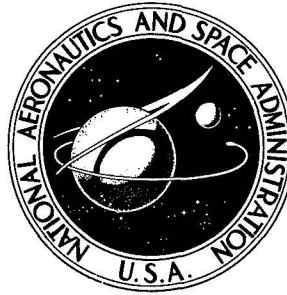


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# USE OF PRESTON TUBES FOR MEASURING HYPERSONIC TURBULENT SKIN FRICTION

*by Earl R. Keener and Edward J. Hopkins*

*Ames Research Center*

*Moffett Field, Calif.*

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# USE OF PRESTON TUBES FOR MEASURING HYPERSONIC TURBULENT SKIN FRICTION<sup>1</sup>

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## SUMMARY

A brief review is made of supersonic Preston tube correlations which account for the effects of Mach number and Reynolds number for adiabatic surfaces. Experimental results are presented which show that two of these correlations are applicable to nonadiabatic surfaces in an airstream at a Mach number of 7. Direct measurements with a skin-friction balance were used for the calibrations. The Reynolds number ranged from 4 to 110 million, and the ratio of wall-to-adiabatic-wall temperature ranged from 0.3 to 0.5. The major conclusion is that the correlation can be simplified and made independent of the boundary-layer-edge condition by basing the correlation factors on only three measurements: wall temperature, wall pressure, and Preston tube pressure.

## INTRODUCTION

Skin friction is a difficult force to measure directly, requiring a delicate floating-element balance. Preston (ref. 1) showed that at subsonic speeds the pressure from a circular pitot tube placed on a test surface can be related to local skin friction. Similarity parameters given by Preston correlate the effects of Reynolds number and tube size. Thus, the Preston tube can be utilized to measure skin friction in test areas where skin-friction balances are difficult to install. The authors (ref. 2) extended the calibration to supersonic speeds by developing correlation factors that collapse supersonic Preston tube measurements onto the Preston incompressible calibration curve.

This paper presents the results of a recent calibration at a nominal Mach number of 7 on nonadiabatic surfaces. Measurements were made on both a flat plate and on the tunnel wall in the Ames 3.5-Foot Hypersonic Wind Tunnel. Direct measurements of skin friction with balances were used in the calibration. The Reynolds number ranged from 4 to 110 million, and the ratio of wall-to-adiabatic-wall temperature ranged from 0.3 to 0.5. Five methods for possibly correlating the effects of Mach number, Reynolds number, and heat transfer are investigated.

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<sup>1</sup>Presented at the "AIAA 4th Aerodynamic Testing Conference," Cincinnati, Ohio, April 28-30, 1969.

Before presenting the results of the experimental investigation, the existing supersonic and hypersonic Preston tube investigations are reviewed briefly.

#### NOTATION

$C_f$	local skin-friction coefficient, $\frac{\tau_w}{q_e}$
$C_p$	pressure coefficient, $\frac{\Delta p}{q_e}$
$d$	outside diameter of Preston tube
$M$	Mach number
$M_S$	Mach number indicated by Preston tube from the ratio, $\frac{p_s}{p_e}$ , using Rayleigh pitot equation when supersonic
$p_e$	static pressure
$p_s$	Preston tube pressure
$\Delta p$	differential pressure, $p_s - p_e$
$Pr$	Prandtl number
$q$	dynamic pressure, $\frac{1}{2} \rho U^2$
$r$	temperature recovery factor
$R$	gas constant for air, 1716 ft <sup>2</sup> /sec <sup>2</sup> °R
$R_d$	Reynolds number based on Preston tube diameter, $\frac{U_e}{\nu_e} d$
$R_\theta$	Reynolds number based on momentum thickness, $\frac{U_e}{\nu_e} \theta$
$T$	temperature
$U$	velocity
$U_\tau$	friction velocity, $\left(\frac{\tau_w}{\rho}\right)^{1/2}$
$\theta$	boundary-layer momentum thickness
$\mu$	dynamic viscosity
$\nu$	kinematic viscosity
$\rho$	mass density

$\gamma$	ratio of specific heats
$\tau$	local shear stress
$( )'$	variables based on a reference temperature condition
$(\bar{\phantom{x}})$	variables in a constant properties (incompressible) flow

#### Subscripts

aw	adiabatic wall conditions
e	boundary-layer-edge conditions
H	Harkness
HK	Hopkins and Keener
M	Moore
s	local flow conditions indicated by Preston tube
S	Sigalla
t	total conditions (isentropic stagnation)
w	wall conditions

#### REVIEW OF PRESTON TUBE CALIBRATION FACTORS

In a comprehensive study of Preston tubes (ref. 2) the authors reviewed most of the existing Preston tube investigations in both incompressible and supersonic adiabatic flow. A brief review of that study and investigations at hypersonic speeds, not listed in the study, are discussed as a background to the present results. Additional Preston tube investigations are listed in references 3 to 13.

LOCAL SKIN FRICTION =  $f$  (PRESTON TUBE PRESSURE,  $p_s$ )

Incompressible Flow - Adiabatic

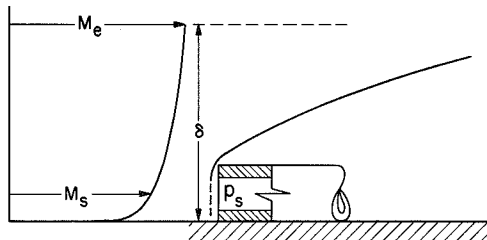


Figure 1 - Preston tube.

A Preston tube (fig. 1) is simply a circular pitot tube touching the surface. Preston (ref. 1) showed that the stagnation pressure,  $p_s$ , from the pitot tube can be related to the surface shear stress (skin friction). He based his suggestion on the Prandtl-Kármán "law of the wall" for turbulent flow, which states that the

fluid properties near the wall are related to the surface shear stress. The resulting universal relationship for the law is:

$$\bar{U}/\bar{U}_\tau = f(\bar{U}_\tau y/\bar{\nu}) \quad (1)$$

Preston showed that similarity parameters for a surface pitot tube may be obtained from the law of the wall (also from dimensional analysis) and that these factors correlate the effects of Reynolds number and tube size. Preston's resulting functional equation is:

$$\bar{\Delta p} d^2 / 4 \bar{\rho} \bar{\nu}^2 = f(\tau_w d^2 / 4 \bar{\rho} \bar{\nu}^2) \quad (2)$$

where  $\bar{\Delta p} = p_s - p_e = q_s$  (the dynamic pressure indicated by the Preston tube) and where  $d/2 = y$  in equation (1). Preston calibrated several surface pitot tubes of different diameters in turbulent pipe flow (ref. 1).

