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Report 957

NAVY DEPARTMENT

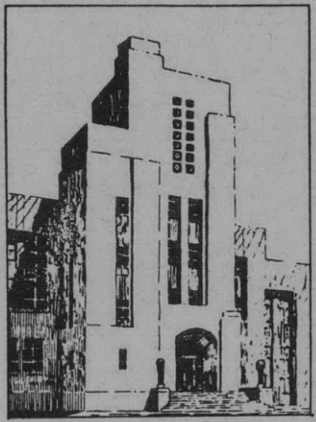
THE DAVID W. TAYLOR MODEL BASIN

WASHINGTON 7, D.C.

THE MEASUREMENT OF LOCAL TURBULENT SKIN FRICTION BY MEANS OF SURFACE PITOT TUBES

by

E.Y. Hsu, Ph.D.



RESEARCH AND DEVELOPMENT REPORT

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NOTATION

A	Constant
a	Inner radius of the surface tube
B	Constant
b	Outer radius of the surface tube
C	Constant
$c_{\tau} = \dfrac{\tau_0}{\frac{1}{2}\rho U^2}$	Local shearing stress coefficient
$d = 2b$	External diameter of the tube
$H = \dfrac{\delta^*}{\theta}$	Shape parameter
K	Constant
k	Computed constants
n	Constant
P	Pressure recorded by the surface tube
p_0	Static pressure at the wall
$R_x = \dfrac{Ux}{\nu}$	x-Reynolds number
$R_\theta = \dfrac{U\theta}{\nu}$	θ-Reynolds number
$t = \dfrac{a}{b}$	Thickness ratio of the tube
U	Velocity outside the boundary layer
U_t	Velocity at the throat of divergent test section for adverse pressure gradient
U_0	Undisturbed velocity for zero pressure gradient
u	Mean longitudinal velocity at a point in the boundary layer
$u_\tau = \sqrt{\dfrac{\tau_0}{\rho}}$	Frictional velocity
x	Distance along the boundary
y	Normal distance from the boundary

δ	Boundary-layer thickness
$\delta^* = \int_0^\delta \left(1-\frac{u}{U}\right)dy$	Displacement thickness
$\theta = \int_0^\delta \frac{u}{U}\left(1-\frac{u}{U}\right)dy$	Momentum thickness
ν	Kinematic viscosity
ρ	Density of fluid
σ	Area of the tube opening
τ_0	Wall shearing stress
ϕ	Parameter

ABSTRACT

The surface pitot tube technique for the determination of local skin friction has been extended for boundary-layer flow with adverse pressure gradients. The calibration of round tubes on flat surfaces with zero pressure gradient and with adverse pressure gradient gave results which check almost identically with those obtained in Preston's pipe experiments. It was concluded that the performance of the surface pitot tubes can be calculated by using simplified assumptions. In addition, the ratio of the inner to outer diameter of the tube was shown analytically and experimentally to have a negligible effect on the results.

INTRODUCTION

Knowledge of the skin friction in turbulent motion is of paramount importance not only in the field of resistance predictions for ships and for aircraft at subsonic speeds but also in the field of fluid mechanics for a better understanding of the law governing shear flows. Since the law governing laminar flow is known, local shearing stresses can be computed on a strictly theoretical basis from any known velocity distribution. However, because present knowledge of turbulence is inadequate, the same procedure cannot be applied to turbulent flow. The shearing stresses due to turbulent exchange are still unknown, and information concerning the shearing stresses in turbulent flow must still depend on experimental investigations.

The measurement of local skin friction or wall-shearing stress is a very difficult technique, except for some special cases such as fully developed flow in pipes or channels where it can be evaluated accurately from the pressure drop. The measurement of shearing forces on an isolated floating surface element would be a direct approach in obtaining the local skin friction, although this technique requires complicated instrumentation. In fact, at least three successful attempts have been made for flat surfaces. In 1929, Kempf[1] measured the surface friction on the flat bottom of a ship model in his towing test; his results are the only existing direct skin-friction measurements at high Reynolds numbers ($10^7 < R_x < 3 \times 10^8$). Schultz-Grunow[2] later used a similar technique to measure the frictional force on a wind-tunnel wall. More recently, Dhawan[3] has obtained further skin-friction data on a flat plate by a floating isolated element in the region of lower Reynolds numbers ($2 \times 10^5 < R_x < 6 \times 10^5$). Unfortunately this technique is very difficult for general or even laboratory use. Fage and Falkner[4] used a calibrated half-pitot tube embedded in the laminar sublayer. The difference in pressure between the pitot tube and the local static pressure is correlated with the local skin friction. Because of the extremely small size of the half-pitot tube, the difficulty in handling and the extreme sensitivity of the test probe have been serious obstacles.

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[1] References are listed on page 14.

Local turbulent skin friction can also be obtained indirectly from a velocity traverse together with the momentum equation. This method is both tedious and inaccurate since a differentiation process is necessary in evaluating the local skin friction. In addition, the Reynolds normal-stress term cannot be neglected by the usual Prandtl thin boundary-layer assumption, especially near separation; it has been shown by experiment[5] that the normal-stress terms are comparatively large near the surface. Ludwieg[6] developed the hot-spot technique and obtained the local skin friction by measuring the heat loss from a heated spot into the flow medium. Great care must be taken to allow for the imperfect heat insolation between the hot spot and its surroundings since an unknown amount of heat is transferred to the wall.

In view of the previous discussions, it is clear that simple and yet accurate means for determining local turbulent skin friction would still be a valuable addition to the existing experimental technique.

