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CORRELATION OF TRANSONIC-CONE PRESTON-TUBE DATA AND SKIN FRICTION

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Moffett Field, California 94035

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CORRELATION OF TRANSONIC-CONE
PRESTON-TUBE DATA AND SKIN FRICTION
NASA Research Grant Number NAG 2-74

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ACCOMPLISHMENTS

A correlation has been developed which expresses turbulent skin friction as a function of Preston-tube measurements taken on the AFDC Transition Cone. The correlation equation appears below:

\[ \chi = 0.0272(\chi^a)^2 + 0.5137 \chi^a + 0.1140 \chi^* - 0.5149 \]

(1)

The corresponding scatter in skin-friction coefficient is 1.125%, see Fig. 12 of the attached report. The details involved in the development of Eq. (1) can be found in the attached M.S. thesis by A. Nassirharand.

In order to compare this correlation with previously developed correlations for laminar skin friction, it is more convenient to delete the dependence on \( \chi^a \). This permits a simple plot of \( \chi^a \) vs. \( \chi^* \). When \( \chi^a \) is deleted via the data is refitted with only \( \chi^* \), the following equation is obtained:

\[ \chi = 0.0195(\chi^*)^2 + 0.6124 \chi^* - 0.7339 \]

(2)

The corresponding scatter in skin-friction coefficient increases only slightly to 1.17%. A plot of this equation is shown on the following page along with the previously developed correlations for laminar boundary layers. As is readily surmised, the turbulent correlation predicts higher values of \( \chi^* \) for a given value of \( \chi^a \). Also, it should be noted that the turbulent correlation is based on unshifted wind-tunnel data.

As discussed in Nassirharand's report, Allen's correlation was used to estimate skin friction at the match points where the fully-developed turbulent boundary layer were assumed to begin. Allen's correlation was found to overestimate \( \chi^a \) (match points) by 3-6%. This erroneous value of skin fric-
COMPARISON OF TURBULENT AND LAMINAR CORRELATIONS FOR 11-FT TWT

UNSHIFTED TURBULENT DATA

SHIFTED LAMINAR DATA

UNSHIFTED LAMINAR DATA
tion led to erroneous values of $K_{\text{eff}}$ and sometimes required that a large portion of the data be rejected. The rejection criterion is that only values of $K_{\text{eff}}$ which increased with increasing surface distance, are valid. This is discussed on pp. 46-53 of the attached report.
REMAINING TASKS

I. In order to obtain an accurate calculation in the boundary-layer-transition region, it will be necessary to repeat the turbulent calculations using Eq. (1) or (2) to estimate skin friction at the match points (i.e., the beginning of fully-developed turbulent flow, $X_f > X_r$). However, this time the Preston-tube pressures for $Re_f = 3 \times 10^6$ and Run Nos. 70.726 and 72.748 will be corrected based on the increments used in correcting the corresponding laminar data. This procedure is expected to lead to a revision of the coefficients which appear in Eqs. (1) and (2). The resulting correlation equations will then be used to calculate turbulent skin friction at $X_f$. The final series of STW-5 calculations of turbulent skin friction will then be required to produce the correlation value of $(C_f)_{turb}$ at $X_f$. The distribution of $(C_f)_{turb}$ across the transition zone will then be taken from the STW-5 solutions which match $(C_f)_{turb}$ at $X_f$. These solutions will then be used in conjunction with the corresponding distributions of laminar skin friction and an intermittency function to define values of skin friction through the regions of boundary-layer transition.

The revised turbulent correlation will be used together with the corresponding flight correlation to define effective freestream unit Reynolds numbers.

II. The data for each flight will be corrected as was done for the laminar data. The development of turbulent and transitional zone correlations for the flight data will then be performed.

III. The resulting values of effective freestream unit Reynolds numbers will be compared for the laminar, transitional, and turbulent boundary layers. A best procedure will be recommended.
CORRELATION OF THEORETICAL TURBULENT SKIN
FRICITION WITH PRESTON-TUBE MEASUREMENTS ON A SUBSONIC CONE

By
AMIR NASSIRARAND
Bachelor of Science in Mechanical Engineering
Oklahoma State University
Stillwater, Oklahoma
1980

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF SCIENCE
December, 1981
Name: Amir Nassirharand  Date of Degree: December, 1981
Institution: Oklahoma State University  Location: Stillwater, Oklahoma
Title of Study: CORRELATION OF THEORETICAL TURBULENT SKIN FRICTION WITH PRESTON-TUBE MEASUREMENTS ON A SUBSONIC CONE
Pages in Study: 124  Candidate for Degree of Master of Science
Major Field: Mechanical Engineering

Scope and Method of Study: The distribution of Preston-tube pressures along the surface of a sharp ten-degree cone for different free-stream conditions were obtained at the Ames Research Center of the National Aeronautics and Space Administration (NASA). This sharp ten-degree cone, which was designed by engineers at Arnold Engineering Development Center (AEDC), was originally developed to detect transition from laminar boundary layers to turbulent boundary layers. The objective of the present study is to correlate Preston-tube pressure measurements within turbulent boundary layers with the corresponding theoretical values of skin friction coefficient. Three different computer programs were used to analyze the data and to solve the boundary layer conservation equations.

Findings and Conclusions: A new correlation between Preston-tube data and turbulent skin friction on a cone has been developed. The skin friction, which results from using Preston-tube pressures in the correlation equation, has a root-mean-square (rms) error of about one percent. This accuracy is comparable to previous Preston-tube correlations for pipe flows. In the process of analyzing the Preston-tube data it was found that the height above the cone's surface of the effective center of the probe is not a constant. In fact, the effective height of the probe is a function of: (1) the external height of the probe's face, (2) wall friction velocity, (3) wall kinematic viscosity, and (4) Mach number. For a given unit Reynolds number, the effective center of the probe decreases with increasing Mach number. Furthermore, the distance of the effective center of the probe from the cone's surface increases as distance from tip of the nose increases. It is also found that effects of variable fluid properties across the probe's face may be neglected for subsonic freestream Mach numbers.

ADVISER'S APPROVAL  Troy D. Reed
CORRELATION OF THEORETICAL TURBULENT SKIN
FRICION WITH PRESTON-TUBE MEASUREMENTS ON A SUBSONIC CONE

Thesis Approved:

Troy D. Reed
Thesis Adviser

Dean of Graduate College
ACKNOWLEDGMENTS

I wish to express my gratitude to every single member of my family for their understanding, encouragement, and many sacrifices.

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**NOMENCLATURE**

1. speed of sound (FT/S) ($c_{\text{sound}}$)
2. constant in logarithmic region of mean velocity distribution (5.0 (dimensionless))
3. skin friction coefficient ($2c_{w}/\rho U^2$) (dimensionless)
4. nondimensional difference between skin friction coefficient ($\left( c_{f_t} - c_{f,C} / c_{f,t} \right)$)
5. pressure coefficient based on the difference between a Pitot and static pressure reading ($P_p - P_w \left/ q_w \right.$) (dimensionless)
6. geometric parameter - ft (see Figure 4)
7. external diameter of a round Pitot tube - inches
8. equivalent external diameter of the oval shaped Pitot probe used in NASA Ames experiments (inches) (see Equation 4.26)
9. Allen's first calibration parameter (see Equation (2.1)) (dimensionless)
10. Allen's second calibration parameter (see Equation (2.2)) (dimensionless)
11. Fenter-Stalmach's first calibration parameter (see Equation (2.5)) (dimensionless)
12. Fenter-Stalmach's second calibration parameter (see Equation (2.6)) (dimensionless)
13. conversion factor (32.171 LBM - FT/S)
14. external height of face of the oval probe (0.109 inches)
nondimensional effective center of the Pitot probe (see Equation (3.2))

L  axial length of cone (11.5 inches)

Ma  Mach number (dimensionless)

P  pressure (LBF/FT²)

Q  dynamic pressure (LBF/FT²)

f  recovery factor (0.884) (dimensionless)

R  gas constant (53.35 LBF-FT/LSM-°R for air)

Re  Reynolds number for compressible flow based on diameter D
   (see Equation 4.22) (dimensionless)

Re₁  freestream unit Reynolds number - 1/ft (see Equation (4.3))

Re₂  Reynolds number based on the product of Uᵦ/Uₑ and boundary-layer momentum thickness.

T  temperature - °R

Tₚ  nondimensionalized temperature (see Equation (5.4))

\( \bar{U} \)  mean velocity inside boundary layer - FT/S (see Equation (2.8))

\( \bar{J}_e \)  velocity at outer edge of boundary layer - FT/S

\( \bar{J}_m \)  velocity calculated from Preston-tube data - FT/S

\( \bar{J}_o \)  classical wall-shear-stress velocity - FT/S(\( \frac{\bar{J}_m}{\bar{U}} \))

\( \bar{U}_o \)  freestream velocity - FT/S

\( \bar{C} \)  axial distance from physical nose of cone - inches

(\( \bar{z} \))  the location within the laminar boundary layer which has the same Preston-tube pressure as that of the match point (inches)
   (see Figure 5)

\( \bar{C} \)  surface distance along the surface of the cone measured with reference to virtual origin - FT
surface distance between match point and virtual origin - FT (see Figure 4)

\( \ell_{wp} \)

surface distance between match point and tip of the physical cone - FT (see Figure 4)

\( \ell_o \)

surface distance measured with reference to tip of the physical cone - FT

\( \ell_t \)

distance along surface of cone from apex to onset of boundary-layer transition - FT (see Figure 5)

\( \ell_T \)

distance along surface of cone from apex to end of boundary-layer transition (see Figure 5)

\( x^* \)

logarithm of the square of a Reynolds number based on the product \( U_p \) \( \nu_{eff} / \nu_w \) (dimensionless) (see Equation 5.3)

\( y \)

distance normal to the cone surface - FT

\( \nu_{eff} \)

effective height of face of Preston-tube which is defined to be the height above the wall of an undisturbed streamline which has a total pressure equal to the measured Pitot pressure - FT

\( \tau^* \)

dimensionless shear stress for compressible, nonadiabatic flow (see Equation (5.2))

Greek Letters

\( \delta \)
boundary layer thickness

\( \epsilon_m \)
eddies diffusivity for momentum conservation (dimensionless)

\( \gamma \)

specific heat ratio (1.4 for air)

\( \kappa \)
von Karman constant 0.41

\( \nu \)
absolute viscosity (LBF-F)

\( x^* \)
kinematic viscosity (FT²/S)

wake-strength parameter 0.5
density of fluid (LB'/FT)
shear stress (LBF/FT²)
cone half-angle (5°) (see Figure 3)

Subscripts

aw at adiabatic wall conditions
e at outer edge of boundary layer
FP flat plate
f at initial station of turbulent boundary layer calculations
cr calculated based on Preston-tube data
t total
w at the wall of physical cone
∞ at freestream conditions

Superscripts

| evaluated at the reference temperature of Smoler and Smith
(see Equation (2.9)) |
CHAPTER I

INTRODUCTION

In the area of fluid mechanics, the concept of boundary layer transition is still one of the major areas of research. It is an indisputable fact that a better understanding of boundary layer transition will further improve the progress of a wide variety of industries. For example, the auto industry is one of the major areas of industry that uses the concept of a boundary layer to design the shape of an automobile. The drag coefficient of an actual automobile may vary from a value of one to an ideal value of two tenths depending on the shape of the automobile. Achieving low values of drag coefficient reduces the rate of gas consumption of automobiles. Another major industry that heavily depends on the understanding and control of fluid movement is the aerospace industry. The aerospace industry uses the concept of the boundary layer to design aircraft which meet different missions. The design of wings and the prediction of important parameters such as lift, drag, and skin friction require a good understanding of the boundary layer. The concept of a boundary layer is also used in the turbomachinery industry and fluid power control systems.

The concept of a boundary layer was first introduced by Prandtl in 1904 (1). The term boundary layer is due to the fact that a thin layer of fluid near the boundary of a moving body is retarded by fluid viscosity. Boundary layer theory can be illustrated by considering the fluid
plate shown in Figure 1. First of all, one should recognize two distinct regions of the boundary layer: (1) a laminar boundary-layer region and (2) a turbulent boundary-layer region. The region that corresponds to transition from the laminar boundary layer to the turbulent boundary layer is referred to as the transition region.

The overall objective of this research project is to investigate the possibility of using pressure measurements, obtained with Pitot tubes resting on the surface of a ten-degree cone, to develop a method which could be used to characterize the flow quality of a given transonic wind tunnel. For a given transonic wind tunnel, the freestream turbulence and noise inside the wind tunnel cause appreciable errors and inaccuracies in the results of wind tunnel experiments. For example, if a given model is tested in different wind tunnels at ostensibly identical Mach number, unit Reynolds number, and dynamic pressure, different values of lift and drag, for example, are measured. Ideally, the measurement of different variables (e.g., lift and drag) for a given model should be independent of the wind tunnel used. However, in practice this is not the case. If there were a method that could be used to characterize the flow quality of existing wind tunnels, then the measurements of different parameters and variables for a given model would be consistent and independent of the wind tunnel that is used to carry out the experiments.

