AEDC-TDR-63-94

AN ANALYSIS OF INITIAL STATIC PRESSURE PROBE MEASUREMENTS IN A LOW-DENSITY HYPERVELOCITY WIND TUNNEL

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TECHNICAL DOCUMENTARY REPORT NO. AEDC-TDR-63-94

April 1963

AFSC Program Area 750A, Project 8950, Task 895004

(Prepared under Contract No. AF 40(600)-1000 by ARO, Inc., contract operator of AEDC, Arnold Air Force Station, Tenn.)

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NOTICES

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ARO Project No. VL2312

ABSTRACT

An initial experimental program was conducted in 1961 to study the problems in using static-pressure probes for flow calibration purposes in low-density, hypervelocity wind tunnels with continuous flow. This is a review of these data in the light of more recent data on thermal transpiration. Results indicate that such probes may be used for what might be termed secondary calibrations, but care is required in interpreting the results. The present experiment yielded data which are compared to static pressures calculated from impact-pressure probe calibrations.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

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Gas Dynamics Division
DCS/Research

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CONTENTS

ILLUSTRATIONS

NOMENCLATURE

D	Probe outside diameter, in.
d_a	Orifice diameter, in.
d_i	Probe inside diameter, in.
K_1	Constant for normalizing flow conditions
L	Distance from nose of probe to orifice, in.
M	Mach number
$\dot{m}$	Mass flow rate, lbm/hr
p	Pressure
S	Distance from orifice to thermocouple, in.
T	Temperature
x	Inches from exit plane, negative upstream

SUBSCRIPTS

c	Cold end of probe
h	Hot end of probe
m	Measured
o	Stagnation conditions
∞	Free-stream conditions in the inviscid core

SUPERSCRIPTS

	Conditions downstream of a normal shock measured by impact probe

1.0 INTRODUCTION

An initial investigation was conducted in 1961 to study the feasibility of using conventional static-pressure probes for flow calibration purposes in the Low-Density, Hypervelocity Wind Tunnel (LDH) of the von Kármán Gas Dynamics Facility (VKF), Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), U. S. Air Force. The results of this investigation were reported in Ref. 1.

Since that time, extensive experimental work has been conducted on the effect of thermal transpiration on pressure measurements (Refs. 2 and 3), and a more complete theoretical analysis of the nature of the nozzle flow has been accomplished (Ref. 4).

Inasmuch as several parameters which are believed to affect the static pressure measurement have been reassessed since publication of Ref. 1, it was felt that a new analysis of the original data may be useful.

2.0 APPARATUS

2.1 THE LDH WIND TUNNEL

The tunnel is a continuous, arc-heated, ejector-pumped design. Figure 1 is a photograph of the tunnel. The major components are (1) a d-c arc-heater of the constricted, non-rotated arc and non-swirl gas injection type with a 40-kw power supply, (2) a settling section of variable length but normally about 6-in. long, (3) an aerodynamic nozzle of varying design but normally with a 0.10-in.-diam throat and 6-in.-diam exit, (4) a tank of 48-in. diameter surrounding the test section and containing instrumentation and probe carrier, (5) an interchangeable diffuser, (6) an air-ejector of two stages, and (7) the VKF vacuum pumping system. Although a 40-kw power supply is available, normally no more than one-half of maximum power is used.

All critical components of the tunnel are protected by back-side water cooling. The 2-stage ejector system is driven by air instead of steam because of the ready availability of air in the present case. This tunnel has proved highly satisfactory and has always yielded excellent repeatability of data. The working gas normally is nitrogen or argon, although other gases may be used. All data in the present investigation were taken with

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Manuscript received April 1963.

the 15-deg half-angle conical nozzle with nitrogen as the working gas. A complete description of the pressure instrumentation is given in Ref. 5.

2.2 TEST PROBES

Figure 2 gives the dimensions and orifice locations of the various probes from which data have been obtained. The larger diameter probes were uncooled except for natural radiation and conduction, whereas the smaller probes were mounted on a water-cooled sting approximately two inches downstream of the orifice location. Four orifices of equal size were drilled at intervals of 90 deg at the orifice location.

3.0 EXPERIMENTAL PROCEDURE

Each probe was placed on the nozzle centerline with the orifice at a given position in the nozzle. This resulted in the probe nose being at various stations upstream of the orifice depending on the orifice location relative to the probe nose. Data for the larger diameter probes were obtained at several axial stations, whereas the smaller probes were tested with the orifice in the exit plane of the nozzle. Only the data obtained on static pressure at the exit plane are included in the present report. Data taken at other axial stations resulted in the same trends. The data were obtained when the instrumentation system was still undergoing modifications and the experimental scatter was probably greater than would be expected with the present system. Since the investigation was concerned only with the feasibility of using static pressure probes, no great significance is placed on the absolute value of the pressure readings, and the results should not be considered as a calibration of the probes.

The internal temperature of the large probe was measured by threading a thermocouple through the open end to various stations along the probe. The internal temperature of the smaller, water-cooled probe was obtained at the orifice in a similar manner.

4.0 RESULTS AND DISCUSSION

Figure 3 contains the test data obtained with the orifice placed at the nozzle exit plane. The data have been adjusted for the known reference pressure of the transducer which was ≤ 0.40 microns Hg. The data for the large probe and $D/L \leq 0.08$ are discussed in section 4.3, and the small probe data for $T_o \approx 2350°K$ have been shifted on Fig. 3 by the factor K_1 as explained in section 4.1. Figure 3 also contains the stagnation conditions and free-stream conditions at the nozzle exit plane during the test.