Preston[7] has successfully developed a simple method of determining local skin friction on smooth surfaces. The method is based upon the existence of the inner law relating the local skin friction to the velocity profile in pipe flows and utilizes a round total head tube resting on the surface. His calibrations give an empirical relationship for the difference between the total pressure recorded by the tube and the static pressure at the wall, in terms of the local skin friction. More recently, Ludwieg and Tillmann[8] have established the inner law for boundary-layer flow on flat plates with pressure gradient by use of the hot-spot technique. Therefore, by proper use of the inner law, it is possible to extend Preston's method to determine the local skin friction for boundary flows with pressure gradients.

The present report is concerned with boundary-layer studies at the David Taylor Model Basin where round total head tubes were calibrated in the low-turbulence wind tunnel for use in local turbulent skin-friction measurements on a body of revolution. The total head tubes, resting on the tunnel wall, were calibrated in a zero pressure gradient as well as in adverse pressure gradients. The results are compared with those of Preston's pipe experiments. In addition, a formula for estimating the local skin friction is derived which is based upon the inner law. As a more precise formulation, the ratio of the inner to outer diameter of the tube is included in the new formula.

THEORETICAL CONSIDERATIONS

VELOCITY DISTRIBUTIONS NEAR SMOOTH SURFACES

The velocity distribution near a smooth surface depends only upon the density, the viscosity of the fluid, and the shearing stress at the wall. It can be shown by dimensional analysis that the velocity u at a distance y from the boundary may be expressed as

$$\frac{u}{\sqrt{\frac{\tau_0}{\rho}}} = \frac{u}{u_\tau} = f\left(\frac{y\,u_\tau}{\nu}\right) \qquad [1]$$

where ρ and ν are the density and the kinematic viscosity of the fluid, respectively,

τ_0 is the wall-shearing stress, and

$u_\tau = \sqrt{\frac{\tau_0}{\rho}}$ is the frictional velocity.

Equation [1] has been established for pipe and channel flow. Ludwieg and Tillmann[8] have shown experimentally that Equation [1] holds true in general and is independent of pressure gradients.

In regions close to the boundary, there exists a laminar sublayer where the viscous effect is predominant. Here, Equation [1] takes the form

$$\frac{u}{u_\tau} = \frac{y u_\tau}{\nu} \qquad [2]$$

The upper limit for which the laminar sublayer exists is about $yu_\tau/\nu = 30$, and the mean velocity curve in this region has been well defined by the recent data of Laufer[9] and Dhawan.[3]

Further out from the laminar sublayer are the transition region and, finally, the turbulent part of the boundary layer. In a limited region beyond the transitional sublayer, the well-known logarithmic velocity profile law holds. Millikan[10] proved from pipe and channel flows that the existence of the logarithmic law is a necessary mathematical consequence due to the overlapping of the inner law and the velocity-defect law. Ludwieg and Tillmann have further generalized the logarithmic law through their experimental evidence and have discovered its independence of the pressure gradient also. The velocity profile may be expressed as

$$\frac{u}{u_\tau} = A + B \log \frac{y u_\tau}{\nu} \qquad [3]$$

where A and B are empirical constants. For a small range of $y u_\tau/\nu$, the logarithmic representation can be approximated by a power law as

$$\frac{u}{u_\tau} = C \left(\frac{y u_\tau}{\nu} \right)^{1/n} \qquad [4]$$

where C and n are again empirical constants. Equation [4] is simpler to use and will be employed later in deriving the relationship between the wall-shearing stresses and the dynamic pressures of the surface pitot tubes.

RELATIONSHIP BETWEEN WALL-SHEARING STRESS AND DYNAMIC PRESSURE OF SURFACE PITOT TUBES

It is assumed that the disturbances caused by the presence of the total head tube in the boundary-layer flow may be neglected. Hence, if a round total head tube with internal and external radii a and b, respectively, as shown in Figure 1, lies just in contact with a surface in a flow field, the average dynamic pressure experienced by the tube would definitely be

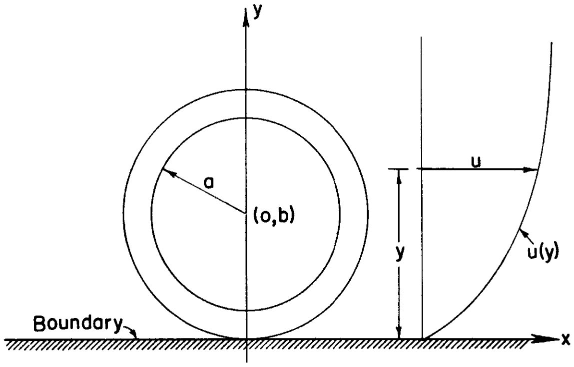


Figure 1 - A Surface Pitot Tube Resting on a Surface in Boundary-Layer Flow

correlated to the local skin friction through the frictional relationship of the velocity distribution near the surface. Such a relationship will be evaluated as follows:

1. In laminar sublayer:

The velocity distribution in the laminar sublayer, as mentioned previously in Equation [2], can be expressed as

$$\frac{u}{u_\tau} = \frac{u_\tau}{\nu} y$$

or

$$u = \frac{u_\tau^2}{\nu} y \qquad [2a]$$

Let P denote the pressure, as recorded by the tube, measured relative to the static pressure p_0 at the wall. The total pressure acting in the tube opening may then be expressed as

$$(P - p_0) = \frac{\frac{1}{2}\rho \int_\sigma u^2 \, d\sigma}{\pi a^2} \qquad [5]$$

where σ denotes the area of the tube opening. Substituting Equation [2a] and $d\sigma$ (expressed in terms of the geometry of the tube) into Equation [5] results in

$$\begin{aligned}(P - p_0)\pi a^2 &= \frac{1}{2}\rho \int_{b-a}^{b+a} \frac{u_\tau^4}{\nu^2} y^2 \cdot 2\sqrt{a^2 - (y-b)^2} \, dy \\ &= \frac{\rho u_\tau^4}{\nu^2} \frac{\pi}{2} \left[a^2 b^2 + \frac{a^4}{4}\right]\end{aligned} \qquad [6]$$