It is interesting to note that a satisfactory method has not yet been developed that can be used to characterize flow quality of a transonic wind tunnel.

The specific objective of the work presented herein is to correlate Preston-tube pressure measurements within turbulent boundary layers on a
Figure 1. Flat Plate Boundary Layer
sharp ten-degree cone to the corresponding theoretical values of the skin friction coefficient.

In 1975, tests were conducted at Ames Research Center of the National Aeronautics and Space Administration (NASA) to obtain the distribution of Preston-tube pressures along the surface of a sharp ten-degree cone for different freestream conditions. The Preston-tubes, which were used in these tests, were oval-shaped Pitot tubes. The cone and apparatus were primarily designed to detect boundary layer transition. The subject cone was designed by engineers at Arnold Engineering Development Center (AEEDC). For this reason, this cone is referred to as the AEEDC Boundary-Layer-Transition Cone. The instrumentation of the AEEDC Cone is shown in Figure 2 (2). The NASA Ames 11-ft Transonic Wind Tunnel (TWI), located at Moffett Field, California, was used to carry out these experiments.

A total of 19 cases are used to develop the correlation between Preston-tube measurements and the corresponding values of skin friction coefficient. The run numbers and the corresponding freestream conditions are presented in Table I.

The STAN-5 computer code, which was developed at Stanford University, is used to solve the boundary layer conservation of mass, momentum, and energy equations (3). The Wu and Lock (4) computer code, which calculates the inviscid pressure distribution, is used to specify the boundary conditions along the outer edge of the boundary layer. The Mini-Basic computer code has been developed by the author to obtain all the necessary input information for the STAN-5 computer code. Finally, the Preston-tube pressure measurements are correlated to the corresponding theoretical skin friction coefficient values by means of a least-squares technique.
NOTE: CS = Cone Station = Distance in inches aft of the nose

Source: Dougherty and Fisher (2, p. 1).

Figure 2. AEDC Boundary Layer Transition Cone
### TABLE I

**WIND TUNNEL CASES STUDIED TO DEVELOP THE CORRELATION EQUATION**

(NASA AMES 11'-7 TWT)

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<tr>
<th>Run No.</th>
<th>Case No.</th>
<th>$M_a$</th>
<th>$R_{e_f} \times 10^{-6}$</th>
<th>$d_m$</th>
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<tr>
<td>29.440</td>
<td>1</td>
<td>0.30</td>
<td>4</td>
<td>239</td>
</tr>
<tr>
<td>51.636</td>
<td>2</td>
<td>0.40</td>
<td>3</td>
<td>246</td>
</tr>
<tr>
<td>60.535</td>
<td>3</td>
<td>0.50</td>
<td>3</td>
<td>302</td>
</tr>
<tr>
<td>25.375</td>
<td>4</td>
<td>0.50</td>
<td>4</td>
<td>404</td>
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<tr>
<td>59.634</td>
<td>5</td>
<td>0.60</td>
<td>3</td>
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<td>23.346</td>
<td>6</td>
<td>0.60</td>
<td>1</td>
<td>477</td>
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<tr>
<td>40.547</td>
<td>7</td>
<td>0.60</td>
<td>5</td>
<td>586</td>
</tr>
<tr>
<td>58.633</td>
<td>8</td>
<td>0.70</td>
<td>3</td>
<td>408</td>
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<tr>
<td>70.725</td>
<td>9</td>
<td>0.70</td>
<td>1</td>
<td>538</td>
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<td>21.338</td>
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<td>543</td>
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CHAPTER II

BASIC TOOLS USED TO CARRY OUT

THE TURBULENT BOUNDARY

LAYER CALCULATIONS

Allen's Correlation

Allen's correlation is the primary tool that is used to start
the turbulent-boundary-layer calculations. Allen developed a set of
Preston-tube calibration equations which relate measurements of Preston-
tube pressure to measured values of turbulent skin friction. These
equations were developed for compressible turbulent boundary layers on
flat plates in supersonic flows. The test data were obtained for adia-
batic wall conditions. The resulting empirical Preston-tube calibration
equations were developed by Allen in 1977. The two calibration para-
eters $F_1$ and $F_2$ are defined by the following equations.

$$F_1 = \frac{e^2}{u_e} \cdot \frac{e}{e} \cdot r_D \cdot \frac{u_D}{u_e}$$  \hspace{1cm} (2.1)

$$F_2 = \sqrt{\frac{e^2}{u_e}} \cdot \frac{u_e}{e} \cdot r_D \cdot \frac{c_f}{U_e}$$  \hspace{1cm} (2.2)

Allen used a linear least-squares curve fit of the data, and the result-
ing linear equation was

$$F_1 = 5.85 \left( F_2 \right)^{1.132}.$$  \hspace{1cm} (2.3)

The experimental data were compared with the correlated values obtained
from Equation (2.3). The results were unsatisfactory at higher Reynolds numbers. For this reason, Allen tried a second-order least-squares curve fit. The equation for this fit was found to be

\[ \log_{10} F_2 = 0.01239 (\log_{10} F_1)^2 + 0.71814 \log_{10} F_1 - 3.4723 \]  

Again, the experimental data was compared with the values obtained from Equation (2.4). It was concluded that Equation (2.4) fits the data very well at both low Reynolds numbers and high Reynolds numbers. The root mean square (rms) error in scatter of skin friction was five and one half of one percent. A third-order least-squares curve fit was also obtained by Allen; however, no appreciable improvement in accuracy of the fit was observed.

As mentioned before, Equation (2.4) was found to be a better representation of the data when compared to Equation (2.3). For this reason, Equation (2.4) is used for the work presented herein.

There exists other Preston-tube calibration equations. For example, the Fenter-Stal-ac (5) calibration equation is

\[ F_3 = F_{ac} (1.35 \log_{10} F_2 - 1.77) \]  

where

\[ F_3 = \frac{\sigma \omega^2}{\pi} \frac{V}{u_0} \cdot \frac{\epsilon}{\delta} \cdot \sin \left( \frac{\lambda_2}{\sqrt{\lambda_2^2 + \lambda_3^2}} \right) \]  

Equation (2.5)

\[ F_4 = \sqrt{1 - \epsilon^2} \cdot \frac{\pi}{\lambda_2} \cdot \frac{\epsilon}{\delta} \]  

Equation (2.7)

The problem with the above calibration equation and other similar Preston-tube calibration equations is the fact that the data collapse is not good at higher Reynolds numbers.
Allen's correlation has some advantages compared to the other correlations. For example, Allen's correlation is simple, can be solved for \( c_e \) explicitly, and it fits the data over a large range of Reynolds numbers \( 3 \times 10^3 < Re_g < 8 \times 10^4 \).

As mentioned before, Allen's correlation was developed for circular Preston-tubes in supersonic flows with zero pressure gradient. However, this research focuses on subsonic flows about cones with favorable pressure gradients. Therefore, one might expect some errors when Allen's correlation is applied to the AEDC Cone data. Allen's correlation is primarily used to evaluate the skin friction coefficient at the starting point of the turbulent boundary layers. Furthermore, it is assumed that any errors at the start of the turbulent boundary calculations are lost as the boundary layer develops downstream.

Musker's Equation

Musker's (6) mean-velocity-profile equation is another primary tool that is used to start the turbulent-boundary-layer calculations. Musker's equation is used to estimate the velocity profile and the boundary layer thickness at the initial station which are required input to the STAN-5 computer code in order to start a calculation of the turbulent boundary layer.

Musker developed the mean-velocity-profile equation in 1972. This equation has the following form.

\[
\frac{u}{U_e} = \frac{1}{\gamma} \log \left( \frac{Y}{Y_e} \right) + \frac{1}{2} \left( \frac{Y}{Y_e} \right)^2 - \frac{1}{6} \left( \frac{Y}{Y_e} \right)^3 + \frac{1}{6} \left( \frac{Y}{Y_e} \right)^2 \left( 1 + \frac{1}{2} \right)
\]  

(2.8)

The recurrence values for \( \gamma \), 3, and \( \frac{1}{2} \) in the above equation are 0.41, 5.0, and 0.5, respectively. Musker's mean-velocity profile gives the
boundary layer profile formed on a smooth wall and is valid from the wall to the outer edge of the boundary layer. Furthermore, Musker's equation was derived for incompressible flows. The derivation and the detailed analysis of Equation (2.8) is given by Musker (6).

The primary advantage of using Equation (2.8) to estimate the initial velocity profile and the initial turbulent boundary layer thickness is the fact that the boundary conditions are satisfied both at the wall and at the outer edge. Another advantage of Equation (2.8) is its simplicity. Musker's equation expresses mean-velocity, \( u \), as an explicit function of \( y \); therefore, it is easy to apply. However, one has to be careful when using Equation (2.8). Equation (2.8) is derived based on the assumption that the flow is incompressible while the flows considered herein are compressible. Therefore, one should not apply Musker's mean-velocity-profile equation, as it appears in Equation (2.8), to a compressible flow field. However, with proper definition of fluid properties, one is able to apply Equation (2.8) to compressible flow fields. In order to do this, a reference temperature must be introduced. Obviously, the value of this reference temperature is higher than the edge temperature but less than the wall temperature. In other words, the selected reference temperature serves as an "average" value for temperature across the boundary layer. Then, all the fluid properties that appear in Equation (2.8) must be evaluated at this reference temperature. Consequently, fluid properties (e.g., density and viscosity) evaluated at the selected reference temperature serve as the "average" values for the fluid properties across the boundary layer. Thus, when the reference kinematic viscosity is used in Equation (2.8), Musker's mean-velocity-profile equation can be applied to compressible, turbulent boundary layers.
The reference temperature derived by Sommer and Snort (1) for compressible turbulent boundary layers has been selected for use herein. This reference temperature is calculated via the following equation.

\[ T^* = T_e \left(0.55 + 0.035 \frac{M_e^2}{2}\right) + 0.45 T_w \]  

(2.9)

For the wind-tunnel tests, it is known that wall temperatures are very close to the adiabatic values given by

\[ T_{ew} = T_e \left(1 - \frac{M_e^2}{2}\right) \]  

(2.10)

As discussed above, Musker's mean-velocity profile is used to estimate the initial turbulent-boundary-layer thickness and the corresponding velocity profile at the initial station. The initial turbulent-boundary-layer thickness is easily estimated by imposing the boundary-layer-edge conditions on Equation (2.8). At the outer edge of the boundary layer, the following boundary conditions apply

\[ u = U_e \]  

(2.11)

and

\[ y = \cdot \]  

(2.12)

The following equation is obtained by imposing the outer-edge conditions to Equation (2.8).

\[ \frac{U_e}{U} \exp \left[ \frac{u}{U} - 3 - \frac{u^2}{2} \right] \cdot \left( \frac{u}{U} \right) \]  

(2.13)

With the known edge velocity and the turbulent-boundary-layer thickness, one can easily use Equation (2.3) to estimate the initial velocity profile of the turbulent boundary layer. This velocity profile is input to the STAN5 computer code.
Wu and Lock Computer Code

The Wu and Lock (4) computer code is another basic tool that is needed to calculate the turbulent boundary layer. This computer program was developed by Wu and Lock at the University of Tennessee Space Institute.

For a given Mach number, cone semivertex angle, azimuth angle, and angle of attack one can use the Wu and Lock computer code to obtain the inviscid pressure distribution along a ray of a sharp-nose cone. Figure 3 presents the Wu and Lock inviscid pressure distribution for a 10-degree cone at zero angle-of-attack and transonic Mach numbers. Along with the pressure distribution, the Wu and Lock computer printout includes the inviscid velocity distribution along the surface of the cone. For a detailed analysis of the development of the Wu and Lock computer code one should refer to Wu and Lock (4).

The rest of this section includes a brief discussion of how the Wu and Lock computer program is used to obtain the inviscid boundary conditions along the surface of the cone. The match point is defined to be the estimated location of the initial station at which a fully-developed turbulent boundary layer begins. For reasons that will become apparent in the next chapter, the inviscid boundary conditions ahead of the tip of the physical cone must be obtained. For this reason, the velocity distribution upstream of the match point is obtained by a simple linear extrapolation of the Wu and Lock velocity distribution upstream of the match point. Unfortunately, the Wu and Lock computer output does not provide the inviscid velocity distribution at evenly spaced locations along the axis of the cone. Whereas, the STAB-5 computer code works better when the inviscid boundary conditions are evenly spaced. From previous Oklahoma
Figure 3. Inviscid Pressure Distribution About a 10° Cone (Wu & Lock)
University (OSU) work, the inviscid boundary conditions are evenly spaced by means of a simple computer program. This program has been modified by the present author so that it accepts the data directly from the \textit{HU} and Lock computer printout. This modified program is used as one of the subroutines in the Mini-Basic computer code. This is done for two reasons. Firstly, it is desirable to obtain the edge velocity directly from the \textit{HU} and Lock data. This saves time and eliminates possible errors that may be introduced by obtaining the edge velocity for each single \textit{STAN-5} computer run by means of hand calculations. The second reason is that this subroutine uses other information within the Mini-Basic computer code, and the printout is in the desired format that can directly be input to the \textit{STAN-5} computer code.