As a matter of convenience, equation (2) may also be written

$$\bar{R}_d^2 \bar{C}_p = f(\bar{R}_d^2 \bar{C}_f) \quad (3)$$

where

$$\bar{R}_d^2 \bar{C}_p = 8(\bar{\Delta p} d^2 / 4 \bar{\rho} \bar{\nu}^2) \quad (4)$$

and

$$\bar{R}_d^2 \bar{C}_f = 8(\tau_w d^2 / 4 \bar{\rho} \bar{\nu}^2) \quad (5)$$

Equation (3) was used in reference 2 and is used in the calibration herein.

#### Supersonic Flow - Adiabatic

Several existing functional equations for calibrating Preston tubes in compressible flow were evaluated (ref. 2) to determine which gives the best correlation with the incompressible curve of Preston. The objective was to correlate the effects of Mach number and Reynolds number ( $R_d$ ). Each equation evaluated consisted of the transformation factors developed to transform  $R_d^2 C_p$  and  $R_d^2 C_f$  into  $\bar{R}_d^2 \bar{C}_p$  and  $\bar{R}_d^2 \bar{C}_f$ . It was shown that the simple substitution of wall density and wall viscosity in equations (4) and (5) does not collapse the data onto the Preston incompressible curve. However, the authors developed satisfactory correlation factors (ref. 2) using the dynamic pressure indicated by the Preston tube ( $\bar{\Delta p} = q_s = (\gamma/2) M_s^2 p_e$ ) and basing the viscosity and density on the reference temperature,  $T'$ , from Sommer and Short (ref. 14). The resulting functional equation (eq. (4), ref. 2) in the form of  $\bar{R}_d^2 \bar{C}_p = f(\bar{R}_d^2 \bar{C}_f)$  is

$$f_2(T') R_d^2 (M_s/M_e)^2 = f[f_2(T') R_d^2 C_f] \quad (6)$$

where  $f_2(T') = (\rho_e/\rho')(v_e/v')^2$ , which is a transformation factor based on  $T'$  for converting to constant-properties flow. Equation (6) is also listed in table I, which summarizes the functional equations used herein.

TABLE I.- SUMMARY OF FUNCTIONAL EQUATIONS USED WITH PRESENT DATA

Method	Calibration factors		Functional equation number
	$\bar{R}_d^2 \bar{C}_p$	$\bar{R}_d^2 \bar{C}_f$	
Hopkins-Keener, $T'$ (ref. 2, eq. (4))	$f_2(T') R_d^2 (M_s/M_e)^2$	$f_2(T') R_d^2 C_f$	(6)
Hopkins-Keener, $T_w$ , (ref. 2, eq. (9))	$(1.4) R T_w (M_s d/v_w)^2$	$2 \tau_w d^2 / \rho_w (v_w)^2$	(10)
Sigalla, $T'$ (ref. 15)	$[(v_e/v') R_d (U_s/U_e)]^2$	$f_2(T') R_d^2 C_f$	(11)
Harkness (ref. 16)	$(1/2) f_2(T_w) R_d^2 C_f (\bar{U}_s/\bar{U}_\tau)_H^2$	$f_2(T_w) R_d^2 C_f$	(12)
Moore (ref. 17)	$(1/2) f_2(T_w) R_d^2 C_f (\bar{U}_s/\bar{U}_\tau)_M^2$	$f_2(T_w) R_d^2 C_f$	(13)

where

$$(\bar{U}_s/\bar{U}_\tau)_H = f(\eta) \quad \text{in equation (19) of reference (18)} \quad (14)$$

$$(\bar{U}_s/\bar{U}_\tau)_M = f(\eta) \quad \text{in equation (33) of reference (17)} \quad (15)$$

and

$$f_2(T) = (v_e/v)^2 (\rho_e/\rho) \quad (16)$$

$$T' = T_e (0.55 + 0.035 M_e^2 + 0.45 T_w/T_e) \quad (17)$$

$$\mu = 2.32 T^{1/2} (10)^{-8} / [1 + (220/T) (10)^{-9/T}],$$

$$\text{lb-sec/ft}^2, \text{ Keyes' equation (ref. 19)} \quad (18)$$

The results of the previous supersonic calibration (ref. 2) presented in figure 2 indicate that the data collapse onto the Preston incompressible calibration curve when the functional equation (6) is used. It is remarkable that the substitution of  $q_s$  for  $\Delta p$  correlates the effect of compressibility for a pitot tube touching the surface; evidently, the interference effects from the probe are also correlated.<sup>2</sup> In the application of the Preston tube calibration, it was recommended (ref. 2) that tube diameters be selected to

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<sup>2</sup>Since publication of reference 2, the authors have found that the law of the wall equation that results from the authors' correlation factors does not adequately correlate velocity profiles. This result is also discussed in reference 20. It has generally been assumed in previous investigations that factors which correlate the law of the wall will also correlate Preston tube pressures and conversely. Evidently, this is not always correct.

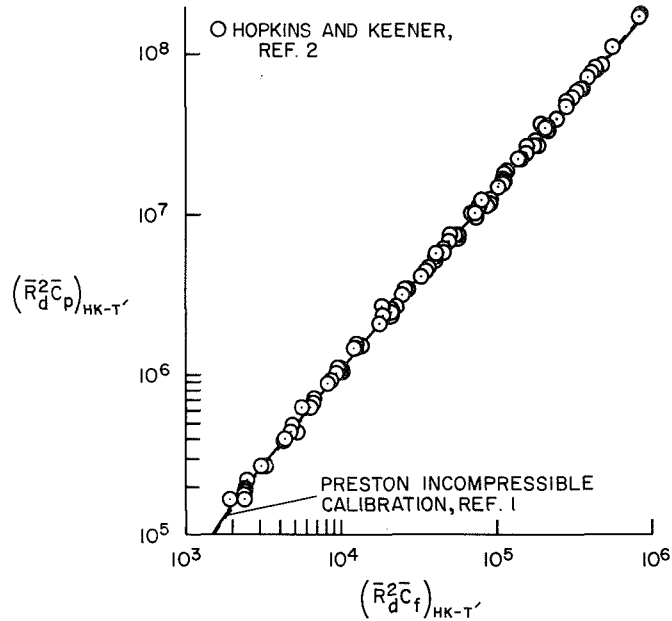


Figure 2.- Previous supersonic Preston tube calibration, equation (6) by Hopkins and Keener; adiabatic,  $M_e = 2.4$  to  $3.4$ ,  $U_e/v_e$ ,  $\text{ft}^{-1} = 1$  to  $3.2 \times 10^6$ ,  $d$ , in. =  $1/32$  to  $1/4$ .

utilize the linear part of the calibration. The equation for the linear part of the Preston calibration curve ( $\bar{R}_d^2 \bar{C}_f > 10^4$ ), using Preston's constants is

$$\log_{10} \bar{R}_d^2 \bar{C}_f = 0.875 \log_{10} \bar{R}_d^2 \bar{C}_p - 1.283 \quad (7)$$

