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REVIEW OF THE PITOT TUBE

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1. INTRODUCTION

Modern engineering practice and research frequently require the measurement of a fluid velocity (both magnitude and direction) at a given point in a flow field. Tubes of various sizes and ingenious shapes have been constructed and calibrated for a large number of conditions. Although much valuable data appear scattered throughout the technical literature, there appears to be a dearth of articles providing a summary of pertinent information for the designer and user of such equipment. This paper is an attempt to summarize most of the available material about such tubes. It will have achieved its objective if this paper eliminates the necessity of some user wasting time in the development or calibration of an unsatisfactory velocity-measuring probe.

Apparently the first description of a tube used to measure pressures for velocity determinations was by Henri Pitot in 1732,[1] and tubes for this purpose have frequently been named after him. He described a tube to meet a practical problem, namely, the determination of whether the fluid velocities in a river were higher near the bottom than they were near the surface. The name "Pitot tube" has been applied to two general classifications of instruments, the first being a tube that measures the impact or total pressures only, and the second a combined tube that measures both the impact and the static pressures with a single primary instrument. D'Arcy mentioned improvements to the instrument in 1854.[2,3] Airey[15] and Guy[16] give a reasonable summary of the history and status of information about the tubes up to about 1910.

As late as the period from 1900 to 1915, lengthy discussions were held about the fundamental form of the basic equation that applied to Pitot tube measurements. The two forms were

$$V = \sqrt{2\ gh}$$

and

$$V = \sqrt{gh}$$

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Typical of the discussions of the period are the papers[18] by White[4,5] and Gregory.[6,9] Conclusive articles were presented by Rowse,[17] Moody,[18] and Groat.[19] Attention during the 1920's was devoted principally to a study of the various shapes of tubes for special conditions and to an investigation of some of the limitations in the use of the tubes. The rapidly growing field of aeronautics presented a fruitful area for application of velocity-measuring probes. Also, the general progress of fluid mechanics required more information about the internal mechanism of the flow system, with the result that more emphasis was placed on determining velocity distributions in a wide variety of circumstances.

During the 1930's there was a revived interest in studying the fundamentals of the Pitot tube and other velocity-measuring tubes as applied to water measurements for quantity rate-flow determinations. The papers by Hubbard,[60] Cole,[45,46,59] and Allen and Hooper[39] are examples of this interest.

Since the late 1930's there has been wide-spread application of velocity-measuring tubes to compressible fluids, incompressible fluids at sub- and supersonic velocities, multiphase fluids, viscous and turbulent flow phenomena, boundary layer investigations (basic to heat transfer and fluid friction), fluids passing through cascade systems as in turbomachinery, air speed of airplanes, rockets, upper-atmosphere investigations, and other scientific and engineering problems. This wide-spread usage developed from a demand for more fundamental information about fluid flow in order to understand the mechanisms involved and to be able to evaluate predictions based on theoretical considerations. A wide range of engineering and scientific literature contributes to our present knowledge about velocity probes.

Although the ASME Power Test Codes for Hydraulic Prime Movers[77] and the Special Research Committee on Fluid Meters[34] describe velocity-measuring tubes of various kinds, the information regarding the variables involved in their application is largely missing. Books devoted to flow measurement, like Ower,[41] Addison,[68] and Linford,[78] although including some design and application details, provide inadequate discussions of velocity-measuring probes for the normal use of the engineer.

A Pitot tube or similar velocity-measuring device consists essentially of three parts: the head or instrument section, the pressure-connecting lines between the head and the pressure-indicating device, and the indicating device. The discussions of this presentation will be limited to the head or instrument section. It is recognized that the connecting lines and the pressure-measuring device are important elements of the system, but in many respects they are adequately treated elsewhere.[110] Although the matter of measurements in pulsating flow is of extreme importance in many applications, this subject will not receive more than a scant mention in this paper since the effect of pulsations cannot be adequately treated without a detailed consideration of the flow in connecting pressure lines and the dynamic characteristics of the pressure-measuring device.

A large variety of geometrical shapes are possible and actually have been used. This complicates the problem when one attempts to analyze and correlate available data for presentation in summarized but adequate form. Any suitable opening in a reasonable geometrical shape will provide a pressure approaching closely the total or impact pressure. Also, any difference in pressure between two pressure openings can be calibrated in terms of velocity or, if the tube is installed in a pipeline, against the rate of flow. This paper attempts to correlate similar phenomena associated with probes, giving references to guide the reader to specific calibration information.