\textbf{STAN-5 Computer Code}

The \textit{STAN-5} computer code is the primary boundary-layer calculation tool that is used in this project (3). This computer code is used to solve the boundary layer conservation equations, and it is specifically used to estimate the theoretical, skin friction coefficient. The \textit{STAN-5} computer program was developed by Crawford and Kays (3) at Stanford University. This computer code is an extension of work originally done by Patankar and Spalding (7) in 1967. In this section, it is intended to give a brief description of the operation of \textit{STAN-5}. A detailed analysis of the theory behind the \textit{STAN-5} computer code is beyond the scope of this report. For a complete understanding of the \textit{STAN-5} computer code, one should consult Patankar and Spalding (7). However, if one is interested only in the basics of how to use the program, he should consult the \textit{STAN-5 Manual} (3). This manual discusses the theory in
reasonable detail. Furthermore, it gives adequate instructions to properly use this sophisticated computer code. The following discussion, which is a brief description on the operation of the STAN-5 computer code is based on the information given in the STAN-5 Manual.

The conservation equations of a given boundary layer are impossible to solve analytically. For this reason, with the progress of the technology of digital computers, it has become routine to use finite-difference techniques to solve the boundary layer equations. The STAN-5 computer program is such a program and employs difference methods to solve the conservation of mass, momentum, and energy equations. Some of the basic features of STAN-5 computer code are discussed in this part of the report.

The STAN-5 computer code uses the concept of eddy diffusivity for momentum conservation, \( \varepsilon_m \), in order to solve for the Reynolds shear stress. There are three options for modeling the eddy diffusivity which appears in the conservation of momentum equation. The first option is to use the Prandtl mixing-length model. The second option is to use the constant eddy diffusivity model. The turbulent-kinetic-energy model was selected for use in this project. The STAN-5 Manual suggests that the turbulent-kinetic-energy model for \( \varepsilon_m \) should be used if there are significant amounts of freestream turbulence which is one of the primary sources of inaccuracy in wind-tunnel experiments.

Computation of the flow field near the wall is the last feature of STAN-5 that is discussed here. The STAN-5 computer code uses the Couette flow equations to compute the flow field near the wall region. In order to achieve this, STAN-5 has two options. The first option numerically integrates the Couette flow equations over the region of high velocity...
gradient. This option, which is referred to the "Wall Function," saves computation time. The second option, which bypasses the "Wall Function," continues the finite difference equations down to the wall with a progressively finer spacing. Although the STAN-5 manual suggests bypassing the "Wall Function" only for flows with large pressure gradients, the wall function is bypassed for the present work because this results in a smoother distribution of skin friction.

There are a number of flag parameters that must be input to the STAN-5 computer code. These flag parameters are fully explained in the STAN-5 manual. Besides these flag parameters, the initial static pressure, the initial velocity profile, and the inviscid boundary conditions along the outer edge of the boundary layer must be input.

The initial static pressure is obtained from the following equation.

$$p_{e,i} = \left( \frac{1 + 0.2M^2_{e,i}}{1 + 0.2M^2_{e,i}} \right)^{1/4} - 1$$  \hspace{1cm} (2.14)

However, in order to solve for $p_{e,i}$, one has to know $M_{e,i}$. This Mach number is related to velocity and temperatures by the following equations.

$$U_{e,i} = \frac{M_{e,i} \sqrt{g \rho \rho_e}}{e}$$  \hspace{1cm} (2.15)

$$e = T_{e,i} \left( 1 + 0.2 \frac{M^2_{e,i}}{e} \right)^{-1}$$  \hspace{1cm} (2.16)

$U_{e,i}$ is obtained from the Wu and Lock computer code. With the known value of $T_{e,i}$, one can combine Equations (2.15) and (2.16) to solve for $M_{e,i}$. With the known value of $M_{e,i}$, Equation (2.14) is used to solve for $p_{e,i}$. Equation (2.9) is used to specify the mean-velocity-profile
at about 40 points across the boundary layer. Finally, the proper inviscid boundary conditions, which are obtained from the JU and Lock computer code, are input to the STAN-5 computer code.
CHAPTER III
THE METHOD DEVELOPED TO COMPLETE
THE TURBULENT BOUNDARY
LAYER CALCULATIONS

A unique method has been developed to complete the turbulent-boundary-layer calculations. In this chapter an overall perspective of this method is presented. This chapter discusses the theory behind the method used to execute the turbulent-boundary-layer calculations. The detailed analysis of the governing equations of this method is presented in the next chapter. Furthermore, Appendix A presents the step-by-step procedure used in the turbulent-boundary-layer calculations.

At this point, two sets of information are available. The first set of information is the primary variables of the wind tunnel for a given run. The primary variables for a given run include freestream Mach number, unit Reynolds number, and the freestream dynamic pressure. The second set of information is the Preston-tube pressure distribution along the surface of the cone. Determination of the location of the imaginary point at which the turbulent boundary layer has zero thickness and the location of match point are necessary information that must be obtained first. The imaginary location at which zero thickness occurs is defined to be the virtual origin of the turbulent boundary layer. The variable $x_{ve}$ is defined to be the distance between the match point and virtual origin. This terminology is defined in Figure 1. Note that the location
\[ d = \frac{(0.5)}{\cos 5^\circ} \text{ ft} \]

**Figure 4.** Terminology for Setting Up STAN-5 Calculations
of the virtual origin may be downstream as well as upstream of the tip of
the physical cone. The location at which the maximum Preston-tube pres-
sure occurs could be used as the match point. However, this is not a
valid choice because at this location the boundary layer may still be
affected by transition. For this reason, the following method is used
to assure that the match point is in the fully-developed turbulent-bound-
cary-layer region. Figure 5 shows the Preston-tube pressure distribution
along the surface of the cone for a typical case. The point at which the
Preston-tube pressure distribution curve corresponding to the turbulent
boundary layer diverges from that of the rest of the boundary layer is
defined to be the match point. A French curve may be used to do this
task. This is indicated by dashed lines in Figure 5. In order to locate
the virtual origin, Allen's correlation is used to obtain an estimation
of skin friction coefficient at the match point. Note that this is just
an estimation. Then, the flat plate equations are used to estimate the
location of the virtual origin on a flat plate. This result is then
transformed by using Teterin's (8) transformation to obtain the corre-
sponding location of the virtual origin on the ten-degree cone.

The next step is to set up STAN-5 and start the boundary layer cal-
culations. As was mentioned before, the Hu and Lock computer code and
Musher's mean-velocity profile are used to define the inviscid boundary
conditions and the initial velocity profile, respectively. In order to
save computer time, STAN-5 is run with the initial station located no
more than six inches ahead of the physical cone. This is an axial dis-
tance. If the location of the virtual origin is such that

$$\rho_{\infty} - \rho_{0} - 3.5/\cos \theta \leq 0 \text{ ft}$$
Figure 5. Determination of the Location of the Match Point and the Corresponding Preston-Tube Pressure

X, DISTANCE ALONG SURFACE OF 10° CONE
then the initial station for beginning computations of the boundary layer is located at one inch downstream of the virtual origin. In this case surface distance is used. It should be mentioned that there are no well-defined criteria for choosing the initial station at which the turbulent-boundary-layer calculations begin. The distances of six inches upstream of tip of the cone or one inch downstream of the virtual origin are based on past experience with STAN-5. Starting STAN-5 very close to the virtual origin uses too much computer time if the location of the virtual origin is located a distance far ahead of the tip of the cone. As the boundary layer develops, any errors at the beginning of the calculations are normally lost as the conservation equations are solved downstream.

The cone is assumed to be an axisymmetric body. The inviscid boundary conditions along the surface of the cone are obtained from the Wu and Lock computer code and are input to STAN-5 by specifying the velocity at a series of points along the surface of the cone and the corresponding radius of the body at those locations. Due to the structure of STAN-5, the virtual origin is the reference point from which distance and radius are measured. From Figure 4, it is apparent that the radial distance is equal to the surface distance times the sine of the cone half-angle. This is the method used to model the cone. However, one could argue this method is not valid due to the fact that the specified radius of a point on the cone corresponds to the radius of the imaginary cone and not to that of the physical cone. Consequently, one could conclude that transverse curvature effects are not modeled correctly. The fact is that transverse curvature effects become important when the radius of the body is of the same order of magnitude as that of the boundary layer thickness.
transverse curvature effects become even more important when the radius of the body is much less than the turbulent-boundary-layer thickness. None of the above cases apply here. In fact, the ratio of the boundary layer thickness to the radius of the body is rather small. Thus, transverse curvature effects are not expected to be a significant source of error in the present work. In order to check this, the cone was modeled using two other methods for a sample run. The sample run was selected as being a worst case. As was mentioned above, the higher the ratio of the turbulent-boundary-layer thickness to the radius of the body the higher is the error in the skin-friction calculations. For this reason, the case that has a high Mach number and low unit Reynolds number was chosen. This corresponds to Run Number 56.631 which was selected to check the significance of any errors introduced by improper modeling of body radius. The first method simply lets the radial distance correspond to the physical cone rather than the imaginary cone. This is possible since the virtual origin is downstream of the tip of the cone for this particular case (see Appendix B, Table XVIII). The second method is to model the cone as a cylinder upstream of the match point, and for the points downstream of the match point let the radial distance correspond to the physical cone. STAN-5 was run twice in order to calculate the skin friction coefficient along the surface of the cone with these two different modeling procedures. The results are tabulated in Table II. The maximum error due to modeling the radius of the cone is about three percent. It should be noted that this is the worst case. In all the other other cases under study, the ratio of the turbulent-boundary-layer thickness to the radius of the body is smaller than that of this sample run. In summary, the method used to model the cone in
### TABLE II

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1(=X_{mi}) - Distance along the surface of the cone measured from tip of the cone, ft.

2 - Skin friction coefficient obtained by the method used to model the cone to carry out the skin friction calculations for all the cases (radial distance corresponds to the imaginary cone).

3 - Skin friction coefficient obtained by letting the radial distance correspond to the physical cone rather than imaginary cone.

4 - Skin friction coefficient obtained by modeling the cone as a cylinder upstream of match point, and for the points downstream at match point letting the radial distance correspond to the physical cone.
well within the accuracy of the wind-tunnel data and the numerical techniques being used.

After completing tasks of modeling and obtaining other necessary information that must be input to STAN-5, the turbulent-boundary-layer calculations are initiated. The skin friction coefficient at the match point is calculated by STAN-5 and is compared to the value obtained from Allen's correlation for the same local flow conditions. If the calculated skin-friction coefficient by means of STAN-5 is larger (smaller) than that calculated by means of Allen's correlation, then it is concluded that the turbulent boundary layer at the match point is too thin (thick). So, the virtual origin must be shifted forward (backward) in order to obtain a thicker (thinner) boundary layer. A one-seventh power law is used to relocate the virtual origin.

\[
x_{eq,1} = \left( \frac{c_f,2}{c_f,1} \right)^{1/7}
\]

This process is continued until the skin friction coefficient calculated by STAN-5 computer code is within plus or minus a half of one percent of that calculated by Allen's correlation. At that point, it is concluded that an acceptable initial velocity profile is obtained. Next the STAN-5 computer code is run to solve the boundary layer equations along the surface of the core all the way up to the point where the wind-tunnel data ends. This procedure is repeated for all the cases. Then, for each case, a modified version of STAN-5 is run to obtain the effective height of the probe. The effective height of the probe is the distance from the wall at which the total pressure within the theoretical boundary layer equals the measured Preston-tube pressure. The effective height of the probe,
\( y_{\text{eff}} \), is nondimensionalized by the following relation.

\[
  k_{\text{eff}} = \frac{y_{\text{eff}}}{h/2}
\]  

(3.2)

In other words, \( k_{\text{eff}} \) is a measure of the location of the effective center of the probe.

Obtaining the values of \( k_{\text{eff}} \) concludes the turbulent-boundary-layer calculations. The values of total Preston-tube pressure, effective center of the probe, skin friction coefficient, location of match point, and the location of the virtual origin is tabulated in Appendix B for 19 different wind-tunnel flow conditions.
CHAPTER IV
DEVELOPMENT OF THE GOVERNING EQUATIONS

So far, the basic procedures, which were followed during this research project, have been described. In this chapter, additional details of the method described in Chapter III are presented.