From equations (6) and (7)

$$\begin{aligned} C_f &= 0.0522 [f_2(T') R_d^2]^{-1/8} (M_s/M_e)^{7/4} \\ &= 0.0522 [(\rho_e/\rho') (U_e d/v')^2]^{-1/8} (M_s/M_e)^{7/4} \end{aligned} \quad (8)$$

and

$$\tau_w = 0.0261 [d^2/\rho' (v')^2]^{-1/8} (\gamma p_e M_s^2)^{7/8} \quad (9)$$

It is shown theoretically (ref. 2) that the calibration factors of equation (6) might be simplified without serious loss in accuracy if  $T_w$  is used rather than  $T'$ . The resulting functional equation (eq. (9), ref. 2), based on three measurements ( $T_w$ ,  $p_s$ , and  $p_w$ ), is given in table I as follows:

$$1.4 \gamma T_w (M_s d/v_w)^2 = f [2 \tau_w d^2 / \rho_w (v_w)^2] \quad (10)$$

Sigalla (ref. 15) presented a reference temperature method similar to equation (6) except that  $\bar{\Delta}p$  in equation (4) was replaced by  $(1/2) \rho' U_s^2$ . Consequently, this method requires a determination of  $U_s = M_s (\gamma R T_s)^{1/2}$ , which requires a determination of  $T_s$  in addition to  $M_s$ . The resulting calibration factors are presented in table I as functional equation (11). It was shown (ref. 21) that the factors in equation (6) give slightly better



correlation for supersonic data, but it was suggested that both methods should be examined at higher Mach numbers with heat transfer to determine the best correlation under these conditions.

One of the most extensive investigations of the compressible turbulent boundary layer prior to 1960 was carried out at the Defense Research Laboratory of the University of Texas. Wilson (ref. 22) developed a compressible skin-friction relation using the von Kármán mixing length in the Prandtl shear stress equation. Fenter and Stalmach (ref. 23) used the Wilson theory to develop a compressible law of the wall, which they applied successfully to Preston tube correlations in supersonic adiabatic flow. (The assumption of isoenergetic flow limited the method to adiabatic surfaces.) This method is discussed in more detail in the previous study (ref. 2).

### Hypersonic Flow - Nonadiabatic

Attempts to develop functional equations for calibrating Preston tubes in a heat-transfer environment were made in two subsequent Defense Research Laboratory investigations. Harkness (ref. 16) developed a method for velocity profiles, and Davidson (ref. 18) applied it to Preston tube measurements. Moore (ref. 17) tried a different form of the Harkness equation. Both methods are extensions of the mixing-length concept to include the effect of heat transfer. These two methods differ primarily in the assumed temperature-velocity relationship through a boundary layer with heat transfer. Harkness utilized a modified Crocco relationship ( $Pr \neq 1$ ) and Moore chose a quadratic form similar to that for the adiabatic wall case. Moore substantiated his approach with wind-tunnel-wall temperature data; however, Seiff and Short (ref. 24) pointed out that tunnel-wall temperature distributions differed from the available free-flight results.<sup>3</sup> The correlation factors developed by Harkness and Moore are listed in table I.<sup>4</sup> Neither method successfully correlated the data available in references 17 and 18. The factors of Harkness

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<sup>3</sup>More recently it has been further demonstrated that the temperature distributions through the boundary layers on flat plates and wind-tunnel walls are likely to differ. For example, it was found in the present investigation and reported in reference 25 that the flat-plate temperature distributions follow the Crocco temperature distribution ( $Pr = 1$ ); whereas, the wall temperature distributions follow more closely the quadratic form used in reference 17.

<sup>4</sup>In order to plot the functions of both Harkness (ref. 16) and Moore (ref. 17) in the form of  $\bar{R}_d^2 \bar{C}_p$  and  $\bar{R}_d^2 \bar{C}_f$ , as used herein, it is necessary to transform their functions, which have the form of equation (1), as follows:

$$\bar{R}_d^2 \bar{C}_p = 4(\tau_w d^2 / 4 \bar{\rho} \bar{v}^2) (\bar{U}_s / \bar{U}_\tau)^2 = 1/2 [f_2(T_w) R_d^2 C_f (\bar{U}_s / \bar{U}_\tau)^2]$$

$$\bar{R}_d^2 \bar{C}_f = 8(\tau_w d^2 / 4 \bar{\rho} \bar{v}^2) = f_2(T_w) R_d^2 C_f$$

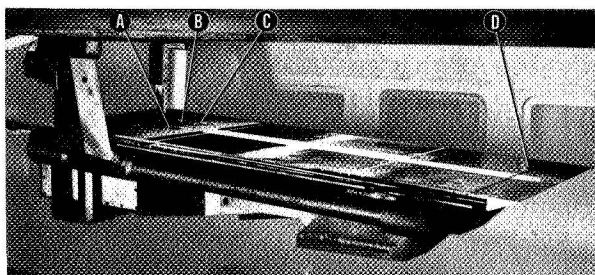
where  $\bar{U}_s / \bar{U}_\tau$  is given by the rather complex function of either reference 16 or 17.

displaced both the adiabatic and the nonadiabatic data from the incompressible curve. The factors of Moore appeared to correlate the adiabatic data but not the nonadiabatic data.

## PRESENT HYPERSONIC EXPERIMENT - NONADIABATIC

In the following sections, a recent hypersonic experimental investigation of Preston tubes mounted on nonadiabatic surfaces is described. The investigation was conducted in air in the Ames 3.5-Foot Hypersonic Wind Tunnel at a nominal Mach number of 7. Preston tubes were mounted on both a flat-plate model and on the wind-tunnel wall.

### Instrumentation



- (A) SKIN-FRICTION BALANCE
- (B) BOUNDARY-LAYER SURVEY COMPLEX
- (C) PRESTON TUBES
- (D) BOUNDARY-LAYER TRIPS

Figure 3.- Flat plate mounted in Ames 3.5-Foot Hypersonic Wind Tunnel.

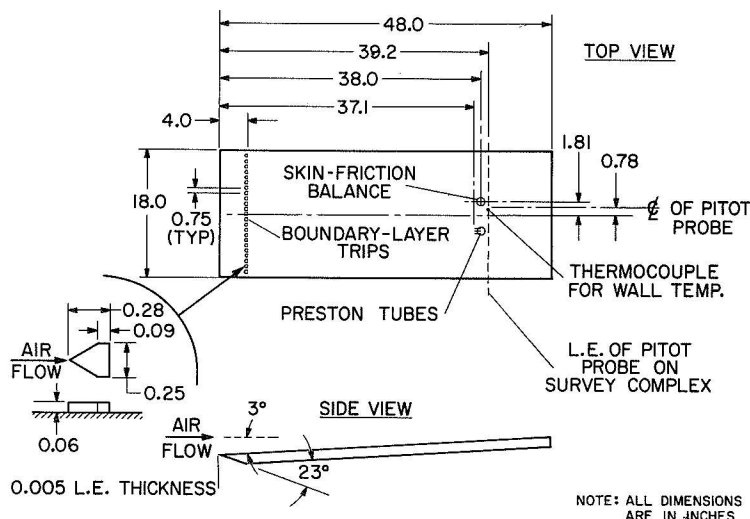


Figure 4.- Geometry of flat plate and other pertinent details of present test.

