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ACCURACY OF PITOT-PRESSURE RAKES FOR TURBULENT BOUNDARY-LAYER MEASUREMENTS IN SUPERSONIC FLOW

by Earl R. Keener and Edward J. Hopkins

Ames Research Center
Moffett Field, Calif. 94035

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The pitot pressures from both the conventional rakes and the probeless rake agree with the single traversing-probe pressure within 2 percent of the edge pitot pressure. The resulting errors in Mach number and velocity ratios are less than 2 percent; momentum and displacement thickness errors are less then 4 percent. These errors are not excessive and indicate that multiple-probe and probeless rakes can be used in measuring turbulent boundary layer.

The low error of the probeless rake indicates that this type of configuration might have useful application at high temperatures where conventional rake probes might warp or fail.

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NOTATION

M	Mach number
$p_{t,2}$	measured pitot pressure
R_θ	momentum-thickness Reynolds number, $\frac{U_e \theta}{\nu_e}$
U	velocity
y	distance from surface
ν	kinematic viscosity
ρ	mass density
θ	boundary-layer momentum thickness, $\int_o^\delta \frac{\rho U}{\rho_e U_e} \left(1 - \frac{U}{U_e}\right) dy$
δ	boundary-layer thickness
δ^*	boundary-layer displacement thickness, $\int_o^\delta \left(1 - \frac{\rho U}{\rho_e U_e}\right) dy$

Subscript

e	edge of boundary layer

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SUMMARY

Boundary-layer profiles from three conventional pitot-pressure rakes and a new probeless rake are compared with those from a single traversing probe in a supersonic turbulent boundary layer on the wall of a wind tunnel. Measurements were made at Mach numbers from 2.4 to 3.4 and at momentum-thickness Reynolds numbers from 26,000 to 75,000. The boundary-layer thickness was approximately 6 inches and the rake heights were 5, 8, and 12 inches with different probe size and spacing.

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INTRODUCTION

Measurements of boundary-layer pitot-pressure profiles are often made with a single traversing pitot probe in order to minimize probe-interference effects. However, it is often prohibitive in an experiment to provide the space for a surveying mechanism or sufficient time to traverse the boundary layer to avoid time lag in the pressure measurement. Consequently, it is convenient in these cases to be able to use multiple-probe rakes. A need for additional experimental data in a thick turbulent boundary layer in flight at supersonic Mach numbers led to the present investigation.

Before describing the investigation, it is appropriate to review briefly the possible errors of pitot-pressure measurements in a boundary layer. Most of the errors involved in using either single or multiple pitot-pressure probes (rakes) are discussed in references 1 to 12 for incompressible flow and references 9 and 13 to 21 for compressible flow. These errors are related to probe geometry, transverse pressure gradient, wall influence, low Reynolds numbers, shock waves from the probes, support interference, fluctuating velocity components in turbulent flow, time lag, and mutual interference between multiple probes. Indications are that circular probes cause smaller errors than flattened probes unless the probes are small enough that the geometry effects are inconsequential (less than 5 percent of the boundary-layer thickness). Special care must be given to any probe in a supersonic laminar boundary layer because the shock-wave-boundary-layer interaction from both the probe and the probe support causes the flow to separate and the boundary layer can be distorted. A similar distortion does not occur in a supersonic turbulent boundary layer. Apparently, the upstream propagation of probe disturbances is suppressed by the turbulent mixing process which thins the subsonic part of the boundary layer and allows the flow to approach the probe without distortion. Mutual interference effects between multiple probes in a turbulent boundary layer appear to be negligible if the probes are spaced at least two diameters apart between center lines.

The present results were obtained as part of a wind-tunnel investigation of the supersonic turbulent boundary layer. The investigation was conducted in support of the NASA Flight Research Center flight test program for the XB-70 research airplane. In the flight test program, measurements were made in boundary layers approaching 10 inches in thickness at subsonic and supersonic speeds. Reference 22 presents the results of the first part of the wind tunnel program – correlation of surface-pitot tubes for use in flight to obtain local skin friction.

In the present investigation, turbulent boundary layers measurements from three XB-70 pitot-pressure rakes, 5, 8, and 12 inches high, were compared with those from a single traversing probe. A new probeless rake designed for use in a high temperature environment was also tested. Measurements were made on the wall of the Ames 8- by 7-Foot Supersonic Wind Tunnel at Mach numbers of 2.4, 2.9, and 3.4 in a turbulent boundary layer that was approximately 6 inches thick. Estimates are presented of the accuracy of boundary-layer characteristics calculated from the pitot-pressure rakes.

INSTRUMENTATION

Photographs and drawings of the test instrumentation are shown in figures 1 and 2. Figure 1(a) is a photograph of the general arrangement of the boundary-layer instrumentation mounted on a 4-foot window blank in the side wall of the Ames 8- by 7-foot wind tunnel. The photograph also shows instrumentation not included in this report that was part of the general investigation of the supersonic turbulent boundary layer. The Preston tube and skin friction data are reported in reference 22.

Four pitot-pressure rakes were used in this investigation. Three were designed for use in the flight test program of the XB-70. They were of conventional design as shown in figures 1(a) and (b) and figure 2(a).

The rakes were 5, 8, and 12 inches high, with probe outside diameters of 0.042, 0.062, and 0.093 inches, respectively, and with different spacing. The fourth rake (figs. 1(d) and 2(b)) was a new type designed for possible application under conditions of high temperature. It was simply a rake with no protruding tubes or probes, and is called herein a probeless rake. The probeless-rake configuration might have application at high temperatures where rake probes might warp or fail. Orifices (0.062 in. diam) were drilled in the front face and connected to tubes inside the support. The front face was 0.125 inch wide which was about 3 percent of the boundary-layer thickness.