4.1 FLOW PROPERTIES FROM IMPACT PRESSURE MEASUREMENTS

The method normally employed in calibration of supersonic wind tunnels includes the measurement of impact pressure, total pressure, and total temperature or enthalpy. With normal shock relationships, these measurements are sufficient to calculate the remaining flow properties if the thermochemical state of the flow is known and if an inviscid core flow exists in the nozzle. For obvious reasons these conditions may not be assumed directly applicable in many tunnels. An independent check, such as a static pressure probe offers, would therefore be valuable to validate some of the assumptions made in the use of impact probe data.

The assumption presently made in regard to the LDH tunnel is that the flow is in thermodynamic equilibrium in the stilling chamber and becomes essentially "frozen" at the nozzle throat. Strong support for this is given in Refs. 4 and 6.

It was noticed that between the time the data were obtained using the large probes and the time the small probes were tested, a change in the impact pressure near the exit occurred. It was found that contamination from the arc jet collected over a period of about six months had coated the sonic throat, resulting in a decreased area and causing a lower p_∞ to be calculated for a given axial station. Throat radius was only 0.051 in.; thus, a coating 0.001-in. thick could change the area four percent, and test section conditions would be affected. The blockage was removed, and the calibration returned to the original values. However, the small probes were tested before this correction was made.

It was desired to combine the data at p_o = 17.79 psia taken with the larger and smaller diameter probes to better establish the limit at D/L = 0. However, the two probes were tested under differing conditions and should approach different limits. These flow conditions were identical in p_o, and the effect of T_o on p_∞ is small. Thus it is considered permissible to effect an adjustment which normalizes the static pressure corresponding to impact pressure under conditions of the test of the smaller static pressure probe to that calculated on the basis of impact pressure under conditions of the test of the larger static probe, i.e.,

$$p_{\infty, m} \text{ (small probe adjusted)} = (p_{\infty, m}) K_1$$

where $$K_1 = \frac{(\text{Theoretical } p_\infty \text{ at conditions of test of large probe, } \mu\text{Hg})}{(\text{Theoretical } p_\infty \text{ at conditions of test of small probe, } \mu\text{Hg})}$$

$$K_1 = \frac{15.75}{13.25} = 1.189$$

The theoretical values are based on measured p_o'/p_o and assumed frozen vibration downstream of the nozzle throat.

Figure 4 shows the gradients in p_o' near the exit plane existing for each probe during the test and also shows the effect of p_o' on p_∞ for p_o and T_o = constant. It may be noted that the relation between p_o' and p_∞ is essentially linear near the exit. Following from this, the data for the small probes and p_o = 17.79 psia may be normalized by the simple relation shown above.

4.2 THERMAL TRANSPIRATION EFFECT

In the pressure and temperature range at which the LDH tunnel operates, the phenomenon known as thermal transpiration begins to introduce sizeable errors when small bore tubing is used to measure static pressure. Extensive experimental work has been accomplished by Arney and Bailey (Refs. 2 and 3). Their analysis and correction curves have been followed in the present report to correct the measured data.

The calculation of the correction due to thermal transpiration depends on the knowledge of the temperature gradient from the hot to the cold end of the probe where the transducer is placed. A thermocouple placed at various positions along the interior of the large, uncooled probe was used to measure this gradient.

Because the smaller, water-cooled probes were cooled from a position two inches downstream of the orifice, the temperature near the orifice would be expected to be the maximum temperature between orifice and transducer. Figure 5 shows the temperature gradient in a typical large probe and temperature at the orifices of the small probes. A thermocouple placed in the transducer port measured a temperature of 311°K. It is assumed in the present analysis that the probe orifice experienced no temperature gradient because of its short length.

With the measured pressure (p_c), probe temperature (T_h), transducer temperature (T_c), and probe inside radius, the pressure at the orifice of the probe (p_h) can be calculated. Figure 6 shows the test data after adjustment for the thermal transpiration effect based on Ref. 3.

4.3 EFFECTS OF FLOW GRADIENTS WITHIN TEST SECTION

As can be seen from Fig. 4, the flow is still expanding at the exit of the nozzle, and the gradient in free-stream static pressure from $x = -3$ to $x = +1$ is also apparent. The gradients become progressively greater toward the throat of the nozzle. These gradients make the present analysis difficult since flow parameters are different at the nose of each probe. Also, the free-stream static pressure varies from the nose to the orifice. However, it is estimated that no more than approximately 2μ Hg error in pressure at $D/L = 0$ was caused by the finite pressure gradients. This is within the experimental scatter obtained with the early pressure instrumentation system.

An examination of Fig. 3 shows that the large probes with $L \geq 2.406$ give erratic and seemingly low readings. It is felt that this may be caused by the growth of the boundary layer on the longer probes and consequent elimination of the inviscid core flow as the nozzle and probe boundary layers merge. There also is a possibility of heating and other flow field interference caused by reflected shocks. These particular data are omitted in Figs. 6 and 7.

Inviscid blast wave theory is a useful correlation method for flow over slender bodies at high Reynolds numbers and Mach numbers. Figure 6 includes a curve showing the pressure predicted by the theory of Ref. 7. It is interesting to note that the form of the curve is similar although the large viscous effects in the LDH tunnel cause a substantial departure from the assumptions of blast wave theory, and it could not be expected to provide complete correlation in this case.