Flat plate.- Figure 3 is a photograph of the model mounted in the Ames 3.5-Foot Hypersonic Wind Tunnel and figure 4 is a dimensional sketch of the flat plate. The model was water cooled internally to obtain nearly isothermal wall conditions. Surface pressures and temperatures were measured, and pitot-pressure and total-temperature boundary-layer profiles were measured at the skin-friction test station. A typical skin-friction balance and the Preston tubes for the flat plate are shown in figure 5. For low Reynolds numbers it was necessary to trip the boundary layer artificially so that turbulent flow would occur at the survey station (fig. 4). Effectiveness of the trips was verified by the sublimation visual-flow technique in which fluorene in a solution of petroleum ether was sprayed on the model (ref. 26).

Wind-tunnel wall.- Preston tube and skin-friction measurements and surveys of

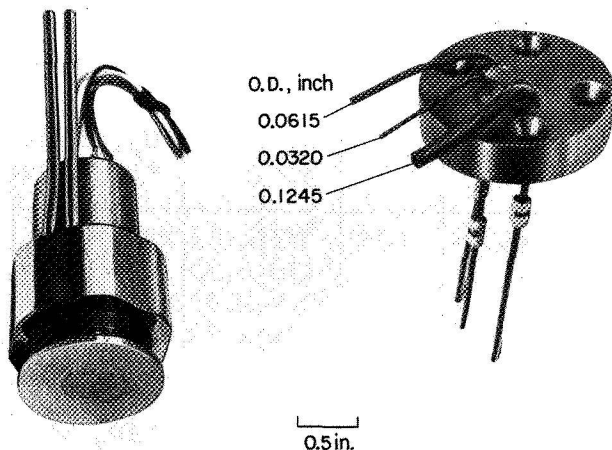
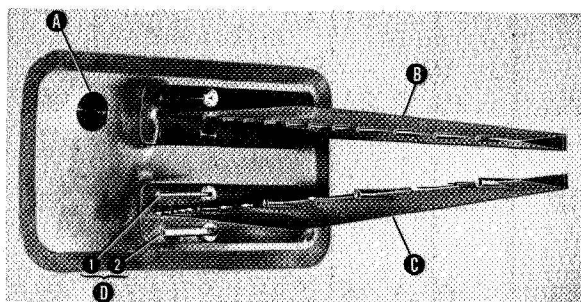


Figure 5.- Skin-friction balance and flat-plate Preston tubes.

pitot pressure and total temperature were made on the test-section wall at a distance of 27.5 feet from the throat and a position 8.5 feet behind the beginning of the test section (fig. 6).

Skin-friction balance.- The skin friction was directly measured by floating-element balances manufactured by Kistler Instrument Corporation (fig. 5). Two different balances were used. The first was made for the flat plate and had a floating-element diameter of 0.370 inch. The second balance was made to fit the curved surface of the test-section wall and had a floating-element diameter of 0.500 inch. The balance elements were self-nulling to the center position with a gap of 0.003 inch and statically balanced in all axes. Electrical components were maintained at temperatures below 200° F by a water jacket. The balances were calibrated against known weights. A calibrated self-test coil in the gage was used to check the calibration between each test run.



- (A) SKIN-FRICTION BALANCE
- (B) PITOT RAKE
- (C) TEMPERATURE RAKE
- (D) PRESTON TUBES (O.D., inch)
  - ① 0.127
  - ② 0.251

Figure 6.- Instrumentation mounted on wall of Ames 3.5-Foot Hypersonic Wind Tunnel.

## Data Reduction

Compressible flow relations including real gas effects were used to calculate the local flow conditions on the flat plate from the measured conditions. Momentum thickness of the boundary layers on the flat plate was calculated from the pitot-pressure profiles and a Crocco linear total-

temperature distribution with velocity ( $Pr = 1$ ), which was found to agree with the measured distribution of total temperatures (ref. 25). Viscosity was calculated by Keyes' equation (eq. (18), table I). The flat-plate data are tabulated in table II.

The reduction of the test-section-wall data was similar to that for the flat plate, except that the calculations of momentum thickness used the measured total-temperature profile, which differed from the Crocco linear distribution on the flat plate (ref. 25). The tunnel-wall data are tabulated in table III.

TABLE II.- PRESTON TUBE DATA FOR FLAT PLATE,  $M_e = 6.5$ 

$U_e$ , fps	$p_e$ , psf	$q_e$ , psf	$T_e$ , °R	$T_w$ , °R	$T_{t,e}$ , °R	$\frac{U_e}{v_e} \times 10^{-6}$ , per ft	$Re \times 10^{-3}$	$\frac{T_w}{T_{aw}}$	$C_f \times 10^3$	$p_s$ , psf	$M_s$	$U_s$ , fps	B. L. trips
4557	22.0	650	205	583	1850	1.70	2.26	0.34	1.57	<sup>a</sup> 87 1.63 2296 <sup>b</sup> 170 2.38 3089 <sup>c</sup> 254 2.93 3510			Off
4702	37.4	1105	218	587	1960	2.62	4.56	.32	1.22	<sup>a</sup> 164 1.74 2480 <sup>b</sup> 259 2.24 3042 <sup>c</sup> 298 2.41 3203			On
3939	14.0	415	153	551	1410	1.64	3.30	.43	1.25	<sup>a</sup> 33 1.17 1520 <sup>b</sup> 68 1.84 2275 <sup>c</sup> 102 2.29 2669			On
4037	21.5	636	161	564	1477	2.37	5.90	.42	1.20	<sup>a</sup> 71 1.47 1918 <sup>b</sup> 126 2.04 2513 <sup>c</sup> 159 2.31 2744			On
4033	13.6	403	160	559	1474	1.49	2.39	.41	1.52	<sup>a</sup> 41 1.38 1806 <sup>b</sup> 86 2.13 2586 <sup>c</sup> 134 2.69 3008			Off
3888	23.1	683	149	561	1376	2.82	3.82	.45	1.23	<sup>a</sup> 80 1.52 1928 <sup>b</sup> 148 2.14 2529 <sup>c</sup> 207 2.57 2837			Off
3550	8.1	238	124	537	1158	1.26	2.18	.51	1.41	<sup>a</sup> 16 1.04 1283 <sup>b</sup> 32 1.65 1938 <sup>c</sup> 59 2.30 2454			On
3625	12.1	356	130	543	1250	1.81	3.89	.50	1.35	<sup>a</sup> 32 1.27 1567 <sup>b</sup> 62 1.90 2188 <sup>c</sup> 94 2.38 2556			On
3679	27.7	820	133	572	1240	4.01	8.33	.51	1.00	<sup>a</sup> 87 1.43 1776 <sup>b</sup> 154 1.98 2302 <sup>c</sup> 184 2.19 2462			On
3665	27.8	822	132	571	1231	4.06	6.42	.51	1.06	<sup>a</sup> 101 1.56 1905 <sup>b</sup> 177 2.13 2417 <sup>c</sup> 232 2.47 2651			Off
3667	41.3	1222	132	571	1232	6.06	----	.51	.87	<sup>a</sup> 175 1.70 2049 <sup>b</sup> 260 2.12 2409 <sup>c</sup> 325 2.40 2603			Off

Pitot-tube diameters: <sup>a</sup>0.002667 ft; <sup>b</sup>0.005125 ft; <sup>c</sup>0.01038 ft.