For a given case, the first step is to calculate the freestream thermodynamic and kinematic properties of the fluid (air). This is a fairly simple task since the primary wind-tunnel flow parameters are given. These parameters are defined as follows.

\[ q = \frac{1}{2} \rho U_a^2 \]  
(4.1)

\[ q = \frac{U_a}{\sqrt{\gamma g_c \gamma}} \]  
(4.2)

\[ \text{Re}_c = \frac{\rho a}{\gamma} \]  
(4.3)

From Equation (4.2) one can solve for \( U_a \) and substitute the result into Equation (4.1). The resulting equation is

\[ q = \frac{1}{2} \frac{\rho a}{\gamma} \left(\frac{\gamma g_c \gamma}{\sqrt{\gamma g_c \gamma}}\right)^{1/2} \]  
(4.4)

The equation of state for a thermally perfect gas is

\[ P = \gamma R_T \rho \]  
(4.5)
Substituting Equation (4.5) into Equation (4.4) and solving for freestream static pressure, $P_\infty$, results in the following relation.

$$P_\infty = \frac{2q_\infty}{\gamma M_\infty^2}$$ \hspace{1cm} (4.6)

The freestream total pressure, $P_{t,\infty}$, is obtained from the following isentropic relation.

$$\frac{P_{t,\infty}}{P_\infty} = (1 + \frac{\gamma - 1}{2} M_\infty^2)^{\gamma/\gamma-1}$$ \hspace{1cm} (4.7)

Now substitute Equation (4.6) into Equation (4.7) and solve for the freestream total pressure, $P_{t,\infty}$.

$$P_{t,\infty} = (1 + \frac{\gamma - 1}{2} M_\infty^2)^{\gamma/\gamma-1} \left(\frac{2q_\infty}{\gamma M_\infty^2}\right)$$ \hspace{1cm} (4.8)

In order to obtain the freestream total temperature, multiply Equation (4.2) by Equation (4.3), and divide the resulting equation by Equation (4.1). This results in the following equation.

$$\frac{M_{\infty}^2 \rho_{\infty}}{q_\infty} = \frac{U_\infty}{\sqrt{\gamma R T_\infty}} \frac{P_\infty}{U_\infty^2} \frac{2}{P_\infty} \frac{U_\infty^2}{\left(\frac{2q_\infty}{\gamma M_\infty^2}\right)^{1/2}}$$ \hspace{1cm} (4.9)

The Sutherland's (1) relation for absolute viscosity, $\nu$, is

$$\nu = \left(2.27 \left(\frac{T_\infty}{198.8}\right)^{1.5}\right) x 10^{-8} \hspace{1cm} (4.10)$$

When Equation (4.10) is substituted into Equation (4.9) and rearranged, the following equation is obtained.
Equation (4.11) is an explicit equation in $T_\infty$, and it can easily be solved for the freestream static temperature. The freestream total temperature is obtained finally from the following isentropic equation.

$$\frac{M_\infty^2}{q_\infty} \left( \frac{Re_{fr}}{q_\infty} \times \frac{2.27 \times 10^{-8}}{2} \times \frac{\gamma}{\gamma-1} \right) T_\infty^2 - T_\infty - 198.6 = 0 \quad (4.11)$$

The equation of state (Equation 4.5) is used to calculate density of the air. The Sutherland's relation for absolute viscosity, Equation (4.10), is used to calculate absolute viscosity. The kinematic viscosity, $\nu$, is defined as the ratio of absolute viscosity to density.

The second step is to use Allen's correlation to estimate the skin friction coefficient at the match point. In order to solve Allen's Preston-tube calibration equations (2.1 and 2.2), the following parameters must be calculated: (1) edge temperature, (2) edge pressure, (3) edge velocity, (4) reference temperature, (5) velocity based on Preston-tube data, and (6) Reynolds number based on the diameter of a circular Preston probe.

Before solving for the edge temperature, one has to solve for the edge Mach number. In order to solve for this Mach number, the following procedure should be followed. The pressure coefficient is defined as follows.

$$c_p = \frac{p_e - p_\infty}{\frac{1}{2} \rho_\infty U_e^2} = \frac{p_e - p_\infty}{q_\infty} \quad \ldots (2.3)$$
By rearranging terms in Equation 4.13, one obtains:

\[
\frac{a_{e}}{a_{m}} = 1 + \frac{P_{e}}{P_{m}} - \frac{P_{e}}{P_{m}}.
\]  

(4.14)

The following equation is obtained by substituting appropriate isentropic relations for the pressure ratios occuring in Equation (4.14).

\[
\frac{a_{e}}{a_{m}} = \frac{1 + 0.2 M_{e}^{2}}{1 + 0.2 M_{e}^{2}} (\gamma - 1)
\]  

(4.15)

By rearranging terms in Equation (4.15), one obtains:

\[
M_{e} = \left[ -5 + 5 (1 + 0.2 M_{e}^{2}) (1 + \frac{a_{e}}{a_{m}} 1^{\gamma - 1}) \right]^{\frac{1}{2}}
\]  

(4.16)

Note that \( c_{p} \) is obtained from the Wu and Lock computer code. With the known edge Mach number, \( M_{e} \), one can use the following isentropic relation to solve for the edge temperature, \( T_{e} \):

\[
T_{e} = T_{t, x} (1 + 0.2 M_{e}^{2})^{-1}
\]  

(4.17)

With the known values of \( c_{p} \), \( P_{m} \), and \( a_{e} \), Equation (4.13) can be used to calculate the edge pressure. The edge velocity can either be obtained from the Wu and Lock computer code, or it can be calculated by employing an equation similar to Equation (4.2), i.e.,

\[
U_{e} = M_{e} (\gamma R_{e} T_{e})^{\frac{1}{2}}
\]  

(4.18)

As discussed before, the Scorrer and Short relation for reference temperature, Equation (2.9), is used to calculate the reference temperature, \( T \).
The velocity based on the Preston-tube data is calculated via the isentropic relations. Starting with Equation (4.2), the following equation can be obtained for $U_{pt}/U_e$.

\[
\frac{U_{pt}}{U_e} = \frac{M_{pt}}{M_e} \frac{\sqrt{T_e}}{\sqrt{T_{pt}}} = \frac{M_{pt}}{M_e} \frac{\sqrt{T_{t,pt}}}{\sqrt{T_{t,e}}} \frac{\sqrt{T_{t,pt}}}{\sqrt{T_{t,e}}}
\]

(4.19)

\[
M_{pt} = \frac{M_e (1 + \frac{\gamma - 1}{2} M_e^2)^{\frac{\gamma}{\gamma - 1}}}{1 + \frac{\gamma - 1}{2} M_{pt}^2}
\]

and

\[
\frac{p_{pt}}{p_{t,pt}} = (1 + \frac{\gamma - 1}{2} M_{pt}^2)^{\frac{1}{\gamma - 1}}
\]

(4.20)

Next, one can use Equation (4.20) to solve for $M_{pt}$.

\[
M_{pt} = \left\{ \frac{2}{r - 1} \left[ \left( \frac{p_{pt}}{p_{t,pt}} \right)^{\gamma - 1/r} - 1 \right] \right\}^{1/2}
\]

(4.21)

In summary, Equation (4.21) is used to calculate $M_{pt}$ and with the known value of $M_{pt}$, Equation (4.19) is used to obtain $U_{pt}$.

The Reynolds number based on probe diameter, $R_D$, is the final piece of information that is needed to solve Allen's calibration equations.

The Reynolds number based on probe diameter, $R_D$, is defined as

\[
R_D = \frac{U_e D_e}{v_e}
\]

(4.22)

The only unknown in the above equation is the diameter of the probe's face.

Allen's Preston-tube pressure measurements were carried out by means of circular Preston tubes. In contrast, the measured Preston-tube pressures for this project were obtained by means of oval-shaped Preston tubes. For
this reason, it is necessary to define an "equivalent" probe diameter, \( D_{eq} \), which can be used in place of the diameter which appears in Allen's correlation. Following the suggestion of Patel (9), the diameter of a circular probe is related to the effective height of the probe by

\[
D = \frac{2y_{eff}}{k_{eff}}.
\]

(4.23)

Patel suggests a value of 1.3 for \( k_{eff} \) for a circular Preston-tube. If one sets \( k_{eff} = 1.3 \) in Equation (4.23) the following equation is obtained.

\[
D = 1.54 y_{eff}
\]

(4.24)

In the case of non-circular probes \( y_{eff} \) is defined as follows.

\[
y_{eff} = \frac{h}{2} \left( k_{eff} \right)
\]

(4.25)

In this equation \( h \) is the maximum external height of the probe's face. The probe used during the NASA Ames wind-tunnel tests had a height of 0.0097 inches. Substituting Equation (4.25) into Equation (4.24) leads to the definition of an equivalent diameter for the oval-shaped probe used during the NASA Ames tests.

\[
D_{eq} = (0.0075) k_{eff}
\]

(4.26)

In order to obtain a reasonable value for \( k_{eff} \) at the start of the turbulent-boundary-layer calculations, the following estimation procedure was used. From the previous work done by Reed and Abu-Mostafa (10), the values of \( k_{eff} \) along the surface of the cone for the laminar boundary layer are available. For each case, a straight-line least-squares curve fit was obtained that correlates \( k_{eff} \) to distance along the surface of the
cone. Since this fit is only valid in the laminar boundary-layer region, it is not correct to use this fit and blindly apply it to turbulent-boundary-layer calculations. However, the laminar values of $k_{eff}$ can be employed by assuming the locations in the laminar and turbulent boundary layer, which have the same Preston-tube pressure, have approximately the same value of $k_{eff}$. Thus, the laminar value of $k_{eff}$ at the location which has the same Preston-tube pressure as measured within the turbulent boundary layer at the match point, is used to estimate an equivalent diameter for use in Allen's correlation. With the known value of $D_{eq}$, Equation (4.22) is used to calculate $r_d$.

All the necessary information to solve for skin friction coefficient is then available. Equation (2.1) is used to solve for the calibration parameter $F_1$. Next, Allen's correlation Equation (2.4), is used to solve for the calibration parameter $F_2$. Finally, the skin friction coefficient is calculated from Equation (2.2).

The third step is to estimate the location of the virtual origin. Unfortunately, the exact location of the virtual origin along the surface of a cone cannot be obtained. However, the flat plate equations may be used to estimate an approximate value of $X_{eq}$ on a flat plate. Then, the flat plate $X_{eq}$ may be converted to the cone $X_{eq}$. The following equation is used to estimate the flat plate $X_{eq}$:

$$X_{eq,fp} = \left(\frac{g_c}{0.08 - \frac{U_e}{c_f}}\right) \left(\exp\left(\frac{0.455 c_r}{c_f}\right)\right)^{\frac{1}{4}} \tag{4.27}$$

Equation (4.27) is based on an empirical skin friction formula for flat-plate turbulent boundary layers in incompressible flow, viz.,
The following relation between wetted length on a flat-plate and a cone has been suggested by Tetervin \((8)\) in the case of equal skin friction at the two \(X\) locations:

\[
X_{\text{eq}} = (2.26B) \left( X_{\text{eq}_{\text{fp}}} \right) \tag{4.29}
\]

Once the location of the virtual origin is fixed, the inviscid velocity from the Wu and Lock computer program is extrapolated forward from the match point to obtain the edge velocity at the initial station at which the turbulent-boundary-layer calculations are started with STAN-5. As previously discussed, the remainder of the inviscid boundary conditions are obtained from the Wu and Lock computer code.

The final step is to use Musker's mean-velocity-profile, Equation \((2.8)\), and calculate the initial velocity profile of the turbulent boundary layer. At this point, all the necessary information that must be input to STAN-5 is available.

The procedure discussed above is automated by means of the MINI-Basic computer code. This code is fully documented in Appendix A.
CHAPTER V

ANALYSIS OF DATA AND THE
CORRELATION EQUATION

Once the turbulent-boundary-layer calculations are completed, all the necessary information to correlate the Preston-tube pressure to the corresponding theoretical values of skin friction coefficient are available. Based on the work done by Reed and Abu-Mostafa (10), on laminar boundary layers, the following equation is assumed for this correlation:

\[ \gamma^* = A_1(X^*)^2 + B_1(X^*) + C_1(T^*) + D_1 \quad (5.1) \]

where

\[ Y^* = \log_{10} \left( \frac{\nu^2}{\nu^*} \frac{\rho_*}{\rho} \right) = \log_{10} \left( \frac{U_* y_{eff}/\nu}{\nu} \right) \quad (5.2) \]

\[ X^* = \log_{10} \left( \frac{U_* y_{eff}/\nu}{\nu} \right)^2 \quad (5.3) \]

and

\[ T^* = \log_{10} \left( \frac{T^*/T_e}{T_e} \right) \quad (5.4) \]

The correlation parameters \( X^* \) and \( Y^* \) are basically of the same nature as the correlation parameters defined by Allen. From the work done by Reed and Abu-Mostafa, it was found that the effective center of a Pitot probe was a function of \( U_* \), \( \rho_* \), \( \nu^* \), and \( \rho \). Furthermore, it was learned that accounting for the variation of the effective center of the probe resulted...
in less scatter of skin friction coefficient in the laminar boundary layer region. For this reason, unlike \textit{allen}, the variation of the effective height of the probe is included in the calibration parameters.