Included in Fig. 6 are the free-stream static pressures for the flow conditions calculated from measured p_o'/p_o on the basis of equilibrium as well as "frozen" flow. It should be expected that as $D/L \rightarrow 0$ the data should level off to the true static pressure. This condition does not appear to have been attained in the present experiment, but data for lower values of D/L could not be obtained.

The data can be correlated further by normalizing the test points from each probe to the theoretical static pressure which should have been approached as $D/L \rightarrow 0$. The "frozen" value of p_∞ from impact pressure data has been used as the theoretical limit. The data reduced in this manner are shown in Fig. 7. Correlation appears to be quite good over this rather small range of free-stream Reynolds numbers and Mach numbers. It may be noted that the correction factor K_1 is not necessary since the particular theoretical limit is used in all three sets of data.

The results as presented in Ref. 1 were based on the thermal transpiration work of Howard (Ref. 8) while the present analysis followed the work of Arney and Bailey (Refs. 2 and 3). Differences between the two corrections account for the data not being directly comparable. The net effect of using the more recent data of Refs. 2 and 3 seems to be a decrease in the slope of the p_h vs D/L curve in the present analysis. At small values of D/L, the difference between the two corrections is small. The data also appears to correlate with $(D/L)^{1/2}$ as a linear relation using the new thermal transpiration correction. With the older correction, the data appeared to be linear against D/L. Figure 7 shows the result of using $(D/L)^{1/2}$ as the correlating parameter.

Another point of interest is the variation in $M_\infty^3 \sqrt{Re/in.}$ represented by the three sets of data in Fig. 7. Inspection of the data thereon indicates that the effect of the approximately ten percent variation in the viscous interaction parameter was concealed in the data scatter.

5.0 CONCLUSIONS

Several conclusions from the limited data obtained during the investigation are made.

1. The use of static pressure probes in low-density, hypervelocity wind tunnels of the continuous type for examination of relative variations of static pressure throughout the nozzle is feasible if a high degree of accuracy is not expected. They are more suitable for secondary flow studies wherein only an approximate confirmation of more precise methods is desired. For example, regardless of the exact level of $p_{\infty, m}$, the probes used in these tests were suitable for determining the variation of static pressure radially at different cross sections of the nozzle. (No variation was found in the test section.)

2. A more extensive investigation would be necessary before a complete evaluation of all the phenomena influencing probe readings is possible. Although this brief investigation yielded relatively

good results, it would be desirable to investigate the influence of other variables, for example, orifice size.

3. As a general rule, it appears that the strong viscous interaction and thermal transpiration makes it impossible to use conventional static pressure probes for accurate absolute measurements in low-density, high-speed tunnels. It should be noted, however, that such probes will be most useful in large wind tunnels where much smaller D/L ratios will be feasible. In the larger tunnels the extrapolation to D/L = 0 would be less subject to error.