Five simulated orifices were drilled into the face of the rake at $y < 1$ inch, as shown in the drawing, to see if there would be an interference effect from closely spaced orifices. For the last part of the test, the simulated orifices were plugged.

A single traversing pitot-pressure probe (fig. 1(c)) was used to obtain the boundary-layer pitot-pressure profile with minimum interference effects as a reference for the rake pressures. Figure 3 shows the geometry of the traversing probe, which was designed to minimize the flow disturbance of the tip and the deflection under load. The tip was carefully constructed to be free of burrs and imperfections. The probe was moved perpendicular to the wall by means of a screw device to which a height gage with a vernier was attached for measuring the probe height accurately.

Precision mercury manometers, mounted in temperature controlled cabinets, were used to measure reference pressure, calibration pressure, and pitot pressure outside the boundary layer $(p_{t,2})_e$. Test pressures were measured by Ames designed precision electrical strain-gage-type, slack-diaphragm, transducers mounted in a temperature controlled cabinet. The transducers were used to measure the differential between the test pressure and a reference pressure. The reference pressure was set so that the lowest range transducers available (±575 psfd) could be utilized. Each transducer was individually check-calibrated over its range in the laboratory and selected to meet the tolerances described in the section on Data Reduction and Accuracy. Sufficient time (about 2 minutes) was allowed for the pressures to stabilize before each measurement was taken.

TEST CONDITIONS

The investigation was conducted in the Ames 8- by 7-Foot Supersonic Wind Tunnel. The instrumentation was mounted on the side wall where the turbulent boundary layer is approximately 6 inches thick. Test Mach numbers were 2.4, 2.9, and 3.4 at which unit Reynolds number was varied by changing stagnation pressure within the available limit of about two atmospheres. Boundary-layer traverses were made with the single pitot probe at unit Reynolds numbers of 1.0, 2.5, and 3.2 million per foot. Flow conditions correspond to that for a turbulent boundary layer on a flat surface with nearly zero pressure gradient and nearly adiabatic wall temperatures. Additional information is given in reference 22.

DATA REDUCTION

Mach number, Reynolds number, total pressure, dynamic pressure, and static temperature at the boundary-layer edge were calculated from the measured pitot pressure outside the boundary layer, the wall static pressure, and tunnel total temperature. Compressible flow relations in reference 23 were used in the calculations. Edge pitot pressure $(p_{t,2})_e$ was taken to be the pressure measured at a height of 8.50 inches on the 12-inch boundary-layer rake. Wall-static pressures, measured at four locations throughout the test area, agreed to within 0.5 psf. Static pressure was assumed to be constant through the boundary layer. Integral parameters θ and δ^* were calculated assuming an isoenergetic boundary layer (constant total temperature).

ACCURACY

Pressures

Estimated probable errors of the rake pressures were taken to be the RSS(root-sum^2) of the individual instrumentation errors (the RSS being representative of a combination of individual random errors). The following individual errors were considered: reference pressure and $(p_{t,2})_e$ from precision manometer, ±0.28 psf; differential pressure from slack-diaphragm transducers, ±0.29 psf for $y < 2$ inches and ±0.58 for $y > 2$ inches; and maximum zero shift of transducers during test runs, ±0.3 psf. The RSS value of these errors is ±0.5 psf for $y < 2$ inches and ±0.7 psf for $y > 2$ inches. Consequently, the pressure errors are generally much less than 0.3 percent of $(p_{t,2})_e$, which ranged from about 250 to 1240 psf.

Geometric Measurements

The traversing-pitot probe error in height was within ±0.003 inch. This includes the maximum play in the mechanism of about ±0.002 inch at the probe tip and the reading error of ±0.001 inch. The height of the boundary-layer rake probes was measured to within ±0.005 inch.

RESULTS AND DISCUSSION

Conventional Rakes

The results for the conventional pitot-pressure rakes, designed for the XB-70 flight research program, are shown in figure 4 for nominal Mach numbers of 2.4, 2.9, and 3.4. Rake pitot pressures are compared to the pitot pressures measured by the single traversing pitot probe at R_θ from 26,000 to 75,000.

Figure 4 shows that there is general agreement within 2 percent of $(p_{t,2})_e$ between the traversing-probe pressures and the rake pressures throughout the boundary layer. The deviations are mostly random. Although the rakes were separated by about 2 feet from the traversing probe, all pitot pressures near the boundary-layer edge agree within 1 percent. At $y = 8.5$ inches (where $(p_{t,2})_e$ was measured), pressures of the traversing probe and the 12-inch rake agree within 0.5 percent.

Experimental "Probeless" Rake

A new type of rake, designed without probes as shown in figure 2(b) was included in the test program. Five simulated orifices were included in the design within the first inch in height to determine interference effects of closely spaced orifices. Measurements were made with the simulated orifices open and closed (plugged). The results with the simulated orifices closed are presented in figure 5 for a Mach number of 2.9 and for momentum-thickness Reynolds numbers of 27,000 and 57,000, determined from the 5-inch rake profiles. The figure shows that the pitot pressures from the probeless rake and the 5-inch rake agree at $y > 1$ inch. At $y < 1$ inch there is a small difference reaching a maximum of 2 percent of $(p_{t,2})_e$ at $y \simeq 0.5$ inch. Although not shown in figure 5, there was no noticeable change in the comparison between the two rakes with the simulated orifices open.

Other Boundary-Layer Parameters

The desired objectives in a boundary-layer survey are to obtain the Mach number and velocity profiles and the integral parameters of momentum thickness (θ) and displacement thickness (δ^*). Assuming a constant error in rake pitot-pressure ratio $[(p_{t,2}/(p_{t,2})_e]$ of 2 percent and an isoenergetic boundary layer, the maximum probable errors in both M/M_e and U/U_e are of about the same relative magnitude as the error in pitot-pressure ratio (2 percent). Consequently, the maximum probable error in δ^* and θ is estimated to be 6 and 10 percent, respectively. Calculated values of δ^* and θ from the rake and traversing probe measurements agree within 4 percent.