The following method is used to discard the data points that should not be included in the development of a correlation. The values of $k_{\text{eff}}$ along the surface of the cone are tabulated in Appendix B for the various wind-tunnel flow conditions. It should be noted that Reed and Abu-Mostafa correlated skin friction coefficient to the corresponding Preston-tube pressure measurements in laminar boundary layers. Their plot of $k_{\text{eff}}$ vs. $U_xh/\nu_w$ for several cases is shown in Figure 6. This figure corresponds to the laminar boundary layer studies. From this data, it is concluded that the values of $k_{\text{eff}}$ should increase as $U_xh/\nu_w$ decrease. This means the values of $k_{\text{eff}}$ should increase as the surface distance increases. Furthermore, for a given Reynolds number per foot, the values of $k_{\text{eff}}$ decrease with increasing Mach number. The distributions of $k_{\text{eff}}$ for Run Numbers 57.632 and 29.440 do not exhibit this behavior. Apparently, the $k_{\text{eff}}$'s for these two runs were in error. At the completion of this work, it was found that the Preston-tube pressures for these two runs were read incorrectly. Figure 7 is the corrected laminar $k_{\text{eff}}$ distribution. It might be expected that the $k_{\text{eff}}$ distribution along the surface of the cone should have the same trend as that of laminar boundary layer studies. However, this is not exactly true. From tabulated results of $k_{\text{eff}}$, it is observed for most of the cases that the values of $k_{\text{eff}}$ decrease until they reach a minimum at a location downstream of the match point. Then a continuous increase in $k_{\text{eff}}$ is observed. Consequently, it is concluded that the data points preceding the minimum value of $k_{\text{eff}}$ should not be included.
Figure 6. Variation of Effective Height of Probe in Laminar Boundary Layers.
Figure 1. The Corrected Variation of Effective Height of Probe in Laminar Boundary Layers
in the correlation equation. The fact of the matter is that the decrease in \( k_{eff} \) downstream of the match point is probably caused by errors in the estimated skin friction coefficient at the match point, i.e., Allen's correlation and the equivalent diameter does not provide the correct skin friction at the match point. However, it is known that the errors in this estimation are lost somewhere downstream of the match point. This is assumed to occur at the location where \( k_{eff} \) exhibits a minimum. So, for a given case, all the data points ahead of the minimum value of \( k_{eff} \) are discarded. In other words, only the data points that show a continuous increase in the values of \( k_{eff} \), following the minimum value of \( k_{eff} \), are set aside for correlation purposes. Figure 8 and Figure 9 illustrate examples of this procedure. Cases that exhibit a behavior similar to Figure 8 are not included in the correlation equation. The cases that exhibit a behavior similar to Figure 9 are used to develop the correlation equation, and only the points that show a continuous increase in the \( k_{eff} \) values following the minimum value of \( k_{eff} \) are used to obtain the correlation. By employing this method, it is found that Run Numbers 70.726 and 15.231 should also not be used in developing the correlation equation. The distribution of the effective center of the probe vs. \( U_{e} h/\nu_{\infty} \) for 17 cases is shown in Figure 10. As is shown in Figure 10, the distribution of effective center of the probe for Run Number 72.748 is much closer to Run Number 21.318 than it is to Run Number 19.289. Since Run Numbers 72.748 and 19.289 have the same freestream flow conditions (i.e., \( M_{\infty} = 0.8 \) and \( \text{Re}_{\text{e}} = 4 \times 10^{5} \)) except for slight difference in freestream dynamic press, \( \omega_{\infty} = 12 \text{ lb} \cdot \text{ft}^{-2} \), the distribution of the effective center of the probe for these two cases is expected
RUN NO. 15.231
\[ M_{\infty} = 0.95 \]
\[ Re_{\infty} = 4 \times 10^6 \]
\[ q_{\infty} = 693 \text{ psf} \]

Figure B. Criterion for Discarding Unsuitable Cases
Figure 9. Criterion for Gathering Suitable Data Points

RUN NO. 40.547

$M_\infty = 0.60$

$Re_{fl} = 5 \times 10^6$

$q_\infty = 586$

DATA POINTS SUITABLE FOR CORRELATION

UNSUITABLE DATA POINTS
Figure 10. Variation of the Effective Height of Probe in Turbulent Boundary Layers.
to be much closer together. Furthermore, by studying Figure 10, it is apparent that the spacing of the distributions of the effective center of the probe among Run Numbers 72.748, 21.318, and 19.289 does not match with the rest of the $k_{eff}$ distributions. However, the spacing of the $k_{eff}$ distributions for Run Numbers 21.313 and 19.289 is similar to the rest of the run numbers. For this reason Run Number 72.748 is not included in the development of the correlation equation. In summary, a total of sixteen cases have been used to develop the correlation equation, and 259 data points have been set aside to obtain the correlation equation. A second-order least-squares curve fit to this data results in the following correlation equation.

$$Y^* = (0.0272) (X^*)^2 + (0.5337) (X^*) + (0.1140) (T^*) - 0.5419 \quad (5.5)$$

Figure 11 is the plot of $Y^*$ vs. $Z^*$ for the individual wind-tunnel data points where $Z^*$ is defined as follows.

$$Z^* = \frac{(0.2272) (X^*)^2 + (0.5337) (X^*) + (0.1140) (T^*)}{(5.6)}$$

The corresponding rms value of $Z_f$ is 1.125 percent. Figure 12 shows the narrow range of scatter in skin friction coefficient. The scatter in skin friction coefficient is very satisfactory, and it is comparable to the Preston-tube calibrations obtained by Patel (9) for incompressible pipe flows. The coefficient of $T^*$ in the correlation Equation (5.5) is very small and a second correlation equation was obtained by neglecting the effects of variable properties across the probe's face. This equation has the following form.

$$Y^* = (0.0195) (X^*)^2 + (0.6124) (X^*) - 3.7329 \quad (5.7)$$
Figure 12. Preston-Tube/Turbulent-Skin-Friction Correlation Based on a Variable Effective Probe Height

\[ Y^* = Z^* - 0.5419 \]
Figure 12. Deviation of Predicted Skin Friction Coefficient by Equation (5.9) from Theoretical Values
The corresponding rms value of $c_f$ is 1.175 percent. As expected, slightly higher scatter in the skin friction coefficient is observed when the effect of variations in temperature across the probe's face are ignored.

The boundary layer calculations have been repeated for two sample cases using the new correlation equation to estimate skin friction at the match point. One of these cases is Run Number 15.231 which was not included in the development of the correlation equation. The second typical case is Run Number 40.549 which was included. The skin friction coefficient at the match point is estimated by means of Equation (5.5). Then STAN-5 is set up to again solve the boundary-layer equations. Figure 13 and Figure 14 each show two sets of skin friction coefficients vs. surface distance. One distribution of skin friction coefficient corresponds to the estimation of $c_f$ at the match point by means of the new correlation, and the other set of data corresponds to the estimation of $c_f$ at the match point by means of Allen's correlation. Figure 14 further verifies that the method used to calculate skin friction coefficient is correct. Although in the example Allen's correlation underestimates the value of $c_f$ at the match point, the values of $c_f$ eventually converge as the boundary layer develops. The variation of effective center of the probe vs. surface distance along the cone for the two sample cases is presented in Figure 15 and Figure 16. Figures 17 and 18 show the corresponding $k_{eff}$ values plotted vs. $U_h/w$. Here again one distribution corresponds to the estimation of $c_f$ at the match point by means of the new correlation equation, and the other distribution corresponds to the estimation of $c_f$ at the match point by means of Allen's correlation.

Based on these figures, it is concluded that the distribution of $k_{eff}$
Figure 13. Skin Friction Distribution Along the Surface of the Cone for Run Number 15231
Figure 14. Skin Friction Distribution Along the Surface of the Cone for Run Number 40.549

RUN NO. 40.549

\( M_\infty = 0.6 \)
\( Re_{\infty} = 5 \times 10^6 \)
\( q_\infty = 586 \)

• ALLEN'S CORR.
○ NEW CORR.
Figure 15. Comparison of $K_{eff}$ distribution along the surface of the cone using the new correlation and Allen's correlation for Run Number 15.231.
RUN NO. 40.547

$M_{\infty} = 0.6$

$Re_{\infty} = 5 \times 10^6$

$q_{\infty} = 586$

- ALLEN'S CORR.
- NEW CORR.

Figure 16. Comparison of $K_{\text{eff}}$ Distribution Along the Surface of the Cone Using the New Correlation and Allen's Correlation for Run Number 40.549
Figure 17. Comparison of $k_{\text{eff}}$ Distribution as a Function of $U_{\text{T}}h/\nu_w$ Using Allen's Correlation and New Correlation for Run Number 15.231.
Figure 18. Comparison of $k_{eff}$ distribution as a function of $U_{r}/W$ using Allen's correlation and new correlation for Run Number 40.549
resulting from the author's correlation (Eq. 5.5) exhibits the expected pattern of increasing $k_{eff}$ better than the distribution obtained using Allen's correlation. The following observations are made concerning Figures 15, 16, 17, and 18.

1. The minimum value of $k_{eff}$ using correlation Equation (5.5) occurs upstream of that obtained by means of Allen's correlation.
2. The $k_{eff}$'s seem to approach a common asymptote as the boundary layer develop, independent of the initial values.

It should be noted that Allen's correlation was derived based on simultaneous measurement of skin friction and circular Preston-tube pressures within flat-plate, turbulent boundary layers in supersonic free-streams. The above discussion was primarily done to demonstrate that the new correlation equation is valid in spite of the fact that the initial values of skin friction and $k_{eff}$ are erroneous. Comparison of correlation Equation (5.5) with Allen's correlation shows that one should use this equation to estimate the skin friction coefficient on a ten-degree cone at high subsonic Mach numbers.

In order to estimate skin friction on the AEDC Cone, one should use the following method.

1. Estimate the value of $k_{eff}$ from the appropriate tables of Appendix B for a given location on the surface of the cone.
2. Use Equation (5.3) and solve for $X^*$.
3. Use either Equation (5.5) or Equation (5.7) and solve for $Y^*$
4. Use Equation (5.2) and solve for $U_*$. Then skin friction is calculated from the following relation.

$$c_f = \frac{u_f^2}{\rho} \frac{p}{f_e} \cdot \frac{2}{U_{e}^2}$$

(5.8)
5. Obtain $U_t h/\nu_w$ and use Figure 10 to estimate a new value for $k_{\text{eff}}$.

6. Iterate the procedure until no improvement in the value of $k_{\text{eff}}$ is observed.

It should be noted that one may have to interpolate or extrapolate the values of $k_{\text{eff}}$ if the exact freestream Mach number and unit Reynolds number is not found in the tables of Appendix B. The user is warned not to use Tables XI, XV, and XX since the corresponding cases were not included in the development of the correlation equations, Equations (5.5) and (5.7).
CHAPTER VI

SUMMARY AND CONCLUSIONS

The distribution of Preston-tube pressures within turbulent boundary layers along the surface of a sharp-nosed, ten-degree cone have been correlated with theoretical value of turbulent skin friction for freestream Mach numbers less than one. The Mini-Basic computer code, the Wu and Lock computer code and the STAN-5 computer code were used to analyze the data and to solve the boundary layer conservation equations.

This is the first Preston-tube/turbulent-skin friction correlation for flow about a cone. The skin friction which results from using Preston-tube pressures in the correlation equation, has a rms error of 1.125 percent. This precision is very satisfactory and is comparable to previous Preston-tube correlations obtained by Patel (9) for pipe flows. A comparison of two sample cases using both Allen's correlation and correlation Equation (5.5) to estimate the skin friction at the match point suggests that this new correlation is sufficiently accurate for engineering uses.

In the course of this study, it was found that the effective center of the probe is not a constant. The distance above the wall of the effective center of the probe is a function of \( h, U, \nu \) and \( M \). The variation of the effective center of the probe becomes less as \( U, \nu \) increases. The effective center of the probe increases as the surface
distance increases. For a specified unit Reynolds number, the effective center of the probe decreases as the Mach number increases. Furthermore, for a specified unit Reynolds number and Mach number the effective center of the probe increases as \( U_w \) decreases.

It is also found out that the variation of the fluid (air) properties across the probe's face may be neglected for subsonic flows.

Finally, the possible transverse errors caused by the use of the concept of a virtual origin for the turbulent boundary layer was investigated and found to be negligible.

The developed correlation equation, Equation (5.5), is restricted to turbulent boundary layers on a sharp and smooth ten-degree cone at subsonic freestream Mach numbers. Furthermore, this correlation equation is restricted to Preston-tube measurements carried out at NASA-Ames 11-ft TWT by means of an oval-shaped Pitot-probe whose height and aspect ratio are 0.0097 inches and 1.8, respectively.