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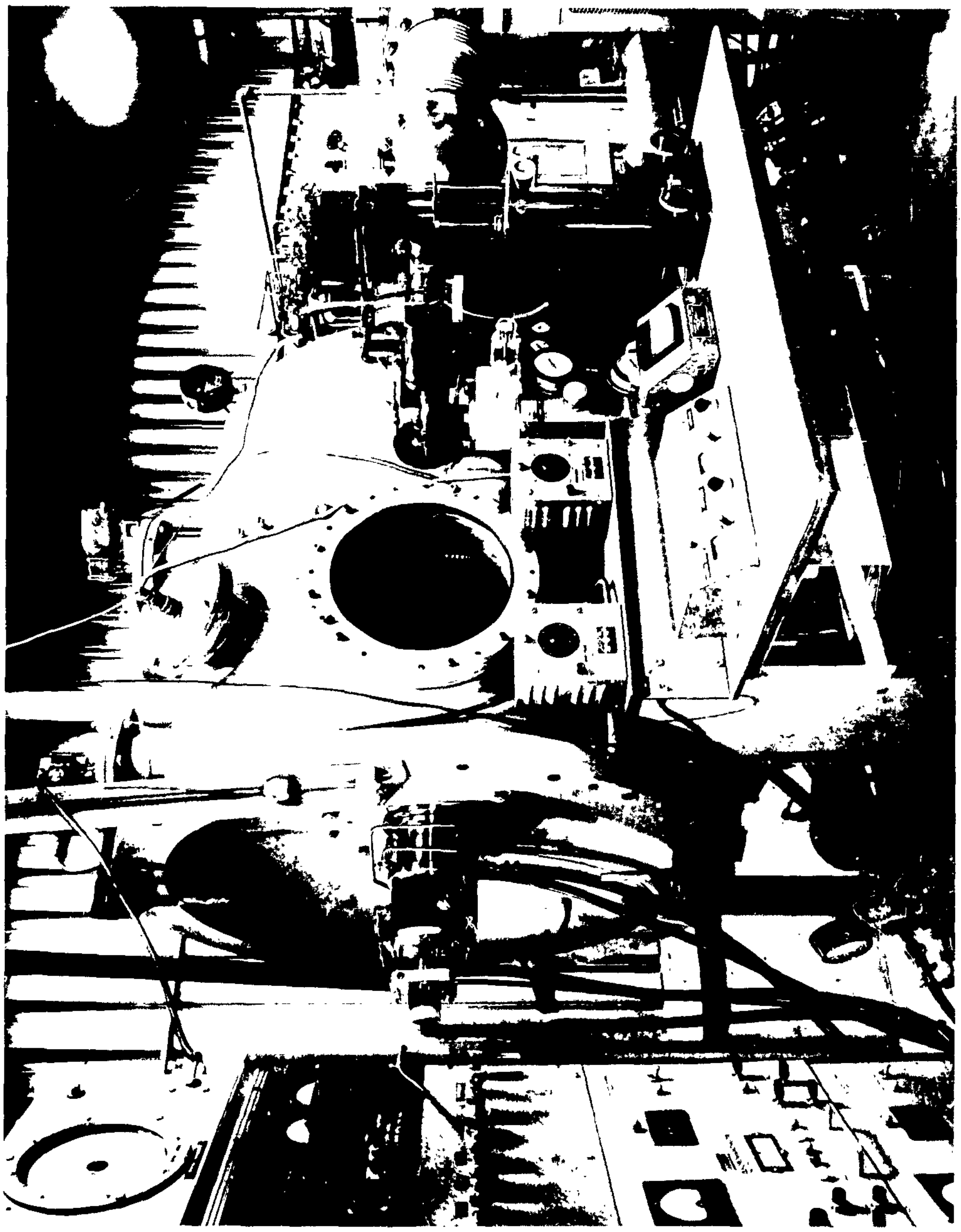
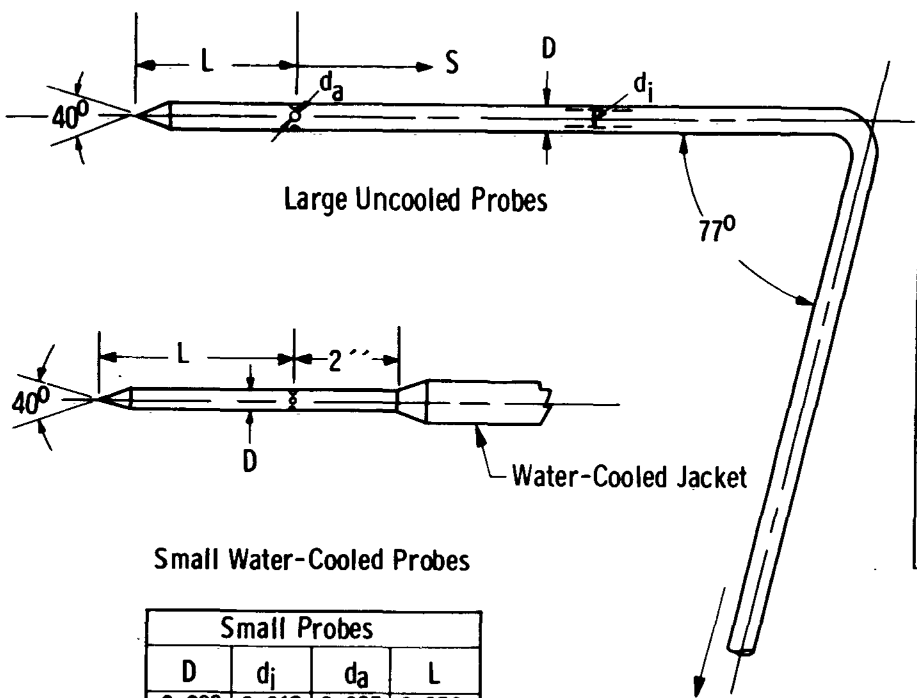


Fig. 1 Photograph of LDH Tunnel from the Operator's Side



Large Probes			
D	d_i	d_a	L
0.1875	0.147	0.078	0.406
			0.703
			1.000
			1.344
			1.954
			2.406
			2.968
			3.968
			4.500
			5.000

Mtl - Stainless

Small Probes			
D	d_i	d_a	L
0.093	0.063	0.025	0.250
			0.500
			0.750
			1.000
			1.500
			2.000
			2.500