These errors are generally within the required accuracy for the proper analysis of boundary-layer characteristics and indicate that multiple-probe rakes can be used in turbulent boundary layer measurements. In many cases considerable experimental time can be saved over the time required for a traversing probe; for example, these measurements required about one hour for each traverse.

CONCLUSIONS

The accuracy with which turbulent boundary-layer characteristics can be determined by use of multiple-probe rakes was investigated in a supersonic turbulent boundary layer on a wind tunnel wall. Boundary-layer profiles from three conventional pitot-pressure rakes and a new probeless rake are compared with those from a single traversing probe. Measurements were made at Mach numbers from 2.4 to 3.4 and at momentum-thickness Reynolds numbers from 26,000 to 75,000. The boundary-layer thickness was approximately 6 inches and the rakes were 5, 8, and 12 inchs high with different probe size and spacing.

The pitot pressures from both the conventional rakes and the probeless rake agree with the single traversing-probe pressures within 2 percent of the edge pitot pressure. The resulting errors in Mach number and velocity ratios are less than 2 percent; momentum and displacement-thickness errors are less than 4 percent. These errors are not excessive and indicate that multiple-probe and probeless rakes can be used in turbulent boundary-layer measurements.

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Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, November 11, 1970

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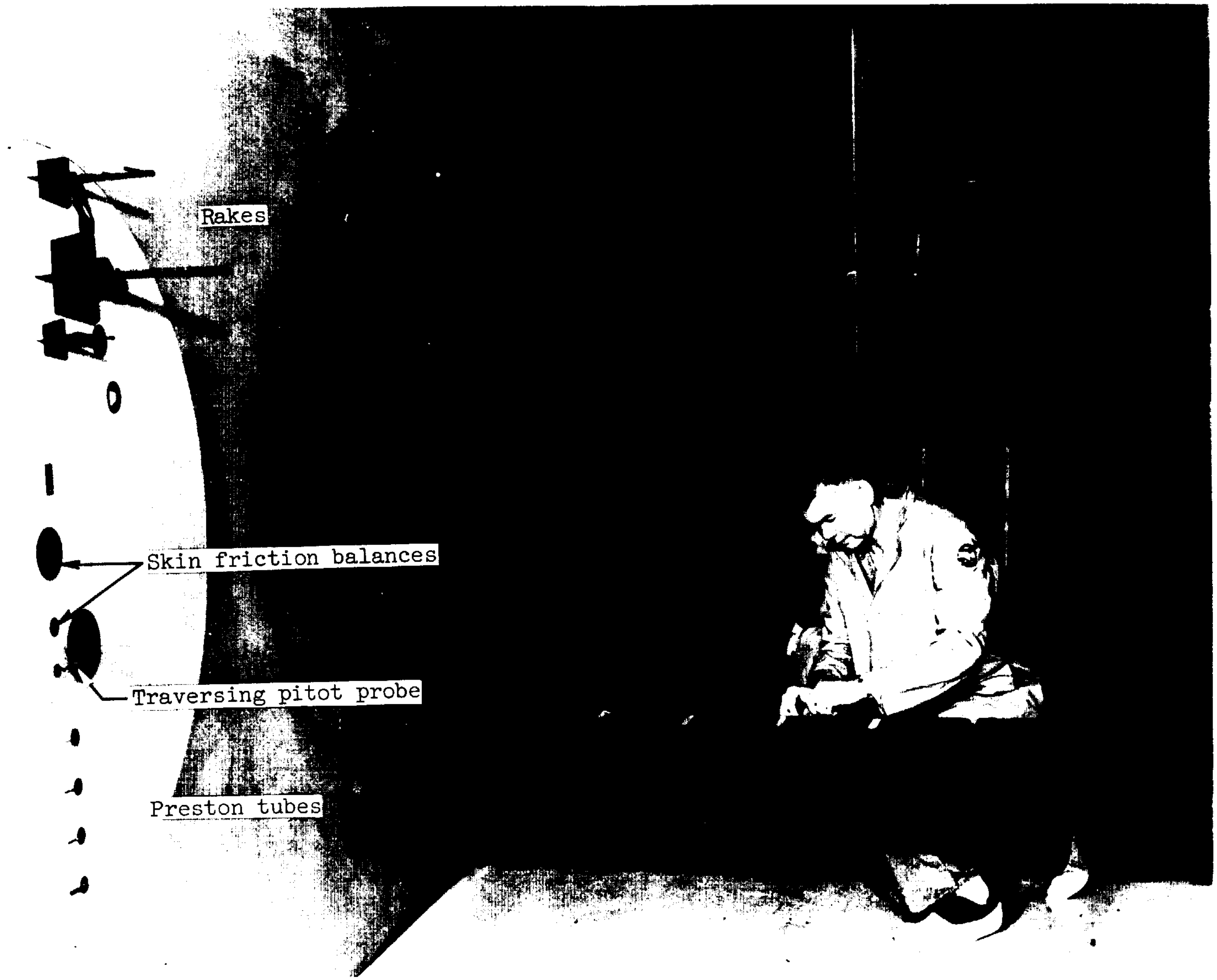
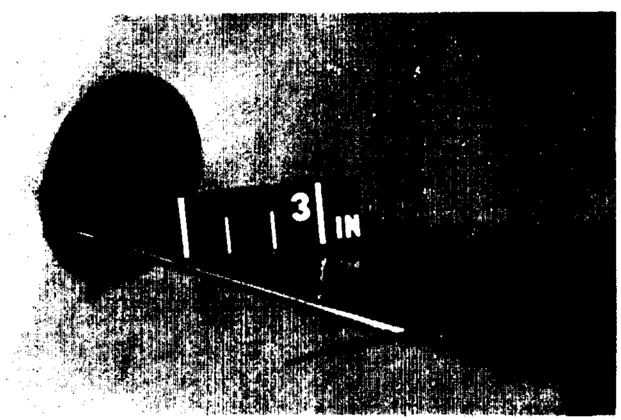


(a) General arrangement

Figure 1.- Photographs of test instrumentation.