The ten-degree cone under study, which is referred to as the AEDC Boundary Layer Transition Cone, was mounted on the nose of a McDonnell-Douglas F-15 aircraft and tested in flight during 1978. The procedure developed herein for analysis of the wind-tunnel tests is expected to be applicable to the flight data. This work is currently being performed by another graduate student. When this correlation becomes available, it will be possible to compare it with the wind-tunnel correlation and thereby define an "effective" unit Reynolds number for the 11-ft Transonic Wind Tunnel at NASA Ames. This new method is needed because the classical definition of a turbulence factor for wind tunnels (e.g., Pope and Harper [11]) is invalid when \( \gamma = 0.35 \).
A SELECTED BIBLIOGRAPHY


APPENDIX A

THE MINI-BASIC COMPUTER CODE
APPENDIX A

THE MINI-BASIC COMPUTER CODE

The Mini-Basic computer code was developed on an Apple II Plus Computer. The two primary reasons for developing this computer code were: (1) to become familiar with the basic features of micro-computers, in general, and (2) to reduce the calculation costs. This computer code requires 48 thousand bytes of memory. It is intended to store most of the variables and parameters as the program is calculating the necessary information. This gives the user the advantage of obtaining the values of different variables and parameters directly from the terminal rather than inserting a lot of commands to check the value of a specified variable in the course of calculation. The logic of the computer code is presented by the flow chart shown in Figure 19.

This Appendix is designed to guide the reader through the complete turbulent-boundary-layer calculations. In order to further clarify this matter, Run Number 59.634 is used as an example run. The following is a step by step procedure that should be followed to complete a turbulent-boundary-layer calculation for this sample run.

1. Use Table I and find Case Number 5 corresponds to Run Number 59.634.

\[\text{TM Apple II Plus is a trade mark of Apple Computer, Inc.}\]

50
Figure 19. Simplified Flow Chart for the Mini-Basic Computer Code
Figure 19. (Continued)
PRINT OUT THE NECESSARY INFORMATION TO SET UP STALL-5

Figure 19. (Continued)
2. Use the wind tunnel data sheets and estimate the following.
   a. The location of the match point, \( X_{MP} = 14.69 \) in.
   b. The Preston-tube pressure corresponding to the match point,
      \( P_{pt} = 148.25 \) lbf/ft\(^2\).
   c. The location in the laminar boundary layer region that has
      the same Preston-tube pressure as that of the match point,
      \( X_4 = 5.25 \) in.
   d. The value of XL. \( XL = X_{MP} \) if \( \left| \frac{c_f(Allen) - c_f(STAN-5)}{c_f(STAN-5)} \right| > 0.01 \); otherwise, XL is equal to the location at which the
      wind-tunnel data ends.

3. Obtain the Wu and Lock printout and do the following.
   a. Obtain the pressure coefficient, \( c_p \), at the match point,
      \( c_p = 0.03755 \).
   b. Input the first eighty-two X/L values into the Mini-Basic
      program as three data statements in line numbers 2570, 2580,
      and 2590. Then, input the corresponding values of edge
      velocity as three data statements in line numbers 2640, 2650,
      and 2660. Be sure not to include the point corresponding
      to X/L = 0.
   c. Obtain the value of NXT. \( NXT \) is the index corresponding
      to the 1st (1≤i≤82) element of X/L values that corresponds
      to the location of the match point. If the exact location
      of the match point is not found in the Wu and Lock table of
      X/L values, then choose the match point such that it coin-
      cides with the nearest value of X/L occurring downstream of
      that found in step 2-a. \( NXT \) is equal to 32 for this sample
      run.
1. Run the Mini-Basic computer code. This program will ask for some or all of the above information depending on the input option. Mini-Basic has four options. The first option is a first-order curve fit of laminar $k_{eff}$'s to the corresponding $X/L$ values for the nineteen cases under study. The second option calculates the initial velocity profile, and the third option calculates the inviscid boundary conditions. Finally, the fourth option should be used when the user is ready to make a STAN-5 run. In order to clarify the operation of the Mini-Basic computer code, two sample printout is included in pp. 66-71. The first run uses option one, and the second printout uses option four.

5. Run STAN-5 computer code and obtain the skin friction at the match point: $c_f = 0.003127$.

6. Re-run the Mini-Basic program, and be sure to let the Mini-Basic code know that a new $X_{eq}$ needs to be calculated. Mini-Basic asks for this information. Again, run STAN-5 and obtain $c_f$ at the match point: $c_f = 0.003340$. If $\frac{c_f(\text{Allen}) - c_f(\text{STAN-5})}{c_f(\text{STAN-5})} < 0.01$, then proceed to step 7; otherwise, go to step 6. For this example, one has to go back to step 5 and obtain the third value of $c_f$ calculated by STAN-5: $c_f = 0.003238$.

7. Re-run the Mini-Basic computer code, and this should be the final run. Set $XL = 32.0$ inches which is at the end of the traverse for this wind-tunnel test. A sample output of the final run of the Mini-Basic computer code for Run Number 59.323 is presented in pp. 72-75. Running STAN-5 for the fourth time should
HERE IS THE MENU

1- THE CURVE FIT RESULTS OF THE LAMINAR REFF VS. K
2- THE INITIAL VELOCIT Profile
3- THE INVISCID COUNTER CONDITIONS
4- OPTION TWO AND OPTION THREE

INPUT YOUR CHOICE NUMBER
I.E. 1, 2, 3, OR 4: 1

WOULD YOU LIKE A HARD COPY?
INPUT 'Y' OR 'N': Y

-------------------------
STRAIGHT LINE CURVE FIT OF LIMITA

KINF VS. X/L

\[ K1 = 0.9849 \times X/L + 0.0474 \]
\[ K2 = 0.5428 \times X/L + 0.0474 \]
\[ K3 = 1.0855 \times X/L + 0.0591 \]
\[ K4 = 1.0473 \times X/L + 0.0604 \]
\[ K5 = 1.73699 \times X/L + 0.07296 \]
\[ K6 = 1.64683 \times X/L + 0.07278 \]
\[ K7 = 1.23162 \times X/L + 0.03371 \]
\[ K8 = 1.0967 \times X/L + 0.09115 \]
\[ K9 = 1.68853 \times X/L + 0.03361 \]
\[ K10 = 1.97129 \times X/L + 0.09109 \]
\[ K11 = 1.30436 \times X/L + 0.0324 \]
\[ K12 = 1.238 \times X/L + 0.00214 \]
\[ K13 = 0.9016 \times X/L + 0.0958 \]
\[ K14 = 1.79573 \times X/L + 0.0596 \]
\[ K15 = 1.24937 \times X/L + 0.1351 \]
\[ K16 = 2.1218 \times X/L + 0.06914 \]
\[ K17 = 1.42198 \times X/L + 0.07427 \]
\[ K18 = 1.50177 \times X/L + 0.07427 \]
\[ K19 = 1.3133 \times X/L + 0.07202 \]
INPUT YOUR CHOICE NUMBER
I.E. 1,2,3, OR 4

WOULD YOU LIKE A HARD COPY?
INPUT 'Y' OR 'N': Y

DO YOU NEED TO SOLVE FOR NEW XEQ(CONE)?
I.E. INPUT 'Y' OR 'N': N

INPUT THE VALUE OF XL IN INCHES: 14.67
INPUT THE VALUE OF X9 IN INCHES: 5.25
INPUT THE VALUE OF XMP IN INCHES: 11.52
INPUT THE VALUE OF PM: 19.1375
INPUT THE VALUE OF P3F IN .53F: 113.6
WHAT IS THE CASE NUMBER: 5

USE THE ?U&LOCK PRINT OUT
TO INPUT THE VALUE OF 'NXT': 32
The Initial Velocity Profile of the Turbulent Boundary Layer

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THE VALUE OF X-INITIAL IS = 0.0833 FT

THE VALUE OF CF(ALLEN) = 3.270E-03

INITIAL STATIC PRESSURE INPUT TO STAN-5 = 1435.22 FSF
HERE IS THE MENU

1- THE CURVE FIT RESULTS OF THE LAMINAR VELOCITY PROFIL
2- THE INITIAL VELOCITY PROFIL
3- THE INVISCID BOUNDARY CONDITIONS
4- OPTION TWO AND OPTION THREE

INPUT YOUR CHOICE NUMBER
I.E. 1, 2, 3, OR 4

WOULDN'T YOU LIKE A HARD COPY?
INPUT 'Y' OR 'N': Y

DO YOU NEED TO SOLVE FOR NEW XEQ(CONE)?
I.E. INPUT 'Y' OR 'N': Y

INPUT THE VALUE OF 'CF': 0.003233
THE VALUE OF 'XEQ' IN 'FT': 11.2272
INPUT THE VALUE OF 'XL' IN INCHES: 32.00
INPUT THE VALUE OF 'C' IN INCHES: 15.25
INPUT THE VALUE OF 'X(MP)' IN INCHES: 11.32
INPUT THE VALUE OF 'CP': 0.03755
INPUT THE VALUE OF 'PPT' IN 'PSF': 196.26
WHAT IS THE CASE NUMBER IS

INPUT THE VALUE OF 'NA1': 32

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<td>Radius (FT)</td>
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<tr>
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<td>C1565</td>
<td>1.6767</td>
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<td>C15312</td>
<td>1.6767</td>
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<td>C15312</td>
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<td>C15312</td>
<td>1.6767</td>
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<tr>
<td>C15312</td>
<td>1.6767</td>
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</table>

**INITIAL STATIC PRESSURE INPUT**

TO STAN-5 = 1434.06 PSF

**THE VALUE OF CF(ALLEN) = 3.270E-03**

**THE VALUE OF R - INITIAL IS = 0.0873**
result in a $c_f$ at the match point that is within 0.50 percent of that calculated by Allen's correlation. Running STAN-5 for the fifth time, one obtains: $c_f = 0.003288$, which is about 0.5 percent of that calculated by means of Allen's correlation.

9. Run the modified STAN-5 computer code to obtain the values of $k_{eff}$ along the surface of the cone. The total Prsentn-tube pressures downstream of the match point at about one-half inch intervals of surface distance must be input to the modified STAN-5 computer code.

Obtaining the values of $k_{eff}$ concludes the turbulent boundary layer calculations.

A complete listing of the Mini-Basic computer code is presented on the following pages.
10 REM MINI-BASIC
20 REM By
30 REM AMIR NASSIFMAFAND
40 REM "******************************************************************
50 REM KEEP IN MIND THAT ALL
60 REM CHF 3.4 COMMANDS ADHERE
70 REM THE PRINTER IN
80 REM DECIMAL NOTATIONS
90 REM THESE ARE CENTIMETERS
100 REM MODEL 735-1 COMPATIBLE
110 REM COMMAND HOME CLEAR:
120 REM THE SCREEN

130 REM
140 HOME
150 DIM MINF(21), REFT(21), GINF(21), Z(50), L0(50), C*(50), T(3), D*(50), A(3)
160 B(3), C(3), X(153), Y(153), A1(22), B1(22), M1(21), M2(21), M3(21), X1(25)
170 X2(250), R(250), U1(250), UT(25),
180 U(50), H*(50), FY(19), F3(21);

190 REM PUT THE CASES IN ORDER
200 REM CASE NUMBERS 1-19

210 FOR I = 1 TO 19:
220 READ P9(I):
230 NEXT I
240 DATA 11,10,5,4,3,2,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,
250 DATA 11,10,5,4,3,2,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,
260 HOME:
270 Q1 = 0:
280 THETA = (5 * 3.1415927) / 190:
290 D$ = "XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX"
300 D$ = "---------

310 S$ = D$
320 REM
OPTION TWO AND OPTION THREE

PRINT 
PRINT "INVERSE:
PRINT "NORMAL:
PRINT 
PRINT "INPUT YOUR CHOICE NUMBER:
PRINT 
IF V1 = 1 OR V1 = 0 THEN 
GOTO 360
HOME:
FLASH:
SEED = 100
PRINT "YOU HAVE CHosen: 1, 2, 3, OR 4":
NORMAL:
SPEED = 255
PRINT 
171.
380 PRINT:
PRINT "WOULD YOU LIKE A HINT OR?:
";
INVERSE:
INPUT "; INPUT 'Y' OR 'N'.
";T$;
PRINT D$;
NORMAL:
IF T$ = "Y" AND T$ = "Y": THEN
HOME:
GOTO 280
390 HOME
400 IF (V1 = 1):
THEN
GOTO 550

ORIGINAL PAGE IS OF POOR QUALITY

410 REM CHECK TO SEE IF
420 REM ITERATION IS REQUIRED
-----------------------------
430 T1$ = "DO YOU NEED TO SOLVE FOR N
440 REM XEQ(CONE)? ":
PRINT T1$;
INVERSE:
INPUT "; I.E. INPUT 'Y' OR 'N'.
";T$;
NORMAL:
PRINT:
IF (T$ = "Y" AND T$ = "Y"):
THEN
HOME:
GOTO 430
490 PRINT D$;
450 IF (T$ = "Y"):
THEN
INPUT "INPUT THE VALUE OF 'CF':
";CF$;
PRINT:
INPUT "THE VALUE OF K IN =
";K$;
PRINT:
460 IF (V1 < > 1):
THEN
INPUT "INPUT THE VALUE OF 'L IN
";L$;
PRINT:
L$ = L$;
DATA 53.35, 32.17, 1.4, 5, 41, 3, 7.6