Mtl - Stainless

Not to Scale

Fig. 2 Test Probes

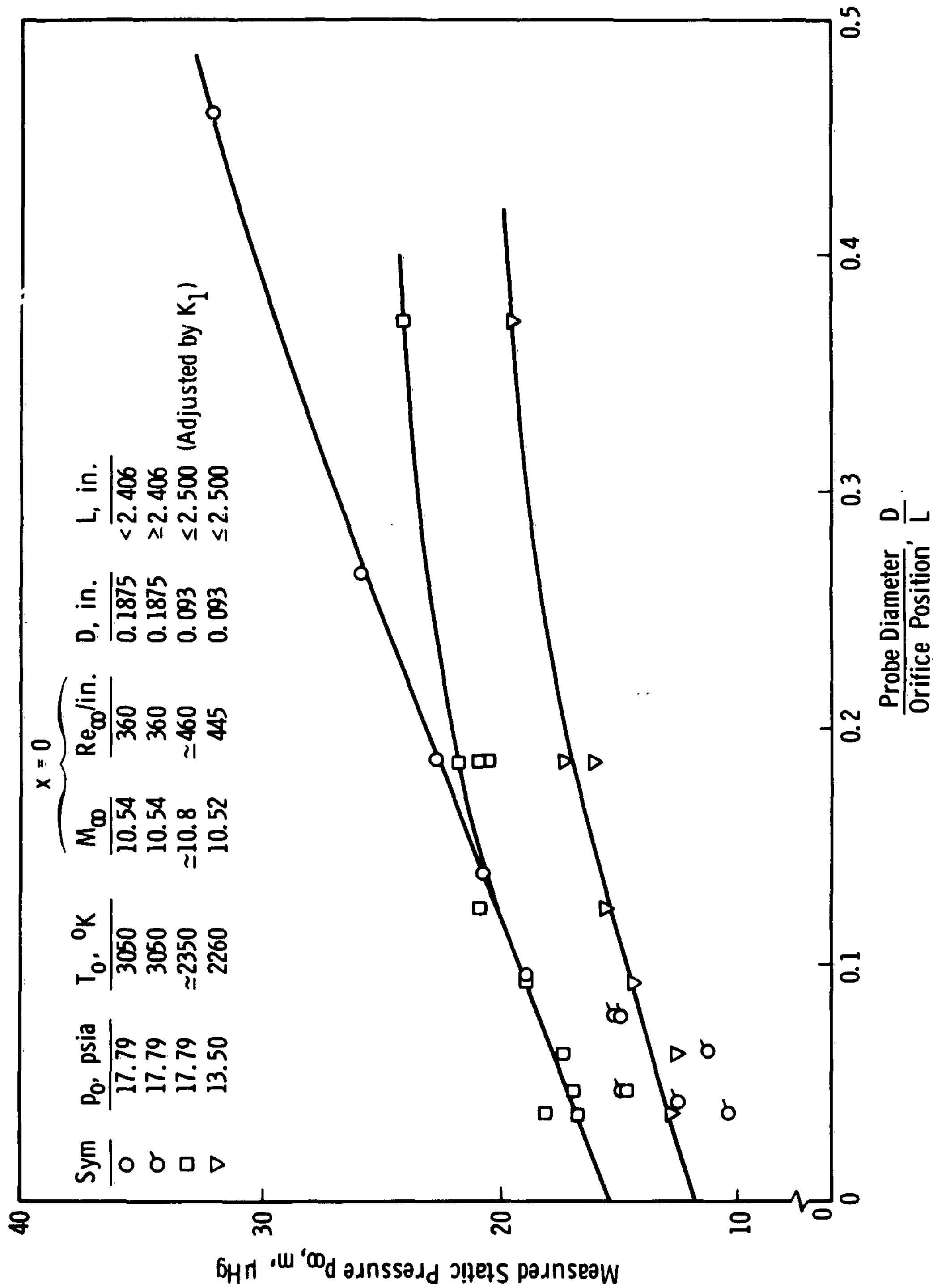


Fig. 3 Test Data

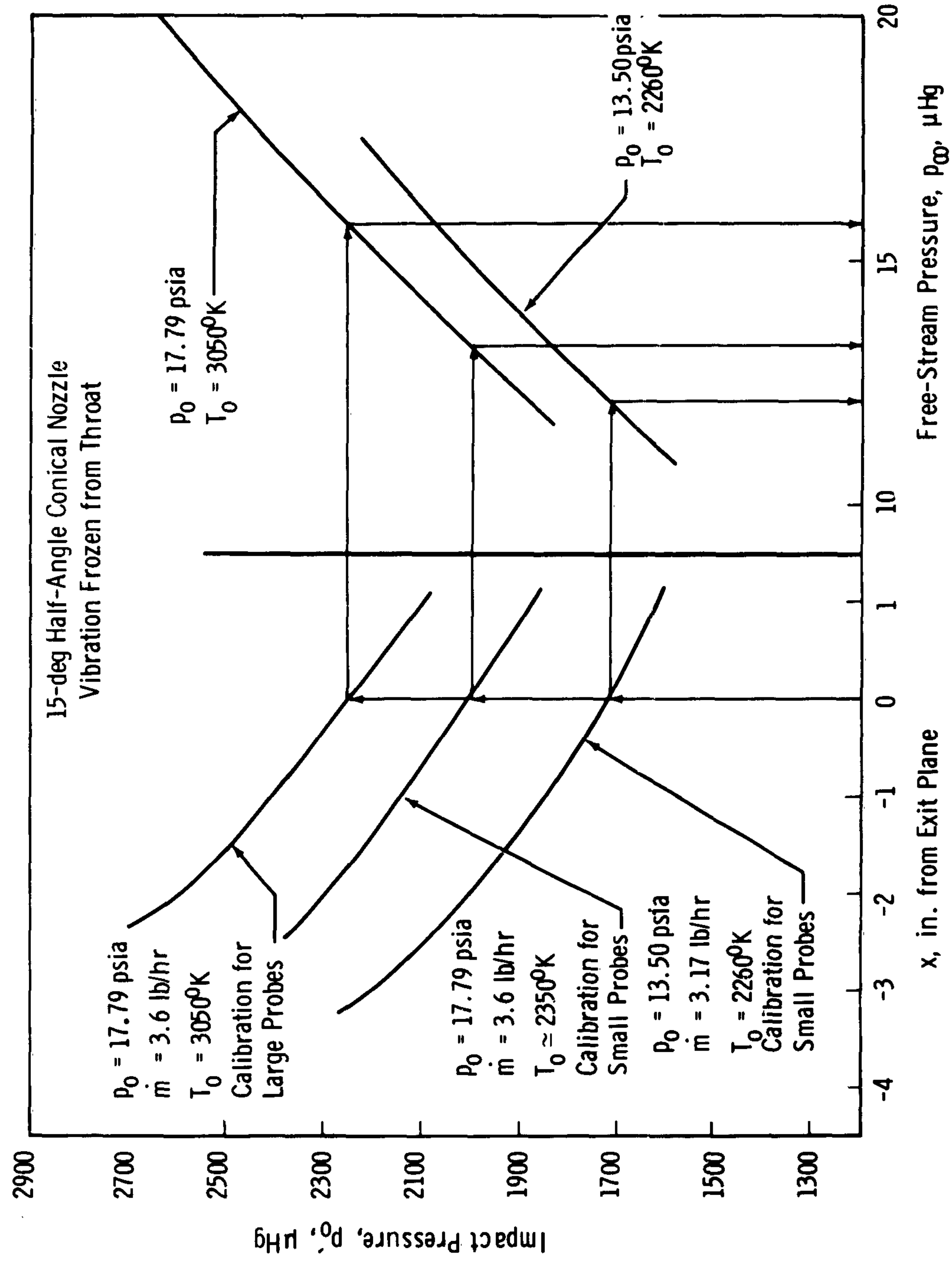


Fig. 4 Impact Pressure and