2. FLOW SYSTEMS

Many flow situations approach closely a one-dimensional flow system. Wind tunnel and water tunnel throat sections are designed for constant velocity outside the boundary layer, i.e., a one-dimensional flow system. Usually, the direction is known, due to the location of the solid boundaries, and the problem is to determine the magnitude of velocity. For this simple flow system Pitot or Pitot-static tubes are suitable instruments for velocity-distribution determinations. The following definitions will be used:

a. Pitot tube - A cylindrical tube with an open end pointed upstream, used in measuring impact pressure.

b. Pitot-static tube - A parallel or coaxial combination of a Pitot and a static tube. The difference between the impact pressure and the static pressure is a function of the velocity of flow past the tube.

Bernoulli's equation is applied most frequently on the basis of the average velocity, which corresponds to the assumption of one-dimensional flow across the cross section considered. Frequently, in practice, two-dimensional flow considerations more nearly approach actual conditions, i.e., the real velocity distribution in pipe flow when symmetrical about the pipe axis. When the magnitude of the kinetic-energy term becomes important, the velocity distribution must be known in order to evaluate α in the equation

$$\text{Kinetic energy (ft-lb/lb)} = \left(\alpha V_a^{\,2}\right)/2g$$

when the velocity distribution is symmetrical with respect to the pipe axis

$$\frac{\alpha V_a^{\,2}}{2g} = \frac{\int_0^R 2\pi r \frac{w}{g} \frac{u^3}{2} dr}{\int_0^R 2\pi r w u dr}$$

and

$$\alpha = \frac{\int_0^A V^3 dA}{A V_a^{\,3}}$$

where A = area of cross section of flow

V = average velocity for area dA

V_a = average velocity for area A

r = radius to center of area dA

R = inside radius of pipe

u = velocity at radius r

$Q = AV_a$ = quantity rate flow through area A.

The problem of velocity-measuring probes for two-dimensional flow is complicated because it becomes necessary to measure pressures in velocity gradients and frequently the direction of flow is unknown. In general, a two-dimensional probe measures an average magnitude and direction of velocity in a small area rather than at a point in a two-dimensional flow field. An example of a typical instrument is a circular cylinder with two or three pressure-tap holes which is placed with its axis perpendicular to the plane of symmetry of the flow.

In turbomachinery, process equipment, and other cases, it is desirable to know the magnitude and direction of the velocity at any point within the flow system. A probe with a spherical[36] or claw head containing five pressure taps forms a suitable instrument for such measurement.

3. TUBE SHAPE

Impact Total Pressure

The results obtained by a large number of investigators have demonstrated that, if the shape of the Pitot head is one in which a stagnation point exists in the flow system, the full impact pressure is measured at a tap located at the stagnation point. It should be pointed out that this conclusion applies only to a uniform-velocity flow field such as that obtained in a wind tunnel or at the centerline position in a pipe, where the velocity gradients with respect to the radius are small and thus the flow approaches one of uniform velocity in the vicinity of the tube. It is conceivable that the full impact pressure would not be measured in the case where the flow about the tube head is changed due to mutual interference effects between the tube and a solid boundary or the tube and a liquid-free surface. The influence of impact-tube size in a uniform-velocity stream was checked by Zahm,[31] using a 1/8-inch-diameter square-ended tube against a 5-inch-diameter pipe as well as a 1/8-inch glass tube against a 0.01-inch-ID hypodermic needle. Both checks gave the same impact pressure within instrumentation tolerances. The ability of Pitot tubes to determine the true impact pressure for a wide range of geometrical shapes has been recognized for a long time, a typical statement in this respect being given by Zahm[8] in 1903: "Almost any size and form of nozzle will convey the impact perfectly, providing it squarely face the wind."

The most common type of Pitot tube has the head mounted on a support stem. The axis of symmetry of the head is parallel to the direction of the velocity and perpendicular to the axis of its stem. The head may have an impact-pressure tap, one or more static-pressure taps, or both impact and static taps in the same head, the latter forming a Pitot-static tube. The generalized dimensions of some typical Pitot-static tubes are given in Fig. 1.

A wide variety of head-tip shapes have been investigated, a general classification being presented in Fig. 2. It should be noted that only two examples of possible combinations of basic types are given. It is necessary to consider the addition of a miscellaneous group classification in order to cover many shapes investigated for special purposes, such as the wedge or cone for static-pressure determinations in supersonic flow.