Denoting a/b equal to t, the thickness ratio of the tube, Equation [6] may be expressed in terms of dimensionless parameters as suggested by Preston as follows:

$$\frac{\tau_0 d^2}{4\rho\nu^2} = \sqrt{\frac{8}{4+t^2}} \sqrt{\frac{(P - p_0) d^2}{4\rho\nu^2}} \qquad [7]$$

or

$$\log \frac{\tau_0 d^2}{4\rho\nu^2} = \frac{1}{2}\log\left[\frac{8}{4+t^2}\right] + \frac{1}{2}\log\left[\frac{(P - p_0) d^2}{4\rho\nu^2}\right] \qquad [7a]$$

where $d = 2b$ is the external diameter of the tube. Equation [7a] represents a straight line on a logarithmic plot with a slope of one half.

2. In turbulent boundary layer:

If the surface pitot tube were of such a size that it extended beyond the laminar sublayer but was still within the region where the universal velocity function holds, a similar procedure could be used. To obtain the average pressure experienced by the surface tube by an integration process, the simple power law of velocity distribution is used. In view of the experimental results obtained by Preston,[7] a good representation of the velocity distribution for $u_\tau y/\nu < 3000$ may be expressed as

$$\log \frac{u}{u_\tau} = 0.935 + \frac{1}{7} \log \frac{y u_\tau}{\nu}$$

or

$$\frac{u}{u_\tau} = 8.61 \left(\frac{u_\tau}{\nu} y \right)^{1/7} = C \left(\frac{u_\tau}{\nu} y \right)^{1/7} = K y^{1/7} \qquad [8]$$

With the laminar sublayer neglected owing to its thinness, the total pressure experienced by the tube may be expressed as

$$(P - p_0) = \frac{\frac{1}{2} \rho \int_{b-a}^{b+a} K^2 y^{2/7} \cdot 2\sqrt{a^2 - (y-b)^2}\, dy}{\pi a^2}$$

Since $y - b = a \sin \phi$, the above expression may be simplified to

$$(P - p_0) \pi a^2 = \rho C^2 u_\tau^2 \left(\frac{u_\tau}{\nu} \right)^{2/7} a^2 b^{2/7} I(t) \qquad [9]$$

where

$$I(t) = \int_{-\pi/2}^{\pi/2} (1 + t \sin \phi)^{2/7} \cos^2 \phi \, d\phi$$

Rearranging Equation [9] into a dimensionless form similar to Equation [7a] yields

$$\frac{\tau_0 d^2}{4 \rho \nu^2} = \left[\frac{\pi}{C^2 I(t)} \right]^{7/8} \left[\frac{(P - p_0) d^2}{4 \rho \nu^2} \right]^{7/8} = k \left[\frac{(P - p_0) d^2}{4 \rho \nu^2} \right]^{7/8}$$

or

$$\log \frac{\tau_0 d^2}{4 \rho \nu^2} = \log k + \frac{7}{8} \log \left[\frac{(P - p_0) d^2}{4 \rho \nu^2} \right] \qquad [10]$$

The thickness function $I(t)$ represents the effect due to the relative proportion of the internal and external diameters of the tube upon the local skin-friction measurements. The function $I(t)$ has been evaluated numerically and its tabulated values are as follows:

t	$I(t)$	k	$\log k$
0	$\frac{\pi}{2}=1.5706$	0.04240	$\bar{2}.6274$
0.1	1.5705	0.04241	$\bar{2}.6275$
0.2	1.5693	0.04244	$\bar{2}.6278$
0.3	1.5672	0.04249	$\bar{2}.6283$
0.4	1.5644	0.04255	$\bar{2}.6289$
0.5	1.5603	0.04264	$\bar{2}.6298$
0.6	1.5553	0.04275	$\bar{2}.6309$
0.7	1.5489	0.04291	$\bar{2}.6326$
0.8	1.5407	0.04310	$\bar{2}.6345$
0.9	1.5295	0.04337	$\bar{2}.6372$
1.0	1.5161	0.04370	$\bar{2}.6405$

For comparison with Equation [10], the empirical equation obtained by Preston in his pipe experiment is stated as

$$\log \frac{\tau_0 d^2}{4\rho\nu^2} = \bar{2}.604 + \frac{7}{8}\log\frac{(P-p_0)\,d^2}{4\rho\nu^2} \qquad [11]$$

It can be seen from the above tabulation that the numerical values of log k vary only slightly with thickness ratio although they differ a little with the constant in Preston's formula. It can be concluded that the relative proportion of the internal and external diameter of the tube is not important here.

The previous analytical development seems to indicate from Equations [7a] and [10] that an indirect measurement of the local skin friction may be obtained on smooth surfaces simply by measuring the dynamic pressures acting on a surface pitot tube resting on the surface. This technique, however, has also been verified experimentally.

APPARATUS AND EXPERIMENTS

The experiments were carried out in the newly constructed low-turbulence wind tunnel at the Taylor Model Basin. A salient feature of this tunnel is the flexible wall in the test section which allows the tunnel to be adapted to many kinds of research, particularly the experimental investigation of the boundary layer in adverse pressure gradients.