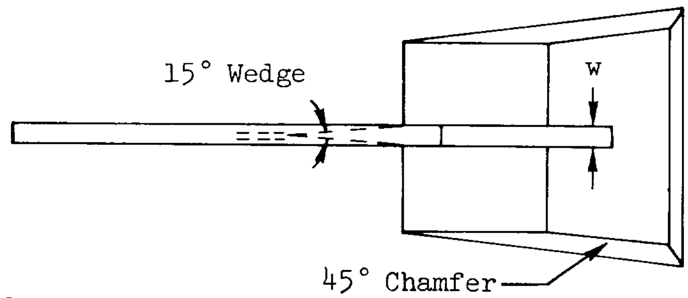
(b) Pitot-pressure rakes



(c) Traversing pitot-pressure probe

(d) Probeless rake

Figure 1.- Concluded.



Top probe is pitot-static tube on 8 and 12-inch rakes

Note: All dimensions are in inches

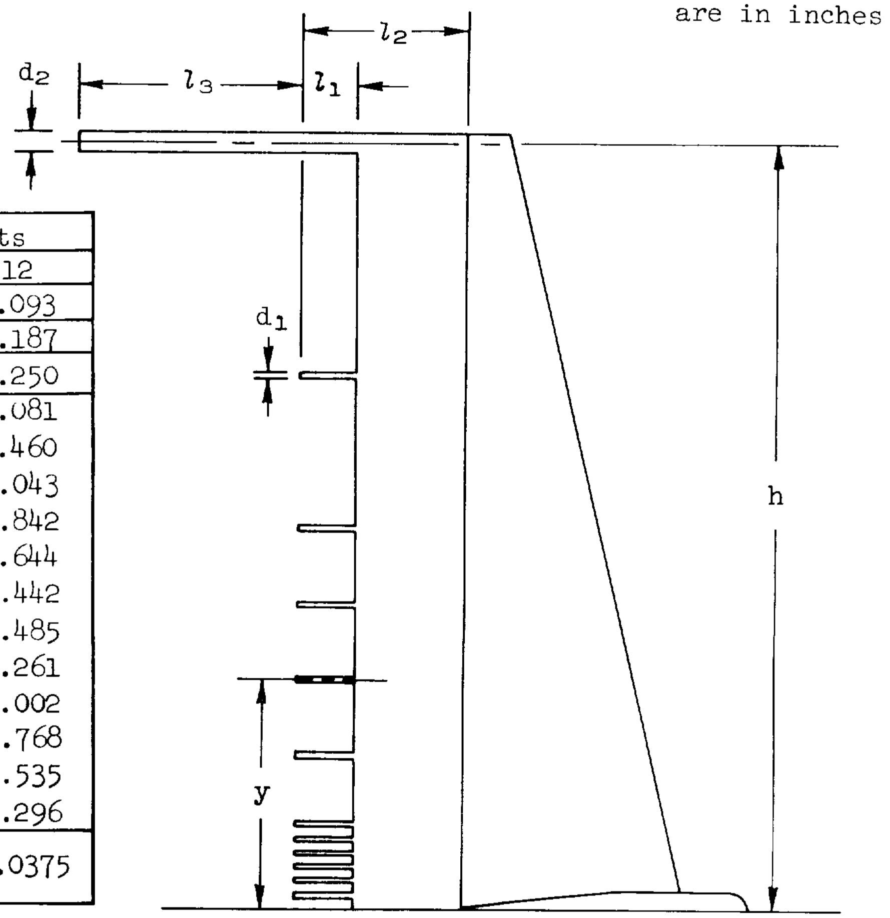
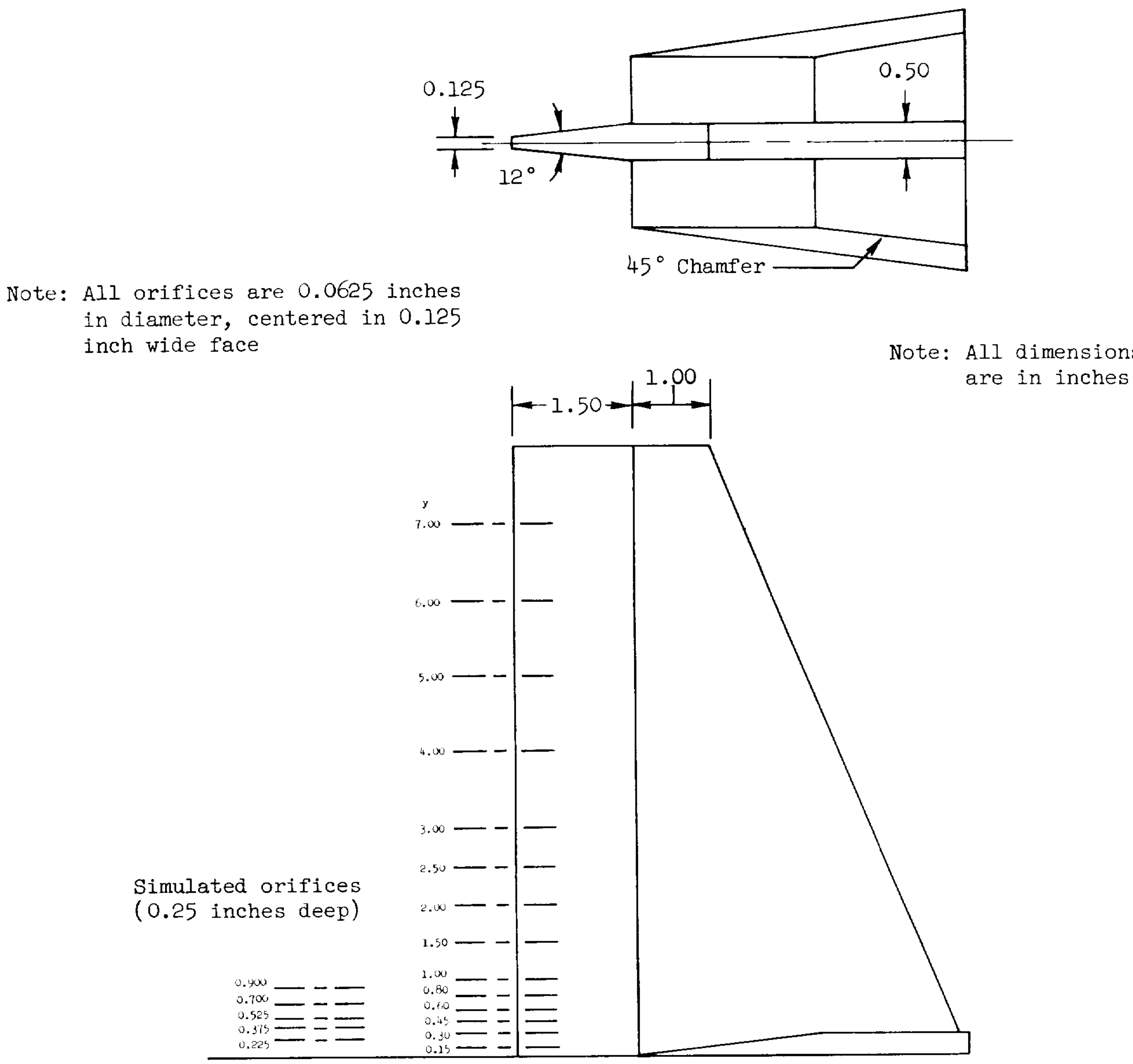