Static Pressure Gradients near Exit

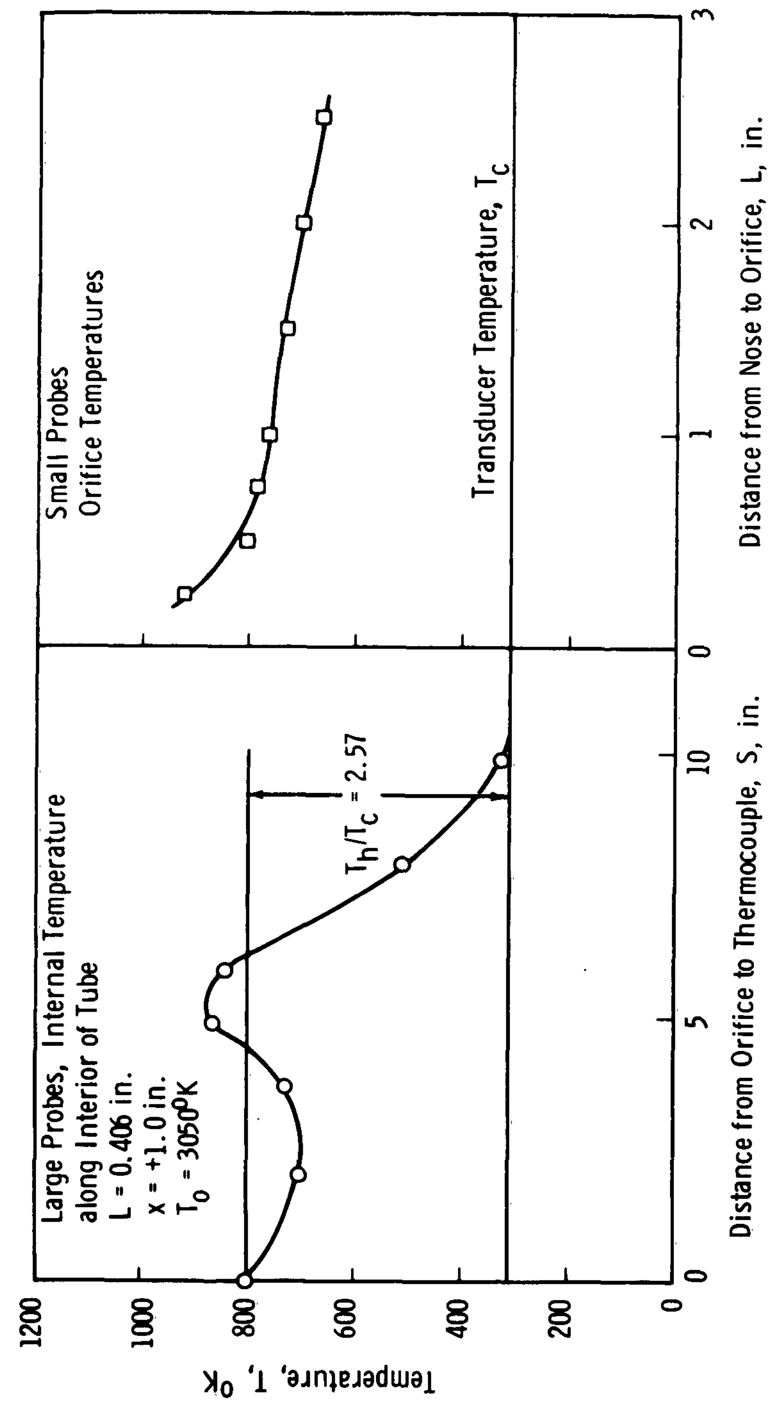


Fig. 5 Probe Temperatures

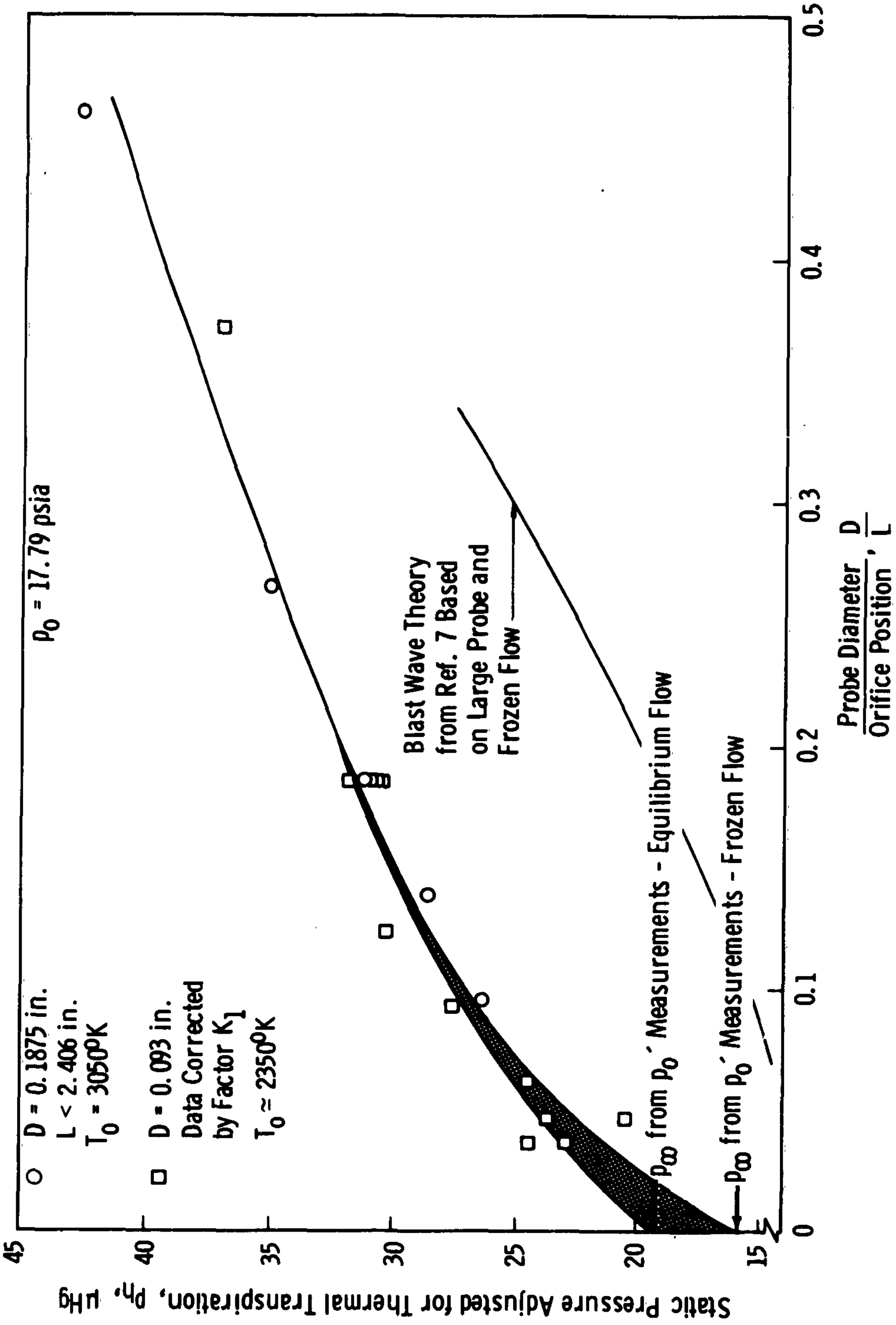


Fig. 6 Test Data Adjusted for Thermal Transpiration Effect