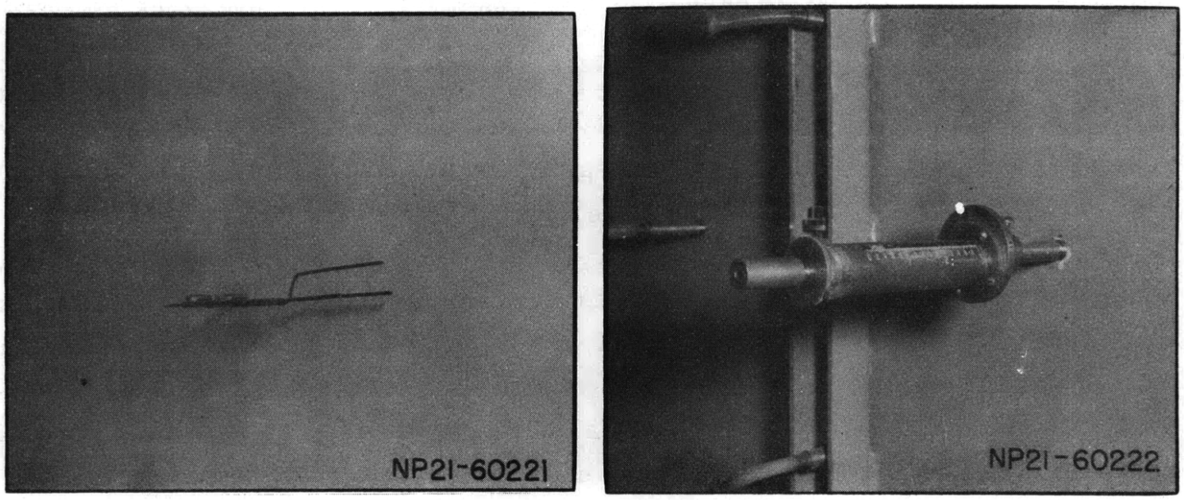


Figure 2a - Boundary-Layer Survey Rake Installed through the Static Opening on the Tunnel Wall

Figure 2b - Micrometer Traverse Mechanism for the Velocity Distribution Measurements in the Boundary Layer

Figure 2 - Experimental Setup for Measuring Local Turbulent Skin Friction

The test section has a rectangular shape 2 ft wide, 4 ft high and a length of 14 ft; the inner wall of the test section is finished in enamel paint and is aerodynamically smooth. The maximum speed obtainable in the parallel-wall test section is approximately 140 fps. Since the tunnel is of the open-return type, the turbulence level is relatively low with a magnitude of 0.1 percent along the flow direction at a speed of 100 fps. Additional details and characteristics of the tunnel are described in Reference 11.

The boundary-layer survey rake is made of 1/16-in. brass tubing. For boundary layers in adverse pressure gradients, a static tube of the same diameter as the total head tube was added to the rake since the readings from the static opening on the tunnel wall did not accurately measure the static pressure in the boundary layer due to the curvature of the streamlines. The rake was installed through the static openings in the test section and was connected to a micrometer, mounted on the tunnel wall as shown in Figures 2a and 2b. The precision of the measurements of the normal distance from the total head tube to the inner face of the tunnel wall is about 0.001 in.

The surface pitot tubes are made of 1/16-in. OD brass tubes whose ends are carefully machined square to their center axes and are also free of burrs. In order to check the effect of the wall thickness of the tube on the calibrations, two pitot tubes with different internal diameters were made. The thickness ratios are 0.896 and 0.676, respectively. The surface pitot tubes were installed on the wall with scotch tape. Great care was taken to insure that the side of the tube was in contact with the wall.

All measurements were made on adjustable, inclined alcohol manometers which had been previously calibrated against one reference tube. The inclination of the manometer board was 1 to 5 for experiments with zero pressure gradients and 1 to 3 for experiments with adverse pressure gradients. The precision in reading the scale which is attached to the manometer was approximately 0.05 in.

The two-dimensional character of the flow in the test section had been checked by velocity surveys from the top to bottom at several stations along the test section. The flow was found to be two-dimensional over the region where the surface tubes were calibrated.

The experimental procedures were the same for the cases of zero pressure gradient and for those of adverse pressure gradients. First, velocity profiles were measured by using the boundary-layer survey rake in the tunnel wall at various stations along the test section at selected tunnel speeds, U_0, the undisturbed velocity, for zero pressure gradient and U_t, the velocity at the throat, for adverse pressure gradient. The surface pitot tubes were then installed at stations where the velocity profile had been measured. The dynamic pressure of the surface pitot tube with reference to the readings at static openings on the tunnel wall, $P-p_0$, were recorded for various tunnel speeds. Runs with the two tubes of different thickness ratio were made at each station. A typical calibration curve of the surface pitot tube is shown in Figure 3. In order to insure that the calibration did not suffer from the effect of time lag, all readings of the surface pitot tube were taken both with increasing tunnel speeds and then with decreasing tunnel speeds.

The configuration of the test section and the corresponding velocity distribution along the tunnel wall for the case of adverse pressure gradient are shown in Figure 4. The velocity distributions in the boundary layer were measured at four stations along the test section. Figures 5a to 5d show the nondimensional velocity distributions u/U against the normal distances y from the wall, where U denotes the velocity outside of the boundary layer. From the measured velocity profiles, the momentum thickness θ, the displacement thickness δ^*, and the shape parameter H can be evaluated.