TABLE III.- PRESTON TUBE DATA FOR WIND-TUNNEL WALL

$M_e$	$U_e$ , fps	$p_e$ , psf	$q_e$ , psf	$T_{e,OR}$	$T_{w,OR}$	$T_{t,e,OR}$	$\frac{U_e}{v_e} \times 10^{-6}$ , per ft	$R\theta \times 10^{-3}$	$\frac{T_w}{T_{aw}}$	$C_F \times 10^3$	$p_s$ , psf	$M_s$	$U_s$ , fps
7.47	3901	14.0	546	114	543	1350	2.95	52.4	0.44	0.684	<sup>a</sup> 84.4	2.07	2433
											<sup>b</sup> 104.5	2.33	2633
7.48	3875	18.1	710	112	555	1333	3.86	56.4	.46	.650	<sup>a</sup> 115.2	2.13	2476
											<sup>b</sup> 136.1	2.34	2628
7.38	3753	5.1	196	108	544	1258	1.16	20.5	.47	.714	<sup>a</sup> 19.9	1.61	1954
											<sup>b</sup> 28.5	1.98	2291
7.44	3730	9.4	363	105	552	1242	1.97	40.2	.49	.676	<sup>a</sup> 48.2	1.90	2216
											<sup>b</sup> 62.1	2.18	2442
7.45	3968	13.8	537	118	558	1395	2.73	48.1	.44	.670	<sup>a</sup> 80.9	2.04	2445
											<sup>b</sup> 100.5	2.30	2651
7.46	3837	18.2	708	110	568	1318	4.01	62.6	.47	.630	<sup>a</sup> 110.9	2.09	2430
											<sup>b</sup> 132.3	2.30	2590
7.37	4021	5.0	192	124	554	1432	.91	18.7	.42	.808	<sup>a</sup> 20.0	1.64	2078
											<sup>b</sup> 29.7	2.05	2474
7.45	3904	9.0	348	114	567	1353	1.88	31.7	.46	.726	<sup>a</sup> 47.2	1.92	2319
											<sup>b</sup> 61.8	2.23	2572
7.41	4218	4.3	166	135	546	1565	.69	16.4	.39	.886	<sup>a</sup> 18.3	1.70	2204
											<sup>b</sup> 27.4	2.13	2632
7.45	4193	8.6	334	132	548	1547	1.44	28.4	.40	.782	<sup>a</sup> 49.0	2.01	2511
											<sup>b</sup> 65.4	2.35	2806
7.44	4301	13.6	528	139	557	1622	2.09	52.6	.37	.733	<sup>a</sup> 87.8	2.15	2700
											<sup>b</sup> 108.9	2.42	2922
7.46	4198	17.8	695	132	568	1550	2.98	53.0	.40	.712	<sup>a</sup> 118.1	2.18	2681
											<sup>b</sup> 144.0	2.43	2879
7.39	4345	4.9	186	144	552	1655	.71	21.1	.35	.912	<sup>a</sup> 21.9	1.76	2325
											<sup>b</sup> 31.8	2.17	2734
7.43	4365	9.1	352	144	562	1668	1.34	30.1	.36	.797	<sup>a</sup> 55.2	2.08	2664
											<sup>b</sup> 70.3	2.37	2921
7.38	4513	4.9	186	156	554	1778	.63	13.2	.33	.945	<sup>a</sup> 22.5	1.78	2416
											<sup>b</sup> 22.0	1.77	2394
7.42	4517	9.3	358	154	564	1777	1.23	33.0	.34	.843	<sup>a</sup> 57.2	2.10	2754
											<sup>b</sup> 75.0	2.43	3054
7.43	4630	13.5	522	162	558	1860	1.66	42.1	.32	.813	<sup>a</sup> 96.5	2.27	2975
											<sup>b</sup> 116.2	2.51	3183

Pitot-tube diameters: <sup>a</sup>0.01058 ft; <sup>b</sup>0.02092 ft.

## Accuracy

The estimated probable uncertainties of the pertinent recorded and calculated quantities are as follows:

$T_{t,e}$	$\pm 50^\circ \text{ R}$	$U_e/v_e$	$\pm 7 \text{ percent}$
$T_w$	$\pm 10^\circ \text{ R}$	$R_\theta$	$\pm 8 \text{ percent}$
$M_e$	$\pm 0.17$	$p_s, p_e$	$\pm 1 \text{ psf}$
$q_e$	$\pm 1 \text{ percent}$	$\tau_w$	$\pm 5 \text{ percent}$

In applying the Preston tube functional equations, the accuracy in obtaining  $\tau_w$  is primarily dependent on the accuracy of  $p_s$ , and is not a strong function of  $M_e$ ,  $U_e/v_e$ , or  $T'$ .

## DISCUSSION OF PRESENT RESULTS

In the presentation that follows, the Preston tube experimental points from the present investigation are used to determine which of the functional equations in table I correlate the data with Preston's incompressible calibration curve. Both flat plate and wind-tunnel-wall measurements are presented in the form of  $\bar{R}_d^2 \bar{C}_p = f(\bar{R}_d^2 \bar{C}_f)$ . The linear part of the Preston incompressible calibration curve is given by equation (7). Before the Preston tube calibrations are presented, the validity of the skin-friction measurements is discussed briefly.

### Skin Friction

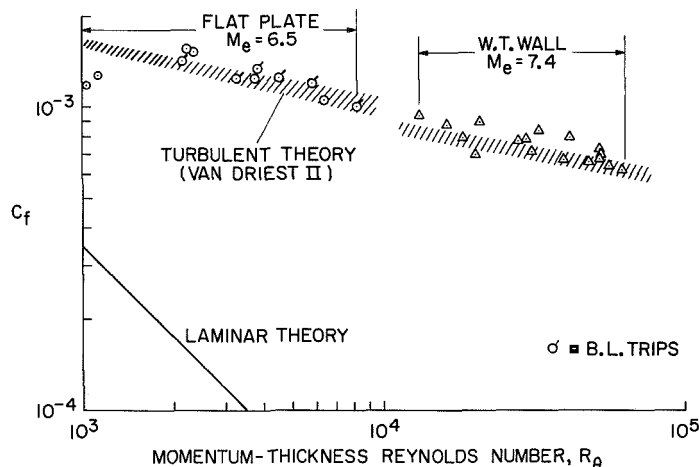


Figure 7.- Present skin-friction measurements;  
 $0.32 < T_w/T_{aw} < 0.51$ .