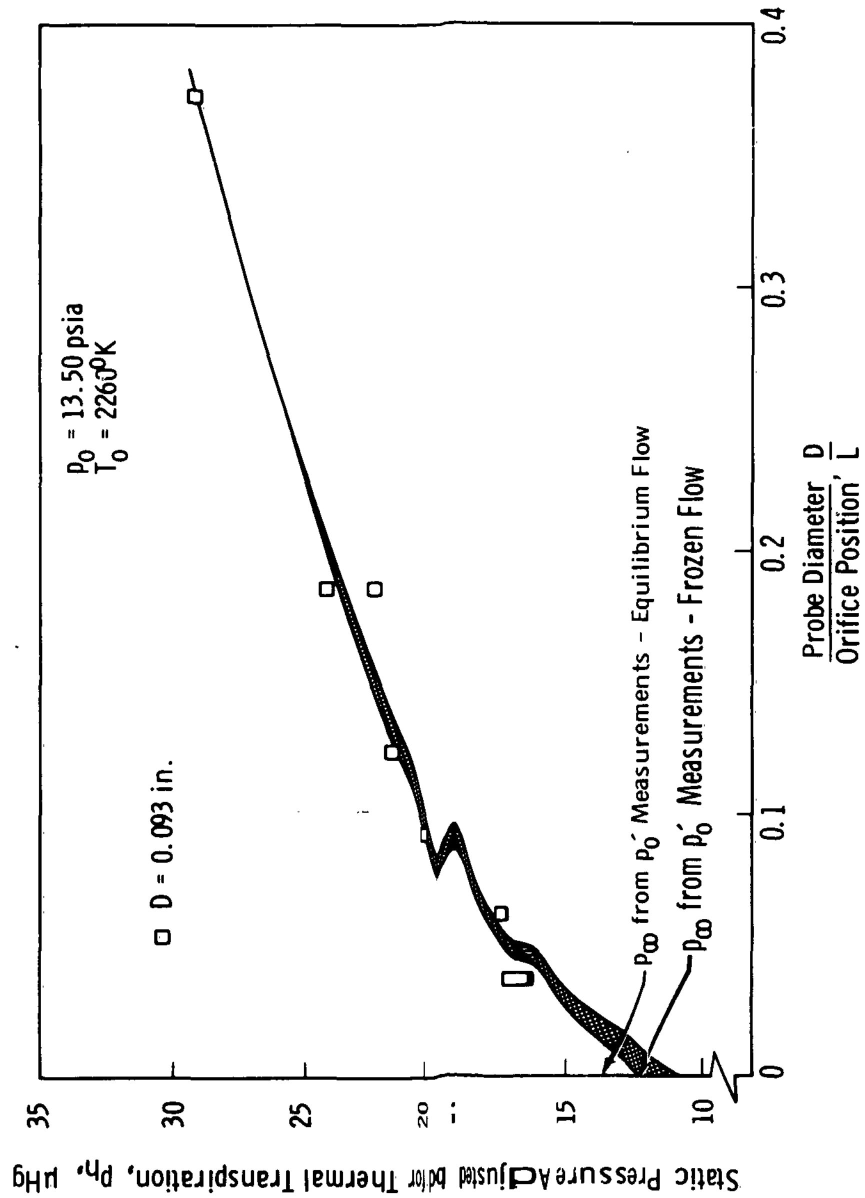


Fig. 6 Concluded

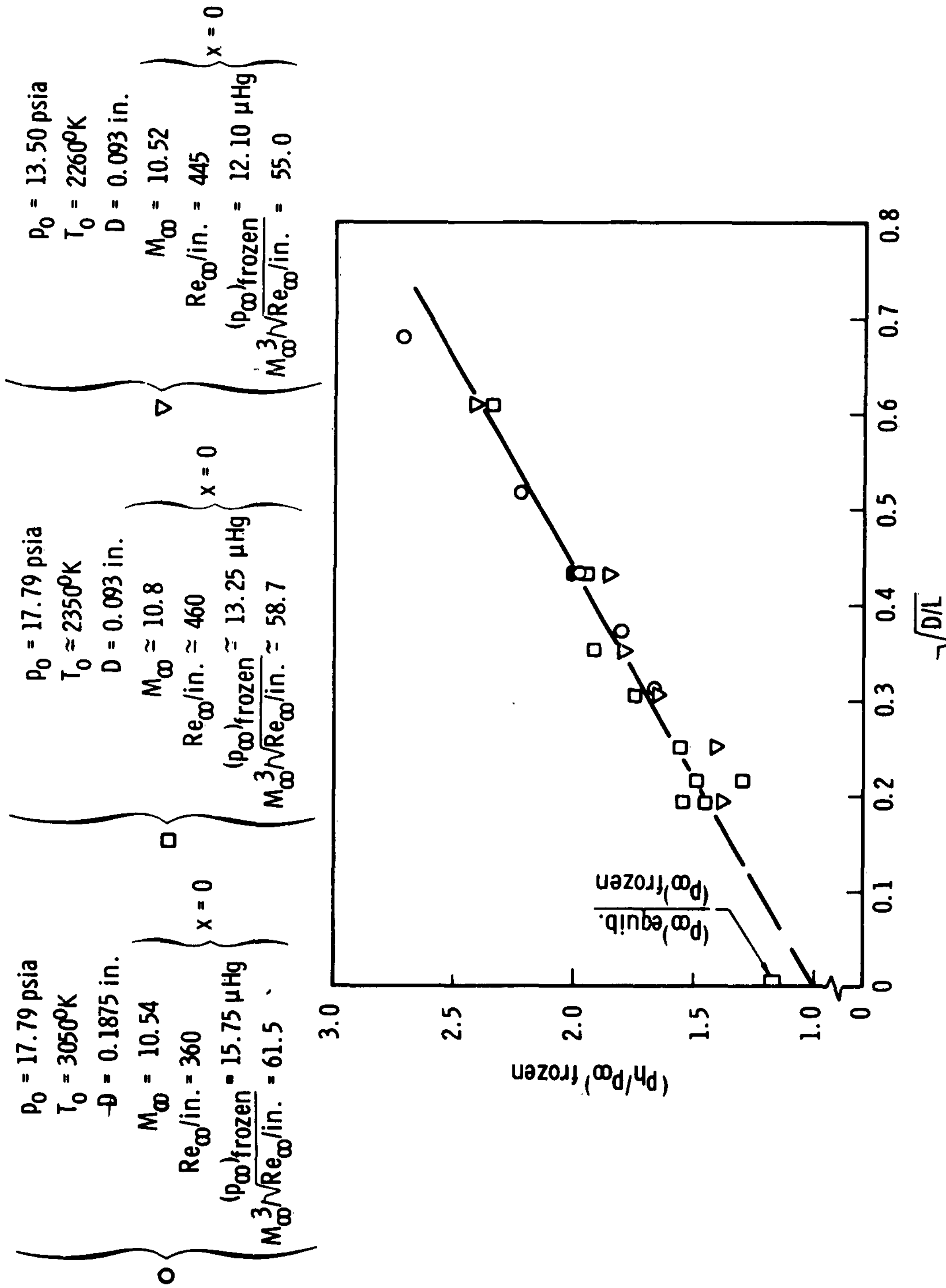


Fig. 7 Data Compared to Calculated Free-Stream Static Pressures

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2. Pressure
3. Measurement
4. Hypervelocity wind tunnels
5. Probes

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