The local skin-friction coefficients were obtained for the case of zero pressure gradient by using Landweber's numerical results[12] relating R_θ, the Reynolds number based on the momentum thickness, to c_T. His analysis is based on "the law of the wall" and the "velocity-defect law," and the numerical values of c_T are almost identical with those of Schoenherr for $R_\theta > 1000$. In the case of adverse pressure gradients, the local skin-friction coefficient was obtained from the empirical formula given by Ludwieg and Tillmann:[8]

$$c_T = \frac{0.246}{10^{0.678\,H} R_\theta^{\,0.268}}$$

where H and R_θ can be calculated from the measured velocity profiles. The values of δ^*, θ, and c_T along the test section with adverse pressure gradient for $U_t = 200$ fps are shown in Figure 4.

The validity of Equations [7a] and [10] may be verified experimentally from the calibration curves of the surface pitot tube and the calculated local skin-friction coefficient.

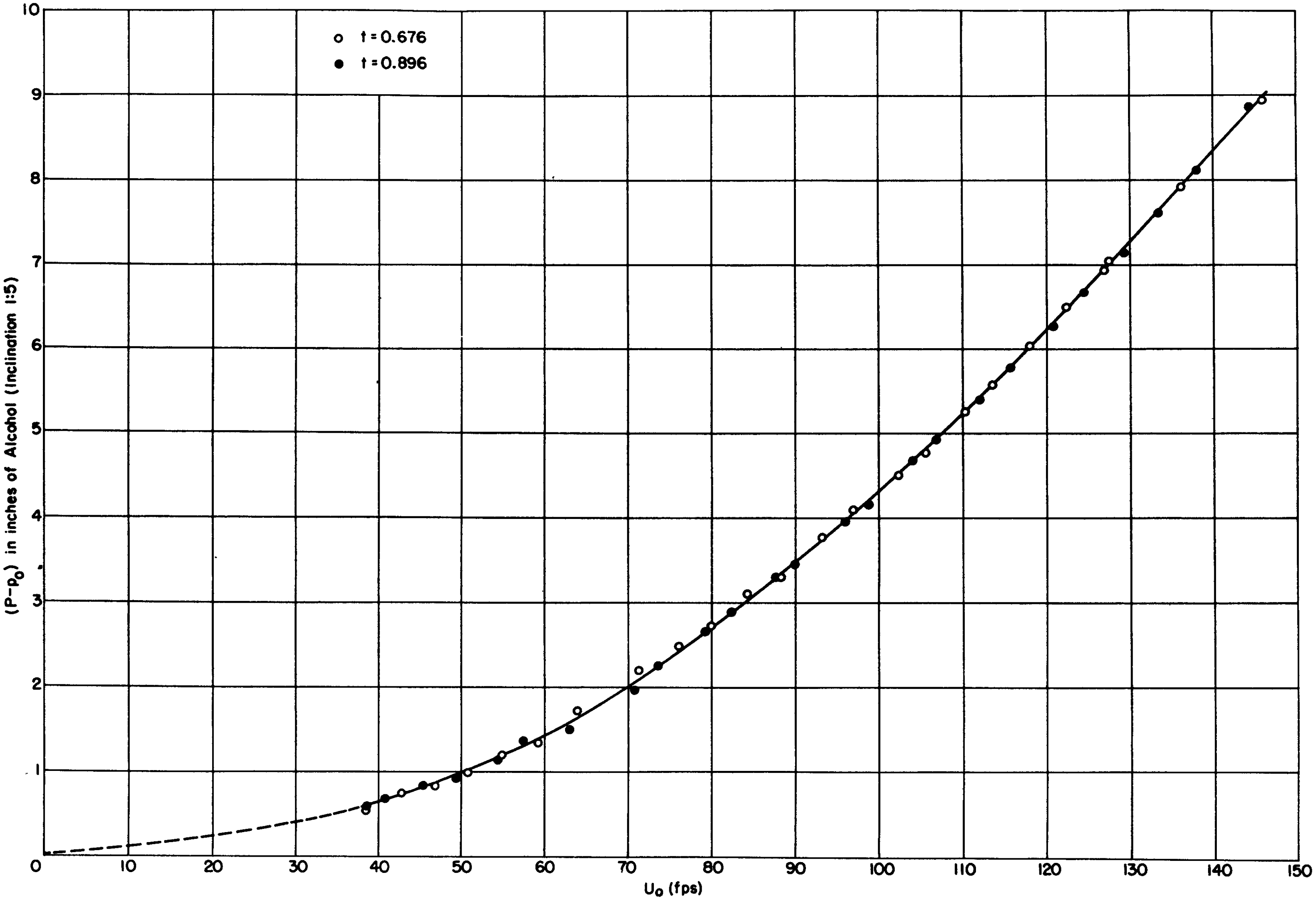


Figure 3 - Typical Calibration Curve of a Surface Pitot Tube

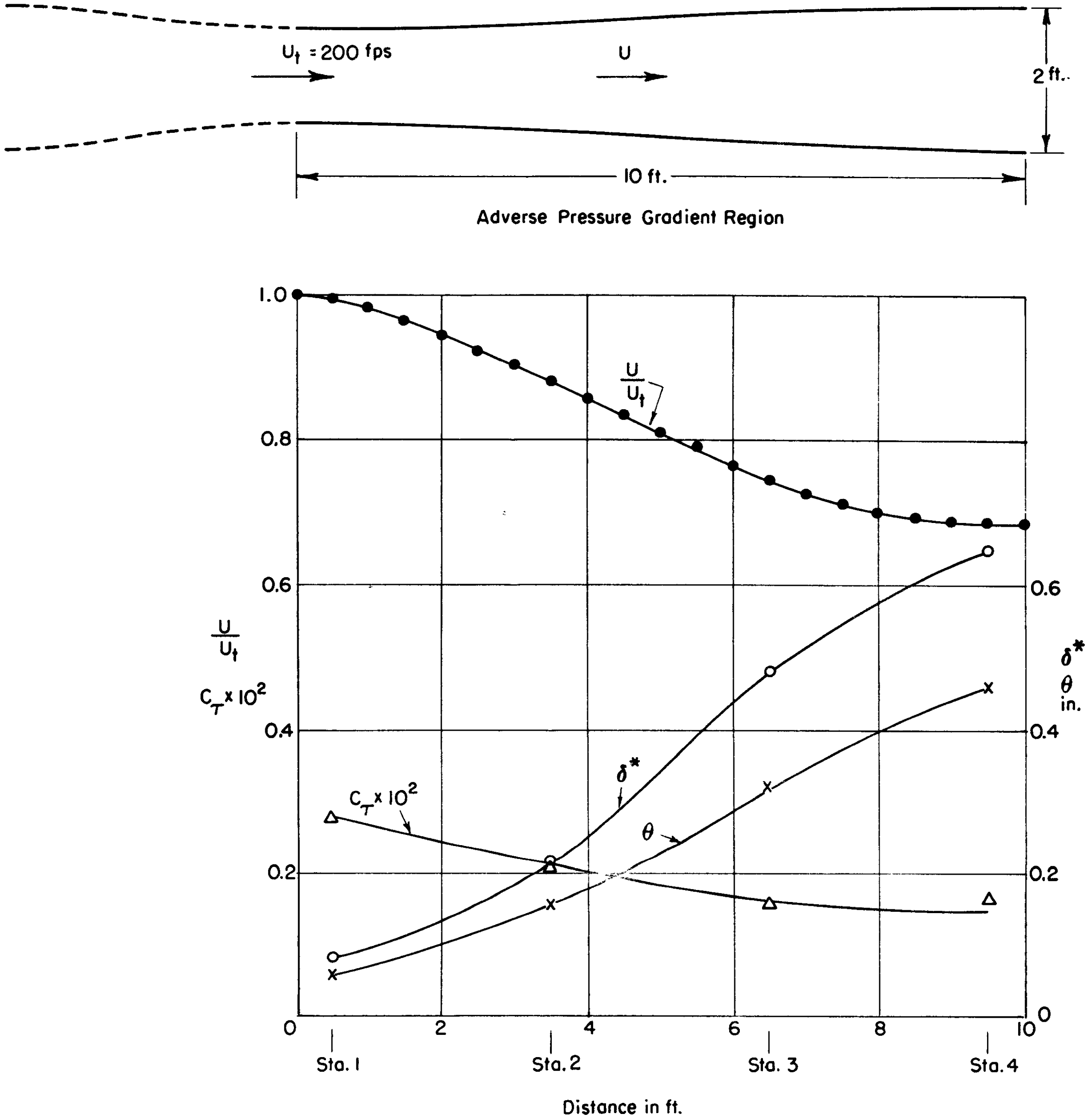


Figure 4 - Configuration of the Test Section and Its Corresponding Velocity Distribution with Adverse Pressure Gradient

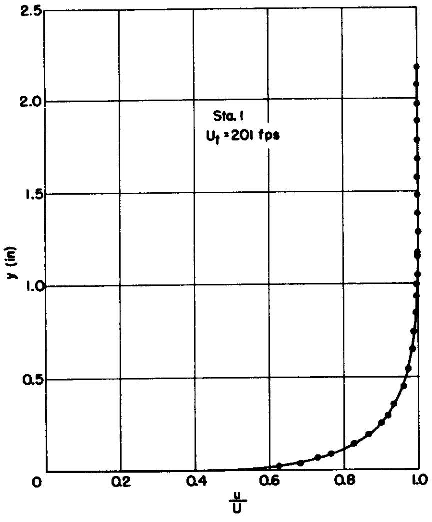


Figure 5a - Station 1, $U_t = 201$ fps

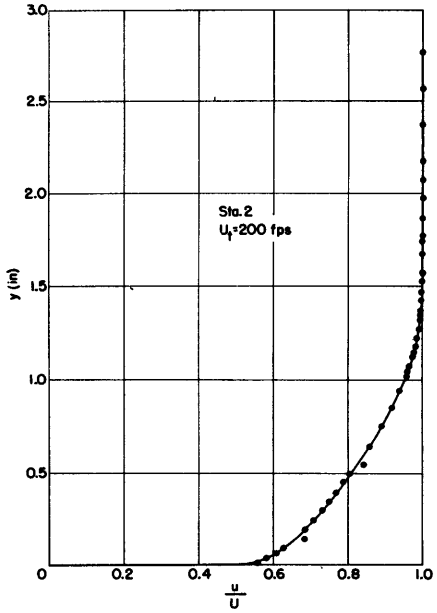
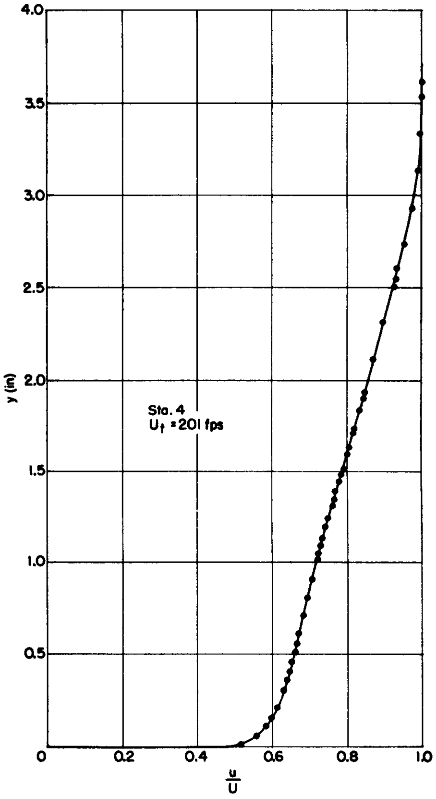