610 REM DO NOT PRINT THE
620 REM KEFF VS. X/L
630 REM IF IT IS NOT SCALED "X"
640 PRINT *
650 GOTO 10
FOR J = 1 TO 19
   FOR I = 1 TO 19
      IF (A1(J) > 1)
      GOTO 730
   NEXT J
NEXT I
GOTO 740
REM F1NF=FTOTAL-IFNT =2

F1NF = (C X NINF Z3) X (GAMA - 1) - (GAMA / (GAMA - 1)) X 1
     X (NINF Z3 X Z)

REM F2

MSE = (Z1 + WINF Z3) X CF
     X (GAMA - 1) / 3.5
     X (MIN
F(Z3) X Z) X 5

ME = SQR (MSE)

REM KAX(TINF^2)+KE*TINF+KC=0

KA = (1 / (2 X QINF(Z3))) X (SQR
     (GAMA X R X GC)) X (2.27E - 03)
     X (MINF(Z3) X RGT(Z3)).
    KE = -1
    KC = -198.6

DTA = KB X 2 - (4 X KA X KC)
TINF = (1 / (2 X KA)) X (-KE -
     SOR (DTA))

IF (TINF < 0)
    THEN
    TINF = (1 / (2 X KA)) X (-KE -
     SOR (DTA))

REM CALCULATION IN OTHER

REM AIR MOPEITIES

TTL = (TINF) X (((MINF Z3) + Z
     X (GAMA - 1)) + 1)

TE = TTL X (1 + (0.2 X MSE)) X
     4

UE = (ME) X (SQR (GAMA X GC X
     R

REM PPT IS THE PRESTON-

REM TUBE PRESSURE
1010 REM A=R04,CA=MUC1,C=MUC:

**S**UB**C**R**I**PT**S****:

**L**=LASH, \( w \) = \( \omega \).

**F**LUID **P**ROPERTIES **E**VALUATED AT T**E**DGE, T**S**TAP, AND T**W**ALL **R**ESPECTI

**V**ELY

1020 \( T_1 = T_E; \)
\( T_2 = T_{STAP}; \)
\( T_3 = T_{WALL}; \)

1030 FOR \( I = 1 \) TO 3:
  \( A(I) = (F_E)^I \times \frac{1}{F(1)}; \)
  \( E(I) = (2.27); \quad (1 - 0.75); \quad (0.75); \)
  \( C(I) = B(I) \times \frac{GL}{A(I)}; \)
NEXT

1040 REM **C**ALCULATION OF CF(ALLen)

1050 MPT = SQR ((2 / (GAMA - 1)) * \(( (PPT / PE) \times ((GAMA - 1) / GAMA) - 1) \))

1060 UPT = SQR ((1 + ((GAMA - 1) \times \( E^2 \)) / (1 + ((GAMA - 1) \times \( (MPT^2) / (21)) \)) \times \( (MPT / ME) \)) \times \( (UE) \))

1070 KEFF = A1(I3) + B1(I3) \times X4:

1080 RD = (UE \times DEQ) / \( C(1) \))

1090 FL = (A(2) / A(1)) \times \( B(1) / E(2) \) : \( RD \times UPT / UE \)

1100 REM **C**ALCULATION OF FL **d**

1110 F3 = LOG (FL) / LOG (10):

1120 F4 = (.01359) \times (F3 \times 2) + (.7514)

1130 Z1 = (B(1) / E(2)) \times RD \times \( SQR ((A(2) / A(1)))); \)

1140 CF = (F2 / Z1) \times 2

1150 REM **E**N**D** OF CF **C**ALCULATION

83
9 REM CALCULATION OF
10 REM XEQ(F.P.),XEQ(CONE),...
120 X1 = (C.55 x A(2)) + A(1) + CF:

 REM XEQ(CONE) ***
1240 X0 = XC - .5 / (COS (THETA)) - <
 M / (12 x (COS (THETA)))

 REM SET THE INITIAL
1250 REM STATION OF STAN-S

 IF (X0 < 0) THEN
X0 = 1 / 12

 REM (* LG=(EQ,F.P.) - INITIAL *)
1290 LG = (1 / 2.263) x X0

 REM LF=CF(INITIAL) ***
1310 LF = (CF) * ((XEQ / LC) ^ (1 -

 REM L=LAMDA(REF.) ***
1320 L = SQR (1 - A(I)) * LF ***
1200 IF (TS = 'Y') THEN
           GOTO 1810
1210 L = E / F + 1. - 2 * L
1220 L = L2 + C(2) * L1 + L
1230 GOTO 1910

1000 REM FIRST ORDER LEAST SQUARE CURVE FIT

1400 ZZ = 0

1110 REM X(I) IS THE SURFACE DISTANCE
1210 REM Y(I) IS THE CORRESPONDING
1310 REM LAMINAR KEFF
1410 REM DATA OBTAINED FROM
1510 REM WORK DONE
1610 REM BY
1710 REM REED AND AEU-MOSTAFAD

1810 FOR I = 1 TO 153:
           READ X(I), Y(I):
           NEXT:

1910 DATA 4.5, 1.013, 6.5, 1.677, 7.1, 0.227, 1.1,
           1.49, 1.013, 6.5, 1.677, 7.1, 0.227, 1.1,
           1.118, 1.163, 6.5, 1.677, 7.1, 0.227, 1.1,
           7.5, 1.248, 6.5, 1.677, 7.1, 0.227, 1.1,
           28, 7.5, 1.258

2010 DATA 9.1, 2.280, 9.5, 1.30, 9.1, 32
           9.7, 1.312, 10, 1.359, 10.5, 1.381, 1
           11.382, 5, 1.106, 5.5, 1.137, 6, 1.158
           6.5, 1.177, 7, 1.197, 7.5, 1.217, 8, 1.
           28.3, 5, 1.257, 7, 1.277, 1, 1.1,
           1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1
           27.3, 1.308, 8.5, 1.324, 7, 1.358, 5.5

3010 DATA 1.371, 10, 1.385, 10.5, 1.3
           11, 1.416, 11.5, 1.424, 1.5, 1.15,
           1.5, 1.15, 1.5, 1.15, 1.5, 1.15
           1.5, 1.15, 1.5, 1.15, 1.5, 1.15
           1.5, 1.15, 1.5, 1.15, 1.5, 1.15
           1.5, 1.15, 1.5, 1.15, 1.5, 1.15
           1.5, 1.15, 1.5, 1.15, 1.5, 1.15
           1.5, 1.15, 1.5, 1.15, 1.5, 1.15
```
1510 DATA 1.293,9.5,1.35,10,1.31,1
1.0,1.355,6.5,1.159,7,1.056,7.5,
1.7,0,1.377,2.5,1.110,0.5,1.225,
7,1.251,7,1.282,5,1.054,0.5,
97.5,1.362,7.5,1.373,10,1.402,7.5.
5.1.422,11,1.429,0.5,1.024,7.1.35

1520 DATA 7.5,1.653,6,1.067,8,5,1.5
5.1.311,4.5,1.256,5,1.071,3.5,
4.1,1,1.341,3.5,1.404,5,1.743,5,
1.032,7,1,1.75,1,1.12,1,1.13,6.
7,1.157,5.5,1.122,6.1.162,0.5,
5.2,1,1.208,-5,1.228,0.5,1.12

1530 DATA 7.1,0.077,7.5,1.088,8,1.1
9.5,1.132,4.5,9.73,5,9.70,5,5.1,
9.6,1.023,6.5,1.029,8,1.021,6.5,
1.035,9,1.057,9.5,1.069,10,1.061,
10.5,1,088,8.5,1.149,9,1.176

1550 DATA 9.5,1.203,10,1.229,10,5,1,
250,11,1.283,1.5,1.314,5,1.915,
5.923,6,1.945,1,1.956,4,1.015,4,
5.1.032,3,1.032,5.5,1.107,6,1.137,
6,1.109,7,1.128,7,1.147,8,1,
16,6,5,1.175,5,96,5,5,5,56,0,5,5
6,5,911

1550 REM ISOLATE THE DATA
1560 REM OF DIFFERENT CASES

1570 LET J = 1 TO 21:
READ IN(J),REFT(J),GINF(J):
NEXT J:
```

1.1) IF \( y_{ij} = 0 \),
    THEN
    FOR \( j = 1 \) TO \( n \)
1.2) IF \( y_{ij} = 1 \)
    THEN
    FOR \( j = 23 \) TO \( 23 \)

---

1530 REM USE THE ABOVE DATA
1540 REM AND OBTAIN THE S.L.
1550 REM CURVE FIT

1560 \( S_1 = 0; \)
1570 \( S_2 = 0; \)
1580 \( S_3 = 0; \)
1590 \( S_4 = 0; \)
FOR \( i = M_H(J) \) TO \( M_J(J) \):
    \( S_1 = S_1 + X(I); \)
    \( S_2 = S_2 + X(I) \times 2; \)
    \( S_3 = S_3 + X(I) \times Y(I); \)
    \( S_4 = S_4 + Y(I); \)
NEXT \( i \);
\( M_J(J) = M_J(J) - M_G(J) + 1; \)
\( Z_2 = M_H(J) \times S_2 - (S_1 \times Z_2); \)
1670 \( B_1(J) = ((M_H(J) \times S_3) - (S_1 \times S_4)) / Z_2; \)
\( A_1(J) = (S_2 \times S_4) - (S_1 \times S_3); \)
NEXT \( J \)
1680 IF \( (V_1 < > 1) \)
    THEN
    RETURN

---

1690 REM SET UP THE PRINT
1700 REM IF IT IS ASKED FOR
1710 REM THE INTERFACE EGA/CO
1720 REM IS ASSUMED TO BE
1730 REM IN SLOT#1

1740 IF \( P_S = "N" \)
    THEN
    RETURN
1750 \( P_S = L \)
1760 PRINT CHR\$ (9); "40N"
1770 PRINT ":
    PRINT ":
1780 PRINT CHR\$ (9); "40-"
ORIGINAL PAGE IS OF POOR QUALITY

A100 REM INIT. VELOCITY PROFILE

A110 IF (TB = "Y")
      THEN
      GOTO 2070

A120 REM USE J.

A130 IF (TB = "N")
      THEN
      YU = X0:
      W = XC
      GOTO 1900

A160 REM REF. THE B.C.'S

A170 REM TO THE V.O.

A180 HOME:
      UV = 0:
      XG = W - (XH / (12 * (COS (TET) / A))):
      FOR I = 1 TO NREF:
         X(I) = XG + XG:
         R(I) = X(I) * (SIN (TET)):
         IF (UV = 1)
            THEN
               NEXT I:
         GOTO 1900:
      IF (X(I)) UV
         THEN
            SI = I:
            UV = 1:
         GOTO 1900

A190 REM INITIAL VELOCITY PROFILE:

A200 REM WALL FRICTION VELOCITY
39

ORIGINAL PAGE IS
OF POOR QUALITY

120: \[ I_2 = I_1 - 1. \]
\[ U_2 = \left( I_1 \times U_1 - I_2 \times U_2 \right) / I_1 \]
\[ L_2 = U_2 / L_1 \]

1820 \[ U(1) = 0 \]

2040 \[ Z(1) = 0; \]
\[ Z(I) = .005 \times L \]

2010 FEM AND SOLVE FOR INITIAL
2115 FEM EDGE VELOCITY

2030 \[ ZS = 0 \]

2040 FOR \( I = 3 \) TO 50

2050 IF \( I = 21 \)

THEN
\[ Z(I) = Z(I - 1) + 1.010 \times (Z(I - 1) - Z(I - 2)) \]

2060 IF \( I > 21 \)

THEN
\[ Z(I) = Z(I - 1) + 1.20 \times (Z(I - 1) - Z(I - 2)) \]

2070 IF \( ZS = 1 \)

THEN
GOTO 2090

2080 IF \( Z(I) = L_4 \)

THEN
\[ X_8 = I - 1; \]
\[ ZS = 1 \]

2090 NEXT

2110 FOR \( I = 1 \) TO \( X_3 - 1 \)

THEN
\[ L_4(I) = Z(I), L_4 \]

NEXT

2115 \[ X_8 = X_3 - 1; \]
\[ Z(X_3) = L_4; \]
\[ L_4(X_3) = 1; \]

FOR \( I = 2 \) TO \( X_8 \)

2120 \( O_1 = \left( Z(I) \times U_0 \right) / C(2) \); \( O_2 = \log (O_1) \)

2130 \( O_3 = I / K1 \);
\( O_4 = O_3 + O_3 \);
\( O_5 = O_3 \times (L_4(I) - 2) \);