The measured skin-friction coefficients are presented in figure 7 as a function of the measured momentum-thickness Reynolds number. The cross-hatched bands represent the skin friction predicted by the theory of Van Driest II (ref. 27). The bandwidth represents the effect of the range of  $T_w/T_{aw}$  of the experiment. A curve for laminar flow is also shown. Two data points at the lower Reynolds numbers are in transitional flow and were not used in the Preston

tube calibration. The remaining points are considered to be in turbulent flow. There is no apparent effect of boundary-layer trips on the correlation with  $R_\theta$ ; the trips simply increase the magnitude of  $R_\theta$ . In general, the level and spread of the measured skin friction on the flat plate and on the tunnel wall are also correlated by the method of Van Driest II, when measured  $R_\theta$  is used. These skin-friction measurements are discussed in more detail in reference 25.

## Preston Tube Calibration - Flat Plate

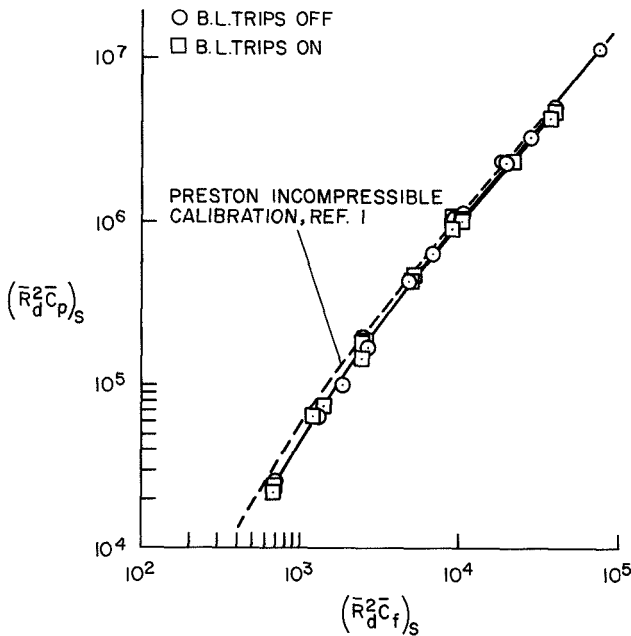


Figure 8.- Present hypersonic Preston tube calibration, equation (11) by Sigalla; flat plate,  $M_e = 6.5$ ,  $U_e/v_e$ ,  $\text{ft}^{-1} = 1.3$  to  $6.1 \times 10^6$ ,  $d$ , in. =  $1/16$  to  $1/8$ ,  $T_w/T_{aw} = 0.32$  to  $0.51$ .

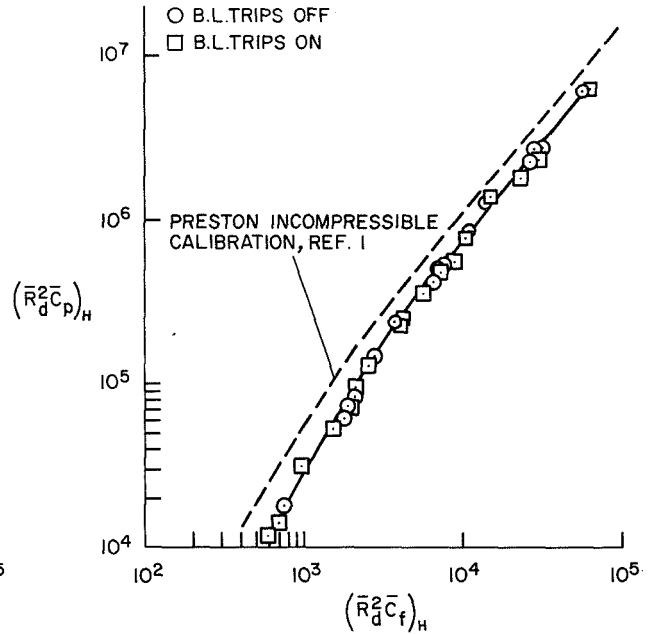


Figure 9.- Present hypersonic Preston tube calibration, equation (12) by Harkness; flat plate,  $M_e = 6.5$ ,  $U_e/v_e$ ,  $\text{ft}^{-1} = 1.3$  to  $6.1 \times 10^6$ ,  $d$ , in. =  $1/16$  to  $1/8$ ,  $T_w/T_{aw} = 0.32$  to  $0.51$ .

Sigalla factors (eq. (11)).- The reference temperature method of Sigalla for correlating Preston tube pressures is presented in figure 8. The data fall close to the linear portion of the Preston incompressible curve. On the basis of these results, it appears that the calibration factors of Sigalla collapse the data for the linear portion of the curve, either with or without boundary-layer trips.

Harkness factors (eq. (12)).- Results in figure 9 indicate that the Harkness calibration factors do not collapse the data onto the linear part of the Preston incompressible curve, either with or without boundary-layer trips. The displacement of the calibration is similar to the results reported in reference 18.

Moore factors (eq. (13)).- Results presented in figure 10 indicate that the Moore calibration factors, like those of Harkness, also displace the data from the incompressible curve.

Hopkins-Keener factors (eq. (6)).- The authors' reference temperature method, which was shown in figure 2 to correlate the supersonic adiabatic-wall Preston tube data, is presented in figure 11. Since the calibration factors of functional equation (6) require a reference temperature, the reference temperature given by Sommer and Short (eq. (17)) was chosen to be consistent with the choice in reference 2. The Sommer and Short prediction of the effect of heat transfer on skin friction is similar to that of Van Driest II. In figure 11, for  $\bar{R}_d^2 \bar{C}_f > 10^4$ , the method correlates the trips-off data

