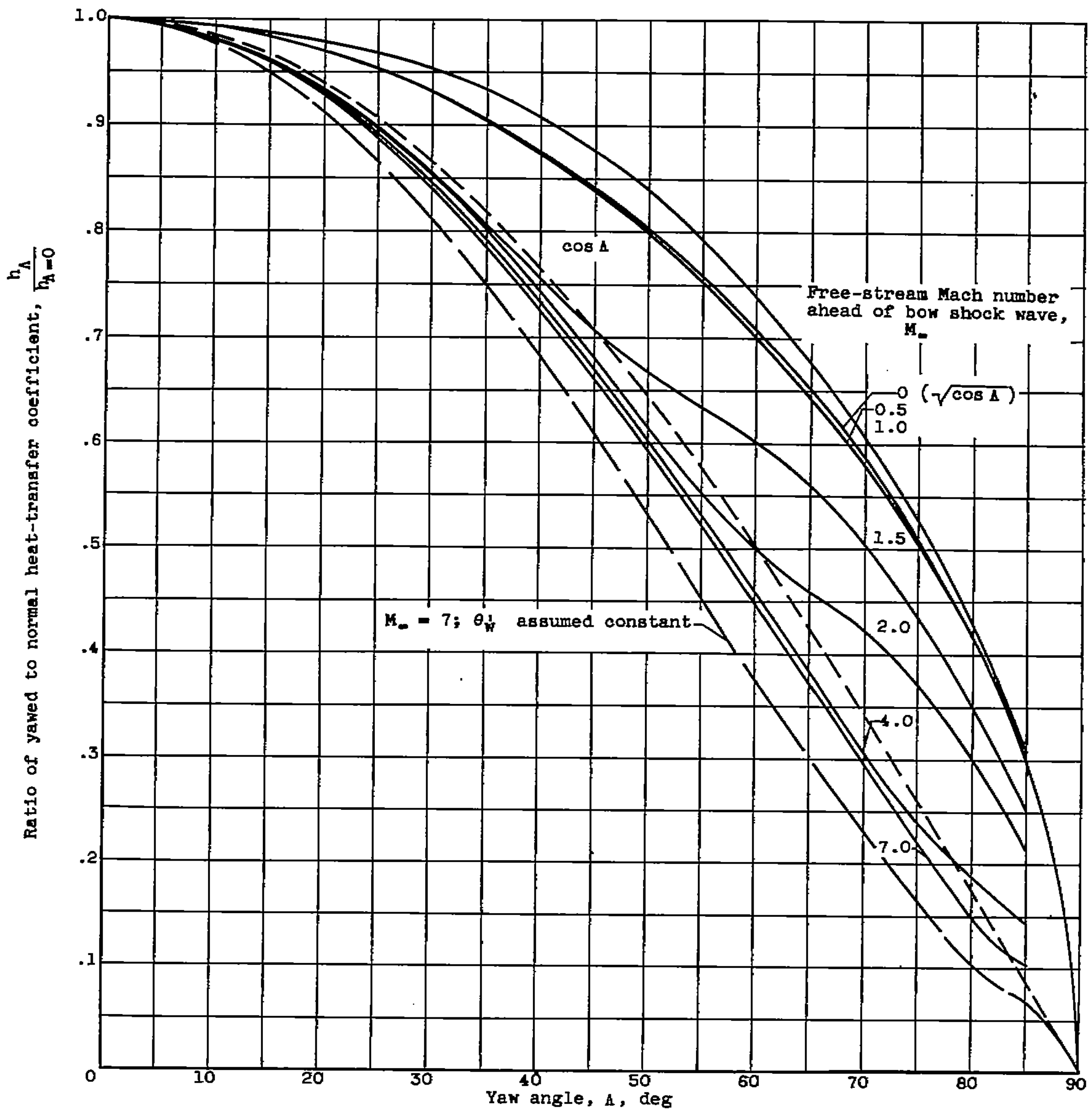


Figure 10. - Effect of yaw on heat-transfer coefficient at stagnation line of circular cylinder with nearly insulated surface. Wall-temperature ratio, $\frac{t_w}{t_0}$, 1.0; Prandtl number, 1.