2140 \( O_6 = O_1 \times \left( L_4(I) \times 3 \right) / O_5 \);
\( O_7 = O_4 \times (O_5 - O_6) \);
\( O_8 = O_3 \times O_2 \);
\( O_9 = O_2 \times (O_3 \times (L_4(I) \times 2) + 1 - L_4(I)) \);

2150 NEXT


210 REM PRINT OUT THE
2120 REM VEL. PROFILE
2190 IF (FB = "N")
2195 THEN
2200 GOTO 2210
2210 REM CHECK AND SEE IF A
2215 REM HARD COPY IS ASKED FOR
2220 PRINT 1
2230 PRINT: CHR$ (9); "ON"
2240 PRINT
2250 PRINT: CHR$ (9); "20L"
2260 PRINT D$: PRINT
IF \( U = 1 \) IF \( U = 1 \) THEN SOTO 250

REM "PRINT CASE OF FILE"
REM "MODEL VEL. PROFILE"

IF \( \text{FILE} = "1" \)
THEN SOTO 250

REM CHECK IF THE SHEET IS A HARD COPY ASKED FOR

PRINT 1
PRINT CHR$(9);"60N"
PRINT CHR$(9);"20L"
PRINT DS$:
PRINT "THE INITIAL VELOCITY FROM FILE OF THE";
PRINT "TURBULENT LAYER";
PRINT DS$:
PRINT :
PRINT "DIST. FROM WALL VELOCITY";
PRINT "FT\times10^{-3}
FT/SEC";
PRINT :
PRINT DS$:
PRINT :
PRINT:
PRINT FOR \( I = 1 \) TO 6:
\( U(I) = \text{INT}(U(I) \times 1000 + .5) / 1000; \)
\( DS(I) = \text{STR}(U(I)); \)
\( DS(I) = DS(I) + "000000" \)

REM USE STRINGS TO FORMAT
REM THE TABLE OF VALUES

\( Z(I) = Z(I) \times 1000000; \)
\( Z(I) = \text{INT}(Z(I) \times 1000 + .5) / 1000; \)
\( Z(I) = \text{INT}(Z(I)); \)
\( Z(I) = Z(I) \times \cdot \cdot \cdot \)
2215  IF (LEN (HS(I)) = 1) THEN
    C(I) = ' ' + CHS(I) + '1.000''
2220  C(I) = " 0.000":
    D$(I) = " 0.000":
    IF (LEN (HS(I)) = 3) THEN
    C$(I) = " + CHS(I) = '0.000'.
2230  IF (LEN (HS(I)) = 2) THEN
    C(I) = ' ' + CHS(I) + '0.00':
2235  I$ = STR$(I): '  
    IF (LEN (I$) = 1) THEN
    I$ = " " + I$
2240  IF (LEN (HS) = 4) THEN
    C$(I) = LEFT$(C$(I), 6)
2250  IF (I = 1) THEN
    2400
2260  IF (INT (Z(I)) = Z(I)) THEN
    C$(I) = " " + STR$(I(I)) = "" + 00000000"
2270  IF (VAL (D$(I)) = INT (VAL (D$(I)))) THEN
    Z(I) = LEFT$(Z(I), 7 - I)
2280  IF (INT (D$(I)) = D$(I)) THEN
    C$(I) = LEFT$(C$(I), 7)
    NEXT I:
    PRINT D9$.
2290  IF (V1 = 2) THEN
    END:
2295  IF (I$ = "N") THEN
    GOTO 3140
2400  IF (D$ = "NEW") THEN
    "E."
REM GET AX/L THE LIVELN OF
REM 10 MOUTH: LIVELN OM
REM NL1 NL2 NL3
REM JS=NSHIFT
REM BY CHANGING NSHIFT
REM THE LIVELN OF
REM WIDER RAGUL CAN
REM 2E LETTERS NSHIFT
REM THE VALUE OF NUM AND 1 H21
REM CAUDE ON LIVELN

REM = JS!
NS = JS!
NL1 = NUM + 1

X1(I) = X/L (FT) FROM WU & LOC
X**x1(I) IS MEASURED ALONG THE A
X**X1(I) IS MEASURED ALONG THE SURFACE OF THE CONE
X2(I) = X**ALONG THE SURFACE OF THE CONE

FOR I = 1 TO NL1:
READ X1(I):
NEXT

DATA .01281, .02307, .3332,
.01281, .02307, .3332,
.01281, .02307, .3332,
.01281, .02307, .3332,
.01281, .02307, .3332,
.01281, .02307, .3332,
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.01281, .02307, .3332,
.01281, .02307, .3332,
.01281, .02307, .3332,
.01281, .02307, .3332,
2670 \text{DX} = X_2(\text{NXT}) - X_2(\text{NXT - 1})

2700 \text{U} = \text{NUM} - \text{NXT + NSH}

\text{NREAR} = \text{NUM} + \text{NSH} + 1

2790 \text{REM} \ NT = \text{NTOT}

-----------------------------

2749 \ NT = \text{NUM} + \text{NSH} + \text{NSH}

-----------------------------

2750 \text{REM} \ \text{NXT1} = \text{NXT}

-----------------------------

2760 \text{NXT} = \text{NXT + 1}

\text{FOR} \ I = \text{NXT} \ \text{TO} \ \text{NUM}:

\text{DX} = (\text{U} \cdot \text{I} + 1) - (\text{U} \cdot \text{I}) - 1

\text{I} = \text{U} \cdot \text{I} + 1

\text{NC}
56.0  REM  MOVE X.
57.0  REM  ** LF.TAN=Q =NL F.**
58.0  REM  ** NE LF.CLF**
59.0  REM  ** XN = I X LF.CLF**

2010  REM  ** NEW XEQ(F.P.)=NF**
2020  NF = 'N / 2.268
2030  REM  ** NEW ((CONE-INITIAL) =NL**
2040  MC = 'N - 5 LF.COS (THETA) - X
2050  MC = 1.0
3010 REM ** NEW LAMDA = N1 **

3020 N1 = SQR ((2 * A(2)) / (NA * A(1)))

3030 REM ** NEW DELTA(REF.)=N4 **

3040 N3 = EXP (UN - B - (2 * P) * K)
N4 = N3 * (C/2) * N1 / 1

3050 L1 = N1:
L4 = N4:
HOME

3060 CS = "NEW";
SU = NC;
UP = (N1:
GUEB (CS)

L2 = SRF _ 1 _ Z _ V _ W _ 0 _... ...
L3 = EXP _ L2 - L _ C _ P _ N _ K:
L4 = L3 * (C/2) _ L1 / UL

3070 PRINT:
PRINT:
PRINT:
HTAE 20 - INT (LEN (DCS) C):
FD2 = DC2:
PRINT:
PRINT:
IF (PS = "N")
    THEN
    INPUT "HIT THE RETURN KEY TO...
    RETURN
3130 IF \( F B = "M" \), THEN
3140 GOTO 3150
3150 PRINT \( "\text{INVISID BOUNDARY CONDITIONS}" \);
3200 HOME:
PRINT \( D:\$\):
PRINT \( "\text{SURFACE DIST. RADIUS EDGE VEL.}":\
PRINT \( "\text{FT FT/SEC}":\
PRINT :
PRINT \( D^\star\):
PRINT :
PRINT :
PRINT :
3220 \( \text{FOR I = SI - 1 TO NREA - 1.} \)
3230 J = J + 1:
3240 \( \text{XZ(I) = INT (10000 \times XZ(I) + .5) / 10000;} \)
3250 \( \text{R(I) = R(I) \times 100;} \)
3260 \( \text{SI = INT (R(I) \times 1000 - .5) \times 1;} \)
3270 \( \text{UL(I) = INT (UL(I) + } \)
ORIGINAL PAGE IS
OF POOR QUALITY

2250  J$ = STR$(U$);  
J$ = STR$(V$(I$));  
C$ = STR$(X$(I$));  
E$ = STR$(W$(I$));  
C$ = C$ + "0000";  
J$ = U$ + "0000";  
IF (LEN(J$) = 1,  
THEN  
J$ = " " + J$  

2260  FEN STRINGS ARE USED  
2270  FEN TO FORMAT THE NUMBERS

3280  IF ( VAL (D$) < 10)  
THEN  
D$ = "0" + D$ + "0000"  
3290  IF ( VAL (C$) < 1)  
THEN  
C$ = "0" + C$  
3300  IF ( VAL (E$) = INT ( VAL (W$) ))  
THEN  
E$ = STR$ (W$(I$)) + "0000"  
3310  IF ( VAL (D$) < 1)  
THEN  
D$ = STR$ (W$(I$));  
D$ = "0" + D$ + "0000"  
3320  IF ( VAL (D$) > 10)  
THEN  
D$ = C$ + "0000"  
3330  PRINT " ";  
PRINT "; LEFT (C$,5);  
" "; LEFT (D$,5);  
; LEFT (E$(1:7));  
NEXT  
3340  PAINT S$;  
PRINT D9$;  

3350  REM OBTAIN THE INITIAL  
3360  REM STATIC PRESSURE  
3370  REM INPUT TO STAN-5

3380  EPI = (((1 + .2) * (MINF(33) ^ 2))  
/ (1 + .2) * (UC * 2) * (C$)  
* D$ * OC) = " " TTL = " " + 
3390  EP = = (MINF(33) ^ 2) + .0;  
...
ORIGINAL PAGE IS OF POOR QUALITY

3420 PRINT SI:
PRINT D?S
3430 IF (T$ = "N")
THEN
NC = X0:
XN = NC
3440 XN = INT (XN * 10000 + .5) 10:
00:
NC = INT (NC * 10000 + .5) 100:
00:
XN$ = STR$ (XN):
NC$ = STR$ (NC):
IF (XN < 0) THEN
XN$ = "0" + XN$ + "00000"
3450 IF (XN  0) THEN
XN$ = XN$ + "00000"
3460 IF (NC  1) THEN
NC$ = "0" + NC$ + "00000"
3470 IF (NC < 0) THEN
NC$ = NC$ + "000000"
3480 PRINT:
PRINT CHR$ (10.):
CFS = ""; (CFS:
3490 PRINT D?S:
PRINT "THE VALUE OF T$ IS: ";
LEFT$ (XN$, 6);" FT":
PRINT D?S:
PRINT "THE VALUE OF X-INITIAL IS: ";
LEFT$ (NC$, 6);" FT":
PRINT D?S:
PRINT "THE VALUE OF CF(ALLEN) = " ;
LEFT$ (CFS, 7);" E-03":
PRINT D?S:
PRINT " INITIAL STATIC FREDGE RE INPUT":
PRINT " TO STAN-S = "; EPI :
PRINT D?S:
PRINT D?S:
PRINT D?S:
PRINT D?S:
3520 REM END THE MINI-EASY
3530 REM COMPUTER CODE
3550 END
APPENDIX B

TABULATED VALUES OF TOTAL PRESTON-TUBE PRESSURE, EFFECTIVE CENTER OF THE PROBE, AND SKIN FRICTION COEFFICIENT ALONG THE SURFACE OF THE CONE FOR 19 CASES
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<th>$k_{eff}$</th>
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### TABLE IV

PRESTON-TUBE PRESSURE, EFFECTIVE CENTER OF THE PROBE AND SKIN FRICTION COEFFICIENT ALONG THE SURFACE OF THE CONE FOR RUN NUMBER 61.636

<table>
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PRESTON-TUBE PRESSURE, EFFECTIVE CENTER OF THE PROBE AND SKIN FRICTION COEFFICIENT ALONG THE SURFACE OF THE CONE FOR RUN NUMBER 25.375

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TABLE IX
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OF THE PROBE AND SKIN FRICTION
COEFFICIENT ALONG THE SURFACE
OF THE CONE FOR RUN
NUMBER 40.547

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COEFFICIENT ALONG THE SURFACE
OF THE CONE FOR RUN
NUMBER 58,633

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COEFFICIENT ALONG THE SURFACE
OF THE CONE FOR RUN
NUMBER 21.318

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### TABLE XIV

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### TABLE XVI

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OF THE CONE FOR RUN
NUMBER 42.549

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PRESTON-TUBE PRESSURE, EFFECTIVE CENTER OF THE PROBE AND SKIN FRICTION COEFFICIENT ALONG THE SURFACE OF THE CONE FOR RUN NUMBER 43.550

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OF THE CONE FOR RUN
NUMBER 15.231

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### TABLE XXI

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Thesis: CORRELATION OF THEORETICAL TURBULENT SKIN FRICTION WITH PRESTON-TUBE MEASUREMENTS IN A SUBSONIC JET

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in Tehran, Iran, on Oct. 1, 1951, the son of Mr. and Mrs. Hassan Massinarian.

Education: Graduated from Negad High School, Tehran, Iran, in May 1977, received Bachelor of Science in Mechanical Engineering degree from Oklahoma State University in December 1980, enrolled in Master of Science program at Oklahoma State University, January 1981; completed requirements for the Master of Science degree at Oklahoma State University in December, 1983.

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