Figure 5b - Station 2, $U_t = 200$ fps



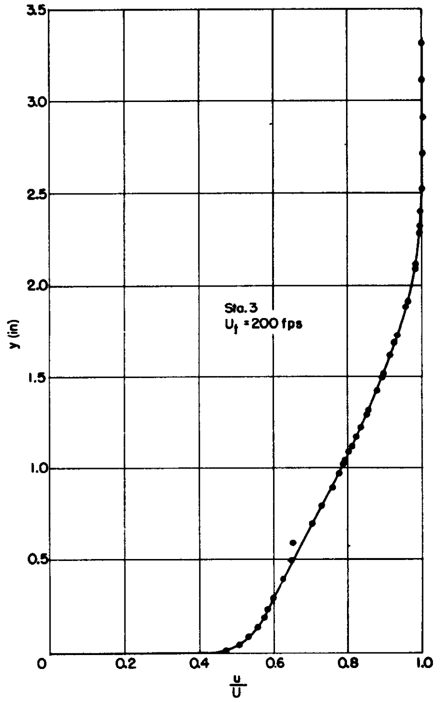


Figure 5c - Station 3, $U_t = 200$ fps

Figure 5d - Station 4, $U_t = 201$ fps

Figure 5 - Velocity Distributions in the Boundary Layer at Four Stations along the Test Section with Adverse Pressure Gradient

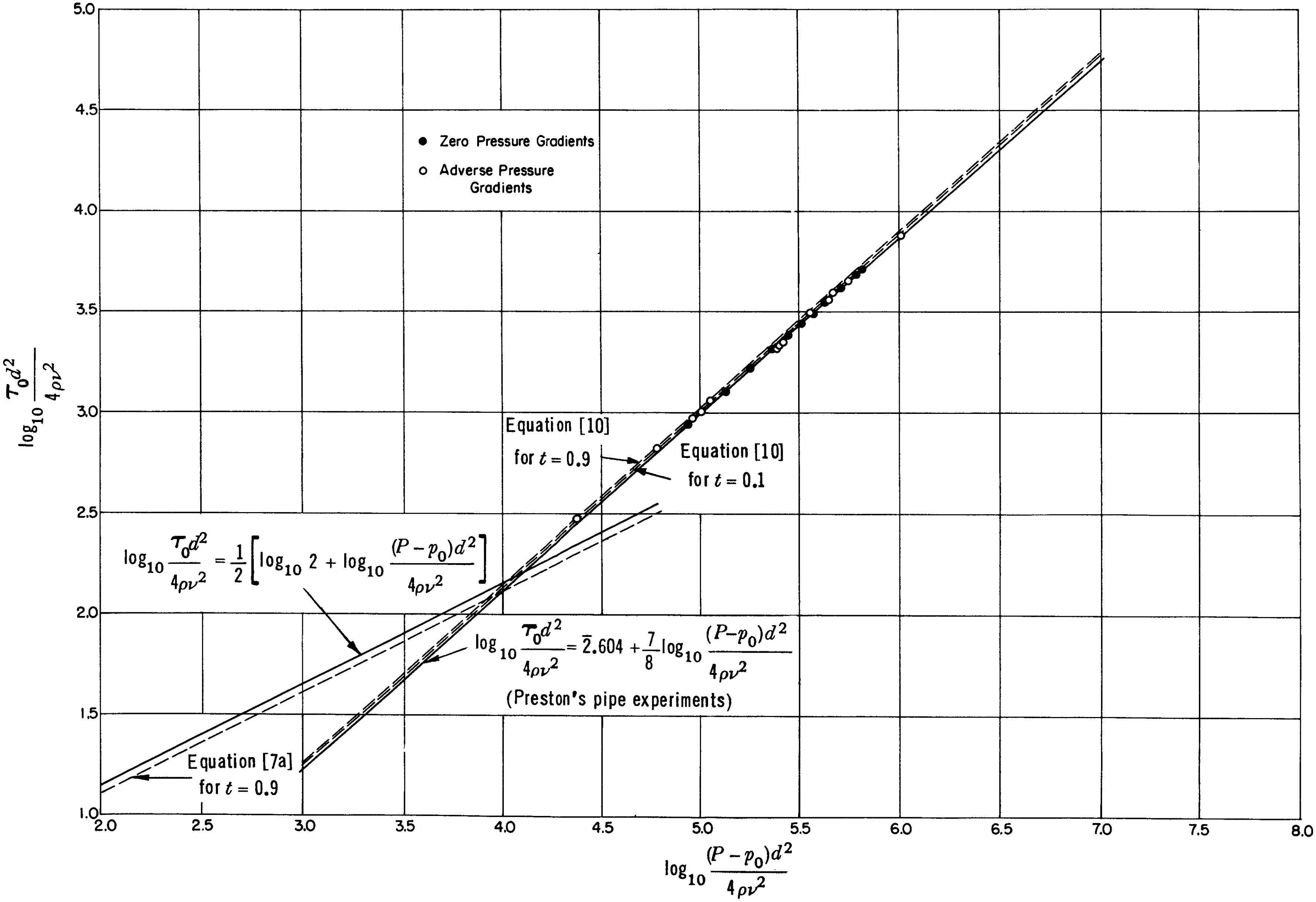


Figure 6 - Nondimensional Plot of the Calibration Curve for Round Surface Pitot Tubes

RESULTS AND DISCUSSION

As mentioned earlier, one of the typical calibration curves is given in Figure 3. It is clearly indicated that the readings from two surface pitot tubes having thickness ratios of 0.896 and 0.676, respectively, yield essentially the same calibration curve. It is therefore concluded that the wall thickness of the tube is not important insofar as the measurement of local skin friction is concerned. The same conclusion* has also been drawn by the National Physical Laboratory in England.