Typical of experiments relating to the magnitude of the impact pressure measured by Pitot heads of different shapes is the work of Merriam and Spaulding[48] and Ower and Johansen.[30] Colė, in the discussion of Hubbard's work,[60] presents a series of tests for tubes in a pipe. Merriam and Spaulding have investigated the effect of the size of the pressure tap with respect to the diameter of the Pitot head in the case of a hemispherical tip within the range of $0.2 < d/D < 0.74$ and found that the size of the hole has no effect on the magnitude of the impact pressure measured at zero yaw. On the other hand, to obtain the true impact pressure, the problem of alignment in yaw of the Pitot head is much more critical in the case of the smaller pressure-tap sizes.

Another common type of tube is formed by installing pressure taps at suitable locations in a tube of uniform cross section placed with its axis perpendicular to the direction of the flow field. The tube may project into the fluid stream from one boundary or it may pass through the fluid stream with the pressure taps located near the middle portion. The tubes projecting into the stream have been designated as cantilevered Pitot cylinder,[113] cylindrical impact tube,[43] and heavy-duty Cole Pitometer.[77] The common head shapes are square-ended, hemispherical, ellipsoidal (oval shaped), and spherical when the tube does not span the flow. The cross-section shape is circular or of some type of streamlined section. In the event the tube passes through the flow field, the probe is known as a transverse tube. In the usual case, the cross section is circular. This type of tube has been designated a transverse Pitot tube,[57] Pitot cylinder,[69] Collins tube,[57] and streamlined Pitot-tube bar.[116]

Static Pressure

In some cases of flow in pipes it is possible to obtain a suitable measurement of the static pressure from a piezometer installed in the pipe wall. Allen and

Hooper[39] investigated types of construction and magnitudes of errors of such pipe-piezometer installations for the determination of static pressure. Within the range of tests in a 12-inch-diameter pipe with average water velocities up to 7.3 ft/sec, variations in the size of piezometer hole from 1/16 to 27/32-inches diameter have no effect. A true square-edged hole without edge burrs, flush with the inside pipe wall, and with a depth of constant cross section for at least two diameters, provides an accurate piezometer when there are no fluid swirls or cross flow. A slight rounding (radius of curvature less than one-fourth of hole diameter) does not change the reading of the piezometer and is easier to produce than a sharp edge without burrs. Errors due to a variety of poor constructions were found to be expressible in terms of a constant percentage of local velocity head existing at the orifice for each type of piezometer. Comparison of readings from piezometers installed downstream from a 90-degree elbow will provide some information about effects of cross flow and swirls on static-pressure measurements. Angus[56] has made such tests and showed pressure variations up to almost one velocity head. The general pattern of pressure variations remained unchanged over the velocity range of his tests from 5.3 to 17.3 ft/sec.

When a Pitot tube is used in a pipe and the static pressure is determined by a pipe-wall piezometer, the pressure distribution about the Pitot tube stem may affect the piezometer pressure. Hubbard[60] presents data from a 12-inch-diameter pipe for the magnitude of the pressure and resulting velocity error for various distances of piezometer ahead of the Pitot tube stem and at different positions around the pipe circumference when the stem extends to the middle of the pipe. For example, if the pipe-wall piezometer were situated 45 degrees from the plane of the Pitot stem axis, the piezometer should be placed about 3.7 stem diameters ahead of the stem centerline to obtain a static-pressure measurement with no error. At 90 degrees, the distance becomes 7 diameters. Within the limits of the tests which extend to 180 degrees and distances of 12 diameters, an over- or underdetermination of velocity magnitude may be made, depending on the relative positions existing for a given arrangement.

When the head of a Pitot tube extends into the region of the plane of a pipe-wall piezometer, the pressure measured by the piezometer tends to be low due to the reduced cross section of flow. For the case of a head-projected area of 0.47 percent of pipe cross-section area and located at pipe centerline, Hubbard[60] found the pressure reduction to correspond to the "Venturi effect" calculated on the basis of average velocities when the tip was five or more tip diameters ahead of the plane of the wall piezometer.