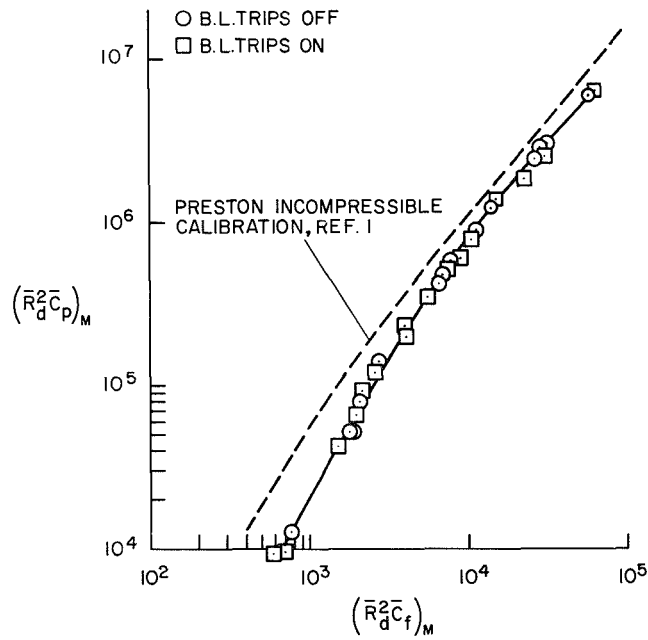


Figure 10.- Present hypersonic Preston tube calibration, equation (13) by Moore; flat plate,  $M_e = 6.5$ ,  $U_e/v_e$ ,  $\text{ft}^{-1} = 1.3$  to  $6.1 \times 10^8$ ,  $d$ , in. =  $1/16$  to  $1/8$ ,  $T_w/T_{aw} = 0.32$  to  $0.51$ .

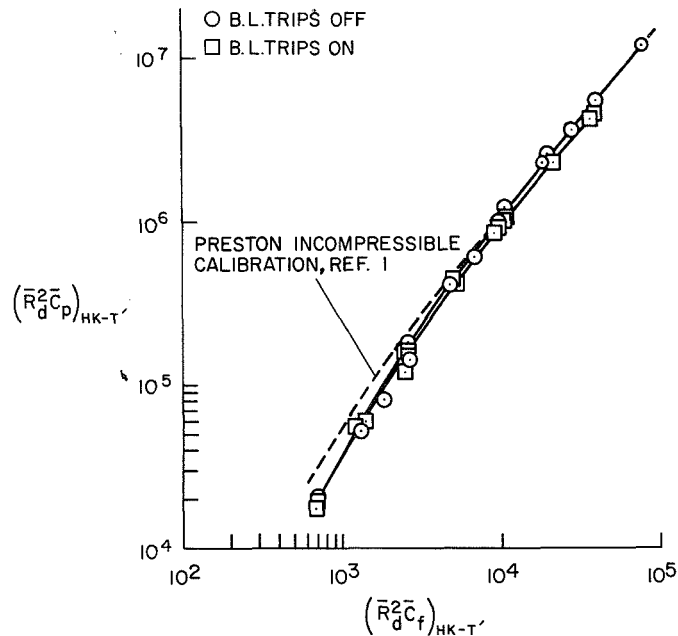


Figure 11.- Present hypersonic Preston tube calibration, equation (6) by Hopkins and Keener; flat plate,  $M_e = 6.5$ ,  $U_e/v_e$ ,  $\text{ft}^{-1} = 1.3$  to  $6.1 \times 10^8$ ,  $d$ , in. =  $1/16$  to  $1/8$ ,  $T_w/T_{aw} = 0.32$  to  $0.51$ .



with the linear part of the Preston incompressible curve. For lower values of this parameter where the curves are nonlinear, heat transfer or Mach number or both appear to affect the correlation. The effects are not considered serious as it is usually possible to use Preston tube sizes such that only the linear part of the calibration curve can be used (generally, 10 to 25 percent of the boundary-layer thickness (ref. 2)). The effect of trips shown in figure 11 does not exceed the tolerable error in skin friction ( $\pm 10$  percent) for most applications.

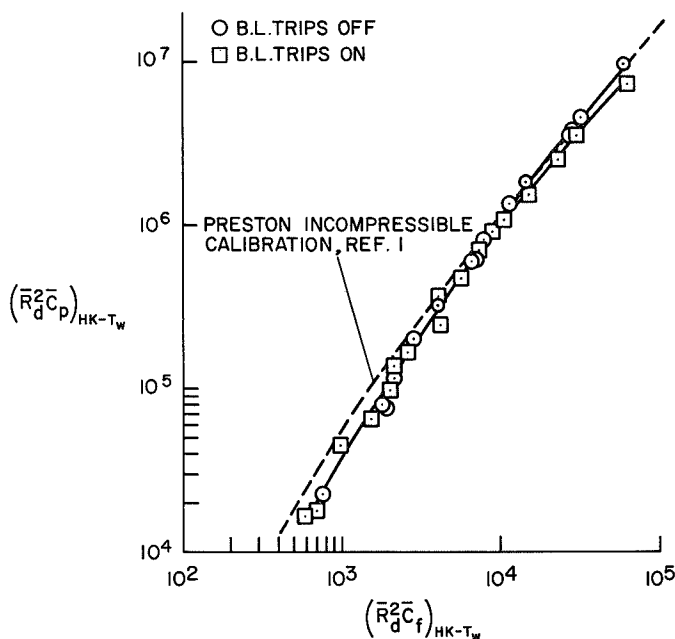


Figure 12.- Simplified hypersonic Preston tube calibration, equation (10) by Hopkins and Keener using surface measurements only; flat plate,  $M_e = 6.5$ ,  $U_e/\nu_e$ ,  $\text{ft}^{-1} = 1.3$  to  $6.1 \times 10^6$ ,  $d$ , in. =  $1/16$  to  $1/8$ ,  $T_w/T_{aw} = 0.32$  to  $0.51$ .

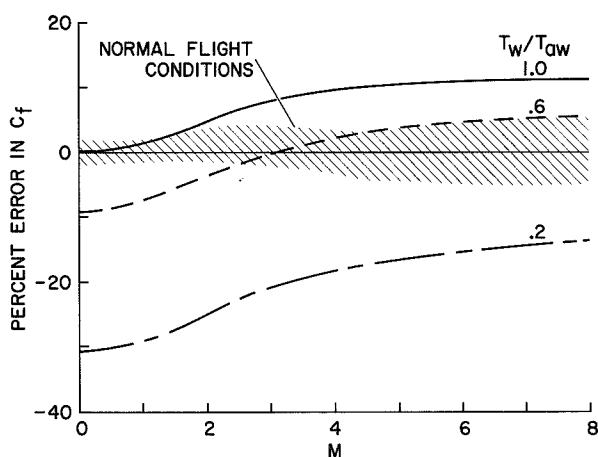


Figure 13.- Predicted error in skin friction using simplified equation (10) based on wall temperature.

#### Simplified calibration

(eq. (10)).- The present authors showed by a theoretical analysis (ref. 2) that the wall temperature might be used as the reference temperature in equation (6) without incurring much loss in accuracy in the correlation. Thus, it would not be necessary to measure the boundary-layer-edge conditions, which are sometimes difficult to determine. For example, at hypersonic Mach numbers the boundary-layer edge might be obscured by the entropy layer induced by leading-edge bluntness. Results from the present investigation with the correlation factors based on wall temperature (eq. (10)) are shown in figure 12. The experimental curve for trips off is coincident with the linear part of the Preston incompressible curve. It follows, therefore, that a good indication of the skin friction can be obtained from Preston tubes from only three measurements: wall temperature, wall static pressure, and Preston tube pressure. There is a shift in the calibration curve when the boundary layer is artificially tripped, similar to the results in figure 11.