Table of tube heights			
h =	5	8	12
d_1 =	0.042	0.062	0.093
d_2 =	0.042	0.187	0.187
l_3 =	0	2.250	2.250
y =	4.995	8.019	12.081
	3.496	5.603	8.460
	2.492	4.001	6.043
	1.992	3.200	4.842
	1.490	2.401	3.644
	0.990	1.601	2.442
	0.589	0.955	1.485
	0.490	0.795	1.261
	0.390	0.636	1.002
	0.292	0.473	0.768
	0.193	0.316	0.535
	0.092	0.152	0.296
$\frac{l_1}{d_1} = 10;\ \frac{l_2}{w} = 6;\ \frac{w}{h} = 0.0375$			

(a) Multiple-probe rakes

Figure 2.- Geometry of boundary-layer pitot-pressure rakes.



(b) Probeless rake

Figure 2.- Concluded.

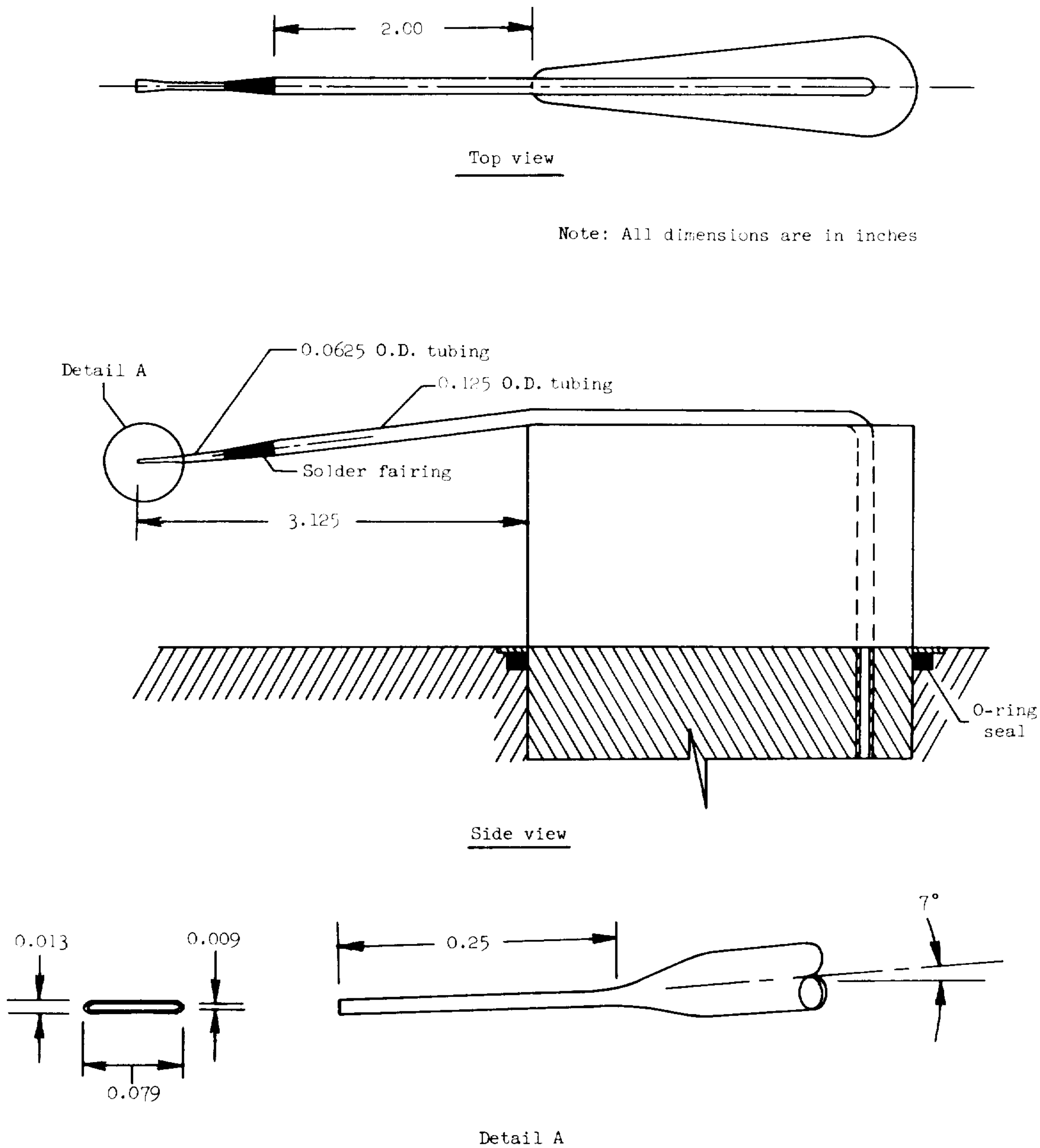
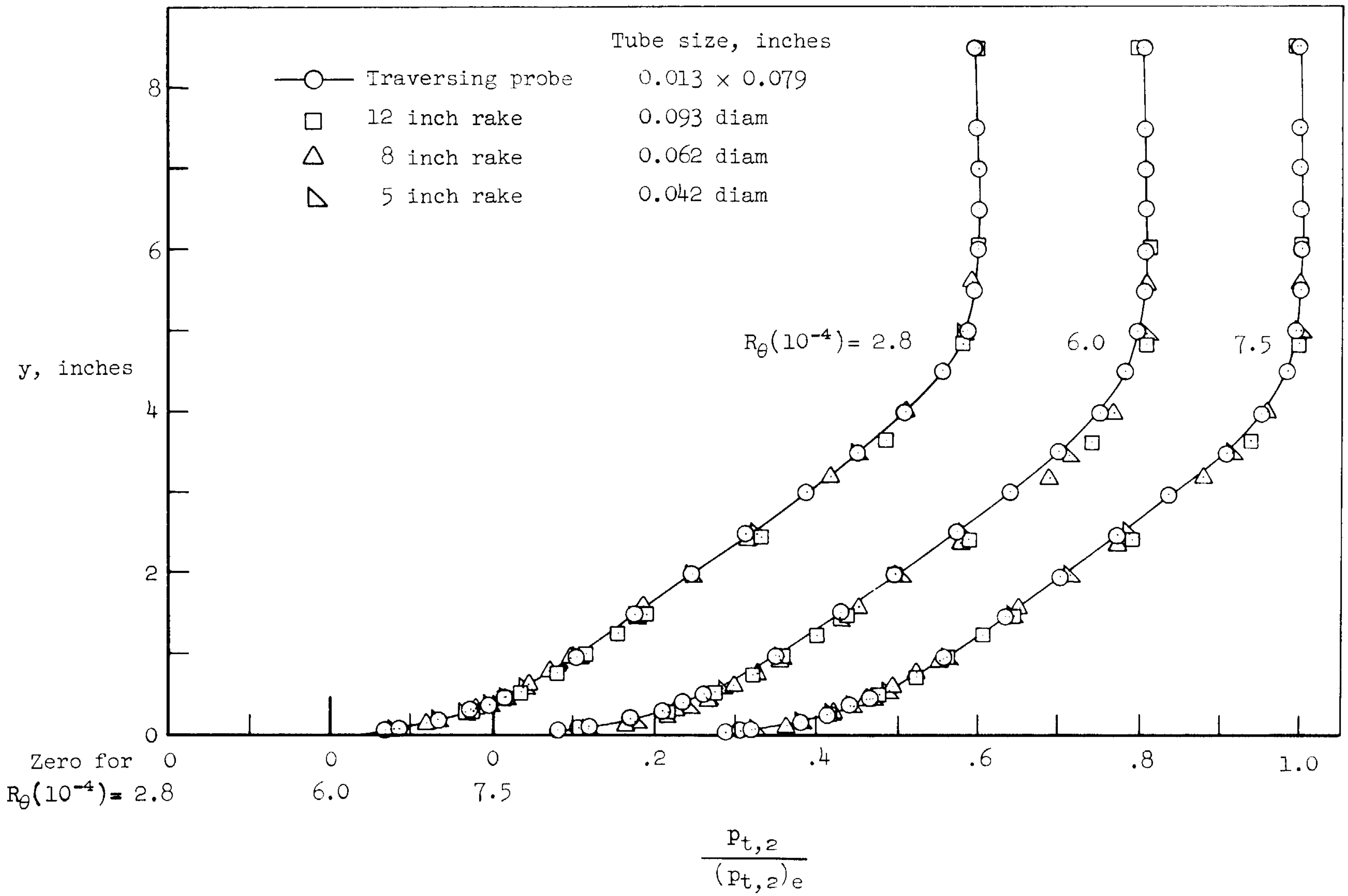
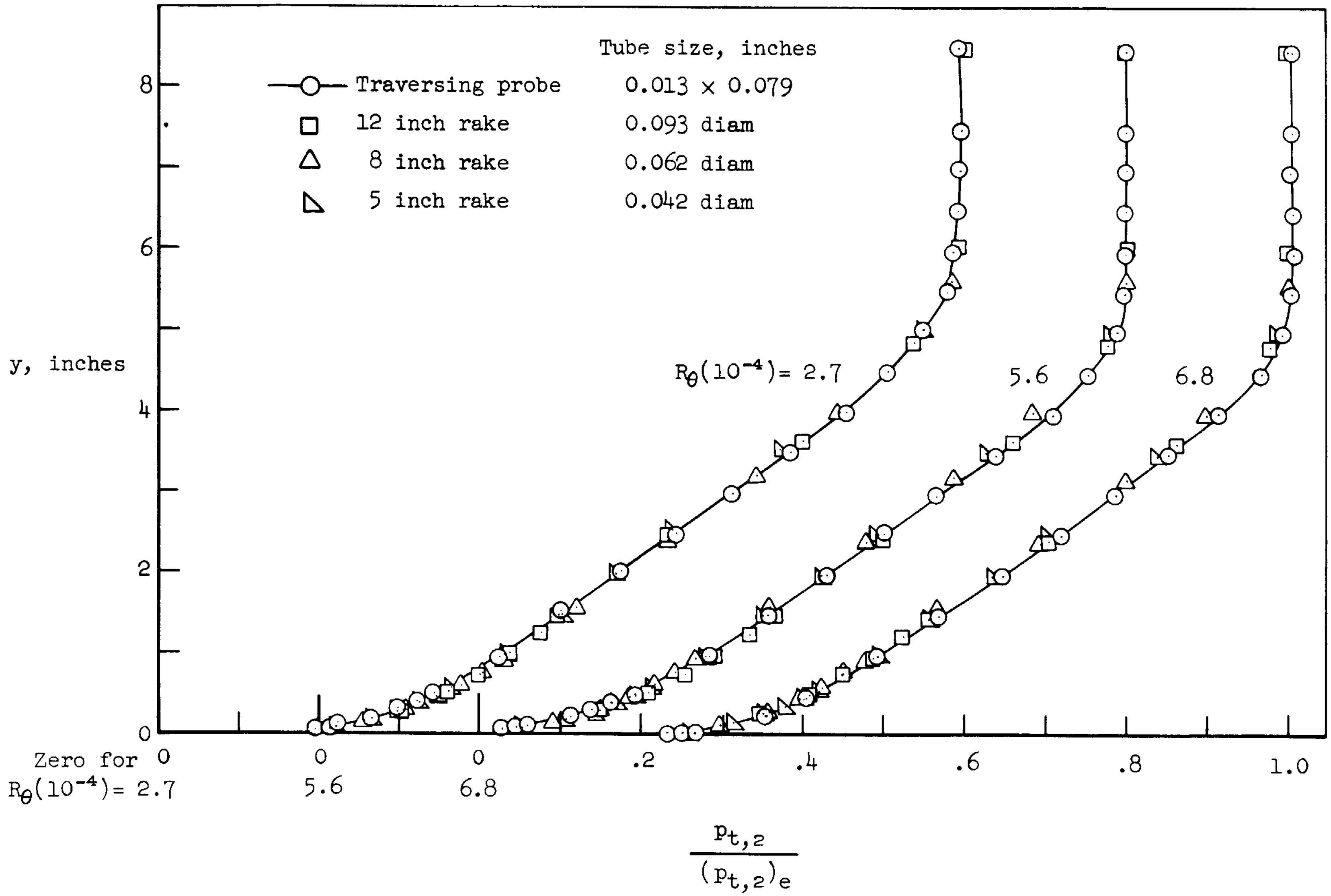