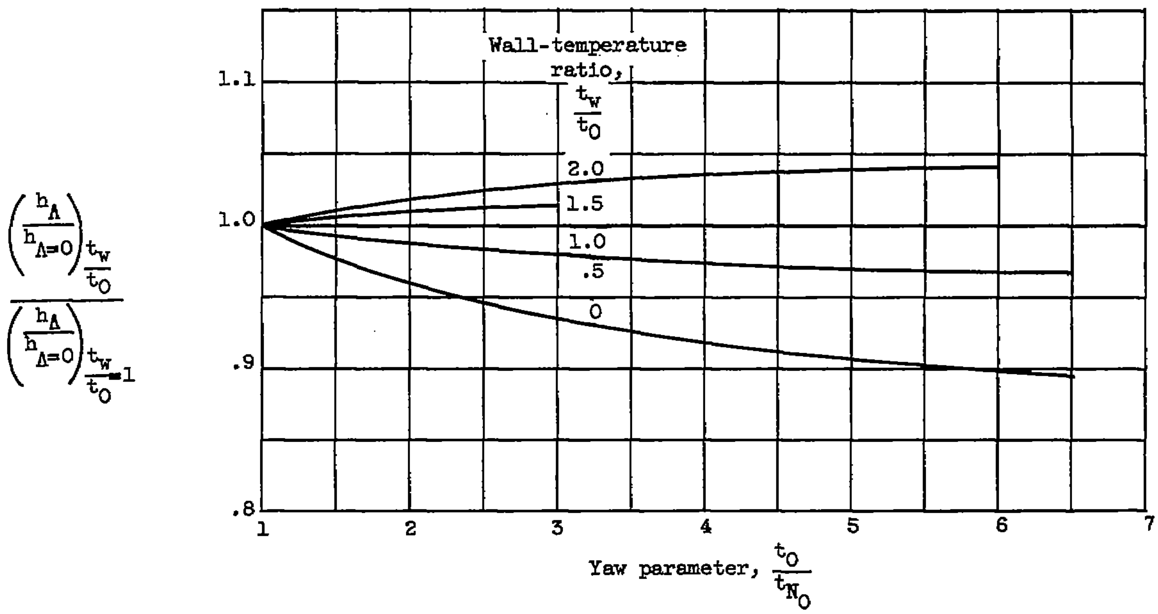


Figure 11. - Effect of surface-temperature level on heat-transfer-coefficient ratio. Prandtl number, 1.

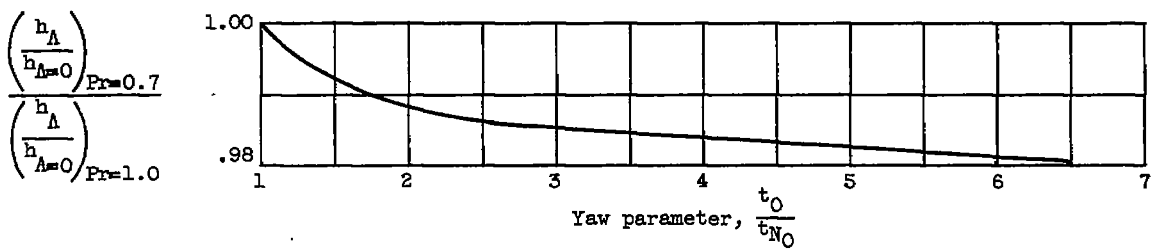


Figure 12. - Effect of Prandtl number on heat-transfer-coefficient ratio. Wall-temperature ratio, $\frac{t_w}{t_0}$, 0.5.