The simplified calibration is investigated further in figure 13 to assess the accuracy. Figure 13 shows the predicted error in skin friction when the authors' correlation factors are

based on wall temperature instead of reference temperature (following ref. 2). The percent error in  $C_f$  was predicted for  $T_w/T_{aw} = 0.2, 0.6$ , and  $1.0$  from the following equation:

$$\begin{aligned} \text{Percent error in } C_f &= \{[(C_f)_{T_w}/C_f] - 1\}100 = (F_w^{-1/8} - 1)100 \\ &= [(T_w/T^*)^{0.317} - 1]100 \end{aligned} \quad (19)$$

where  $(F_w)$  is from equation (11) in reference 2. The shaded area represents the approximate normal range of  $T_w/T_{aw}$  expected for flight vehicles. It appears that the error incurred is within  $\pm 5$  percent for most applications. It should be clarified that the simplified calibration does not eliminate the necessity in most investigations of knowing the local conditions at some of the Preston tube locations in order to correlate the results with predictions or with other measurements.

### Tunnel Wall

It has recently been demonstrated that turbulent boundary-layer temperature distributions on wind-tunnel walls differ significantly from the Crocco linear distribution usually found on flat plates (ref. 25). Consequently, it is of interest to determine if different Preston tube correlations are required. It was shown in figure 7 that local skin friction from both the flat plate and tunnel wall can be predicted within the experimental accuracy by using the Van Driest II theory. Figures 14 and 15 show that the

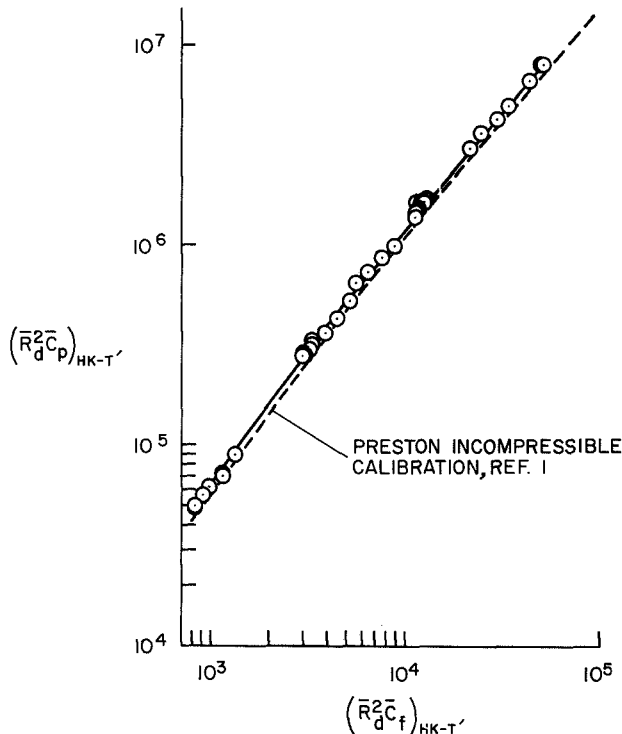


Figure 14.- Present hypersonic Preston tube calibration, equation (6) by Hopkins and Keener; wind-tunnel wall,  $M_e = 7.4$ ,  $U_e/v_e$ ,  $\text{ft}^{-1} = 0.6$  to  $4.0 \times 10^6$ ,  $d$ , in. =  $1/8$  to  $1/4$ ,  $T_w/T_{aw} = 0.32$  to  $0.49$ .

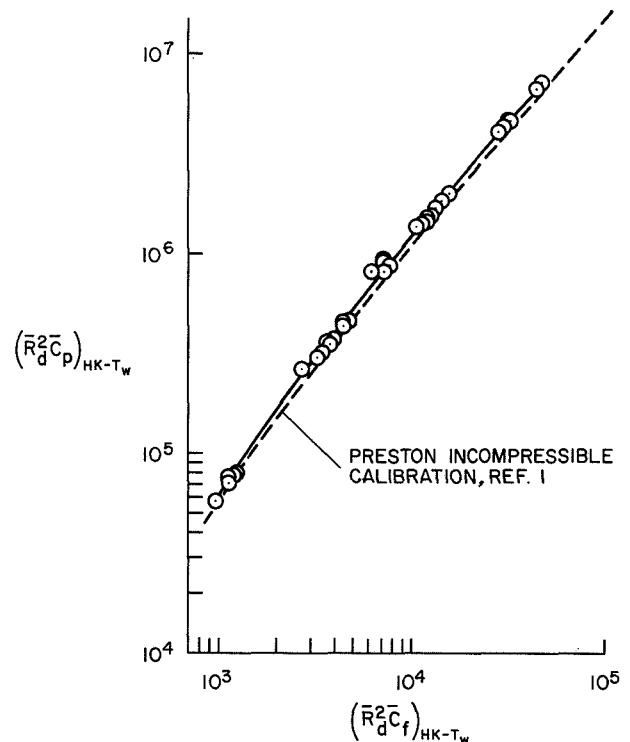


Figure 15.- Simplified hypersonic Preston tube calibration, equation (10) by Hopkins and Keener using surface measurements only; wind-tunnel wall,  $M_e = 7.4$ ,  $U_e/v_e$ ,  $\text{ft}^{-1} = 0.6$  to  $4.0 \times 10^6$ ,  $d$ , in. =  $1/8$  to  $1/4$ ,  $T_w/T_{aw} = 0.32$  to  $0.49$ .

tunnel-wall Preston tube data fall within 8 percent of the Preston incompressible curve when either the reference temperature or the simplified method of the authors is used.

#### CONCLUDING REMARKS

Past and present experiments indicate that Preston tubes are relatively simple instruments for accurately measuring skin friction at Mach numbers up to at least 7. The correlation factors developed either by the present authors (eq. (6)) or by Sigalla (eq. (11)) collapse the Preston tube data onto the linear part of the incompressible calibration curve of Preston. Boundary-layer trips have a small effect on the calibration that does not exceed the tolerable error of most applications. Preston tube measurements made on a wind-tunnel wall also correlate with the Preston incompressible curve.

A simplified calibration (eq. (10)) is presented by which skin friction can be adequately obtained from Preston tubes by basing the correlation factors on only three measurements: the wall temperature, wall pressure, and Preston tube pressure. Because of the simplicity of the Preston tube, it readily lends itself to most turbulent boundary-layer research programs.

Ames Research Center  
National Aeronautics and Space Administration  
Moffett Field, Calif., 94035, August 15, 1969

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