The dimensionless parameters $\tau_0 d^2/4 \rho \nu^2$ and $[(P - p_0) d^2]/4 \rho \nu^2$ can be calculated from the calibration curves and the local skin-friction coefficients. The experimental results are plotted logarithmically in Figure 6. The experimental points for the conditions of zero pressure gradient as well as for adverse pressure gradient are reduced to a single line which has been suggested previously by Equation [10]. It is noteworthy that the results obtained from a flat surface are in good agreement with the empirical equation obtained by the Preston pipe experiments. This additional experimental evidence further substantiates the validity of the inner law as suggested by Ludwieg and Tillmann. Equation [10] is also represented in Figure 6 for the thickness ratios of 0.1 and 0.9, respectively, for the purpose of demonstrating the fact that the relative dimensions of the surface pitot tube are not important.

An additional remark should be made concerning the assumption of a 1/7-power velocity distribution in the derivation of Equation [10]. It is well known that the logarithmic law of velocity distribution replaces the power law when the Reynolds number is large. However, the method of measuring an unknown local skin friction by surface pitot tubes may still be used since one can always select a pitot-tube size such that the dimensionless parameter $[(P - p_0) d^2]/4 \rho \nu^2$ will lie in the range covered by the present calibrations. The maximum value of the $\log_{10} [(P - p_0) d^2]/4 \rho \nu^2$ obtained by Preston is about 6.5.

No additional data were obtained in the laminar-flow region since the original plan was to calibrate the tube for the purpose of local friction measurements on a body of revolution at relatively high Reynolds number where the thickness of laminar sublayer is negligible.

The investigations have been restricted to smooth surfaces. Additional research will be necessary to extend this method to measuring skin friction in rough surfaces where the dimensionless roughness parameters and Reynolds number may be equally important.

CONCLUSIONS

1. The surface pitot tube technique for determining the local skin friction can be used for the boundary-layer flow with adverse pressure gradients.

2. The calibration curve of round surface pitot tubes on flat surfaces with zero pressure gradient as well as with adverse pressure gradients checks almost identically with that obtained by Preston in his pipe experiments.

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*A private communication from Dr. Preston.

3. Based upon the simplified assumption, the performance of the round surface pitot tubes can be calculated either according to Equation [11] or Equation [10] if thickness correction is desired. Performance of a tube of any shape can therefore be calculated and the need for calibration thus eliminated.

4. Based upon the simplified analysis and the experimental results, the wall thickness of the tube if not considered important for local skin-friction measurements.

ACKNOWLEDGMENTS

The author wishes to express his thanks for the suggestions offered by Mr. M.P. Tulin, formerly of the Taylor Model Basin, and for the critical review of this report by Mr. P.S. Granville.

REFERENCES

1. Kempf, G., "Neue Ergebnisse der Widenstandsforschung," Werft, Reederei, Hafen, 10 (1929).

2. Schultz-Grunow, F., "New Frictional Resistance Law for Smooth Plates," National Advisory Committee for Aeronautics Technical Memorandum 986 (1941).

3. Liepmann, H.W. and Dhawan, S., "Direct Measurements of Local Skin Friction in Low Speed and High Speed Flow," Proceedings First U.S. National Congress for Applied Mechanics, Chicago (1951). See also Dhawan, S., "Direct Measurements of Skin Friction," National Advisory Committee for Aeronautics Technical Note 2567 (1952).

4. Fage, A. and Falkner, V.M., "An Experimental Determination of the Intensity of Friction on the Surface of an Aerofoil," Aeronautical Research Committee (Great Britain) Reports and Memoranda 1315 (Apr 1930).

5. Newman, B.G., "Skin Friction in a Retarded Turbulent Boundary Layer Near Separation," Aeronautical Research Laboratory (Australia) Report A.73 (Nov 1950).

6. Ludwieg, H., "Instrument for Measuring the Wall Shearing Stress of Turbulent Boundary Layer," Ing. Archiv., Vol. 17, No. 3, pp. 207-218 (1949). Translated as National Advisory Committee for Aeronautics Technical Memorandum 1284 (1950).

7. Preston, J.H., "The Determination of Turbulent Skin Friction by Means of Pitot Tubes," Journal of Royal Aeronautical Society 110, Vol. 58 (Feb 1954).

8. Ludwieg, H. and Tillmann, W., "Investigation of the Wall Shearing Stress in Turbulent Boundary Layer," Ing. Archiv., Vol. 17, No. 4, pp. 288-299 (1949). Translated as National Advisory Committee for Aeronautics Technical Memorandum 1285 (1950).

9. Laufer, J. "Investigation of Turbulent Flow in Two-Dimensional Channel," National Committee for Aeronautics Technical Note 2123 (Jul 1950).

10. Millikan, C.B., "A Critical Discussion of Turbulent Flow in Channels and Circular Pipes," Proceedings Fifth Congress for Applied Mechanics, Cambridge, Mass., pp. 386-392 (1938).

11. Cooper, R.D. and Tulin, M.P. 'Calibration of TMB's Low-Turbulence Wind Tunnel," David Taylor Model Basin Report (in preparation).

12. Landweber, L., "The Frictional Resistance of Flat Plates in Zero Pressure Gradient," Transactions Society of Naval Architects and Marine Engineers, Vol. 61 (1953).

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