Figure 3.- Geometry of traversing probe.



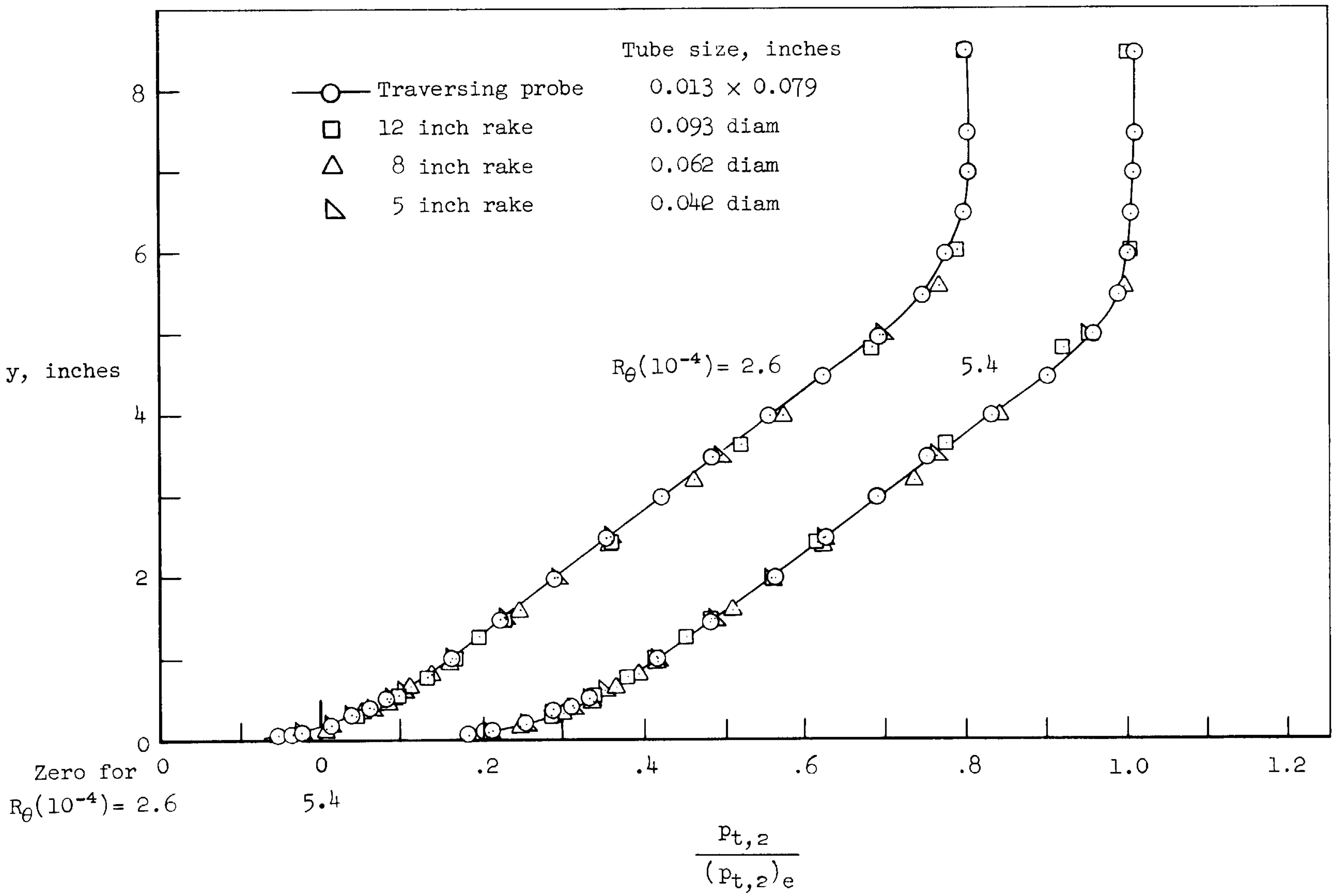
(a) $M_e = 2.4$

Figure 4.- Comparison of rake and traversing-probe pitot pressures.



(b) $M_e = 2.9$

Figure 4.- Continued.



(c) $M_e = 3.4$

Figure 4.- Concluded.

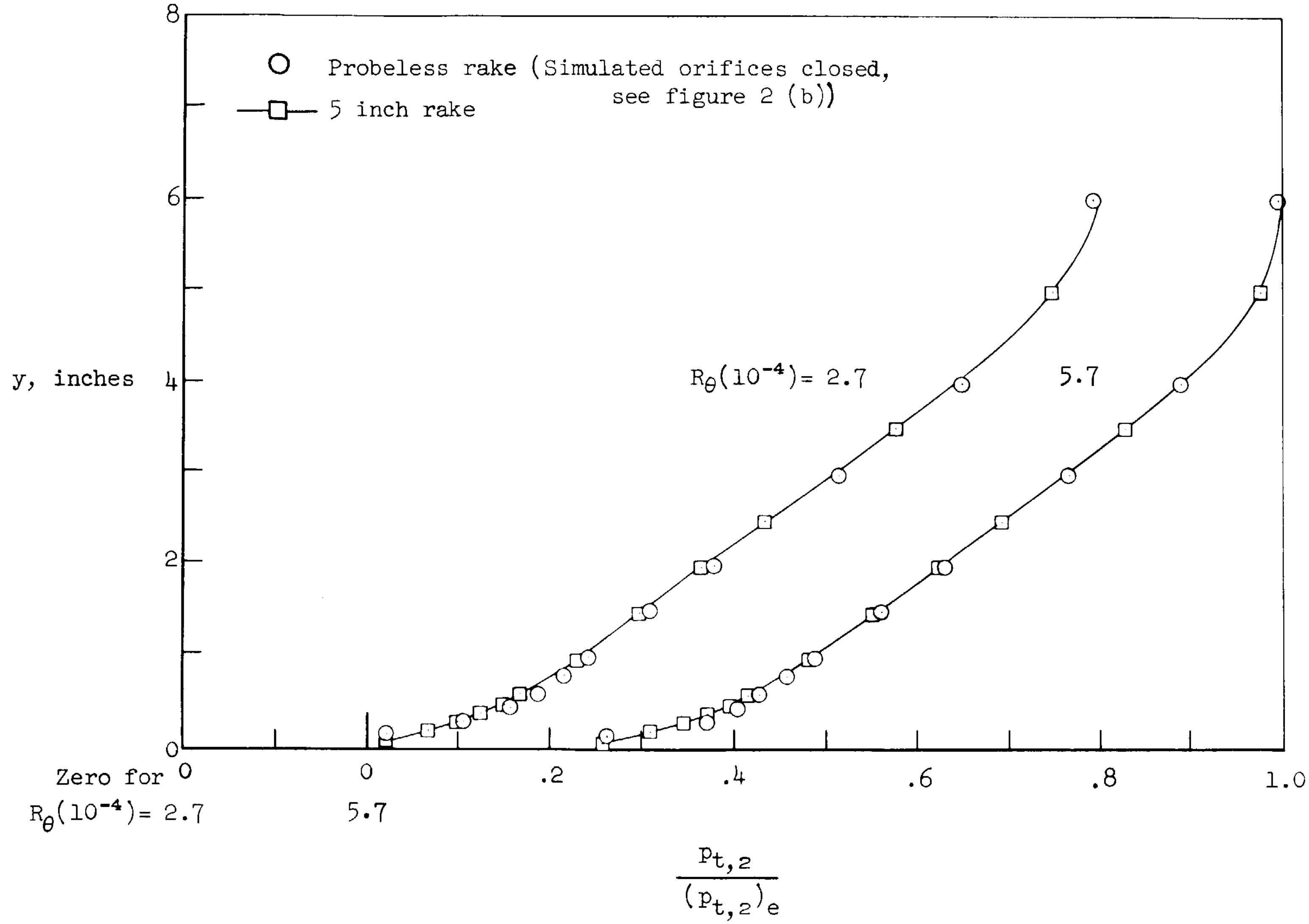


Figure 5.- Comparison of probeless rake and 5 inch rake-pitot pressures; $M_e = 2.9$.