With a Pitot-static tube, the magnitude of the pressure sensed at the static-pressure tap may be a function of the shape of the tip and the distance from the tip to the plane of the holes. If the tube head is a body of revolution, potential flow calculations will provide the approximate pressure distribution. For most real tubes, an experimental calibration is necessary to achieve desired accuracy. Static-pressure distributions on tube heads have been made by several investigators. Fig. 3 shows the difference in indicated and free-stream static pressures as percent of dynamic heads for hemispherical tips as found by Ower and Johansen[30] in a closed-throat wind tunnel at $Ma < 0.1$. Their data on tapered tips showed a similar pressure pattern. Merriam and Spaulding[48] obtained similar results for a wide range of Pitot-static tube tips and static-pressure locations, demonstrating the wide applications possible for the design curves of Figs. 3 and 4. Experimental data by Krause[88] for a hemispherical tip show that the reading at the static-pressure taps located from 3 to 7 tube diameters from the tip is unchanged through a velocity range up to Ma = 0.6. At Ma = 0.9, a change in static-pressure coefficient developed.

The Pitot-static tube must have a support to hold the head in position. Generally the support takes the form of a continuation of the head tube by means of a right angle or a 90-degree bend with reasonable radius to form a stem perpendicular to the head. Any object placed in a stream will influence the static pressure upstream from the object. The approximate magnitude can be obtained from potential-flow calculations such as carried out by Zahm[33] and others. For real fluids and unsymmetrical flows about the head and stem it is desirable to measure the differences in static pressure as the position of the stem with respect to the static holes varies.

Ower and Johansen[30] have investigated the stem effect on static pressures of a Pitot-static head for tapered and hemispherical head tips in a closed-throat wind tunnel at Mach numbers less than 0.1. Merriam and Spaulding[48] completed check investigations for a hemispherical tip in an open-throat wind tunnel for tubes with round and square bend connections between head and stem. All data were for cases where the stem diameter was equal to the head diameter. The results were independent of the type of bend connection for ratios of $x_s/d \geq 4$, where x_s is the distance between the stem and the static-pressure holes and d is the diameter of the head. Fig. 4 shows an averaged curve of the available data from these investigations for the effect of stem position on the static-pressure determination when the static pressure is the average obtained from a row of static taps around the circumference of the tube head.

In the usual case the stem supporting the head joins it on one side only; thus a difference in static pressure will exist around the tube circumference. Test results obtained by Hubbard[60] at the centerline of a pipe and shown in Fig. 5 indicate the magnitudes of the pressure errors as functions of the stem location and angle around the circumference. These results will be modified as the tube head is displaced from its position at the pipe centerline, but magnitudes of variations are not known.

Krause[88] has investigated the stem effects and mutual interference for static-pressure tubes in a rake when used in an open jet. He calls attention to the low registration of a static-pressure sensing device when used in an open jet of limited diameter as compared to an infinite stream. He found the stem effect to be a function of the ratio of stem diameter to jet diameter and of the Mach number in the range 0.3 to 0.9 for the values of $5 < x_s/d_s < 10$, where d_s is the diameter of the stem. He found a change of less than 1 percent for $2 \times 10^4 < Re < 9 \times 10^4$. For correct static-pressure measurements for tubes used in a rake, the centerline distance between heads should be greater than 6 head diameters. Greater distances are required if the Mach number becomes larger than 0.6.

Consideration of the difficulties in measuring the static pressure would lead one to expect a variation in pressure distribution determined for a cylinder if different-sized piezometer holes were used. Hemke[32] has determined some values using a circular cylinder of 1-inch diameter spanning a 6-inch-diameter open jet with air velocities from 30 to 175 ft/sec. Tests covering the range from 0.008- to 0.25-inch-diameter piezometer holes demonstrated that hole diameters must be less than about 0.06 inch for accurate pressure-distribution measurements. The pressures on the rear side of the cylinder were independent of hole size.

4. FLUID-FLOW CHARACTERISTICS

Due to the requirements of a particular flow-measuring situation, there has been a large amount of interest among investigators in the pitch and yaw characteristics of Pitot, Pitot-static, and other velocity-measuring tubes. An extensive literature provides excellent empirical data over a wide range of flow conditions and tube geometries. Characteristic curves for a typical hemispherical-tip Pitot-static tube as obtained by Merriam and Spaulding[48] appear in Fig. 6. (See Ower and Johansen,[30] Hodkinson,[66] Markowski and Moffatt,[71] Gracey _et al._,[85] Gracey _et al._,[86] Russell _et al._,[89] Gracey _et al._,[94] and Schulze _et al._[98]) These characteristic curves are a function of the geometry of the tube and must be determined for each tube over the expected operating range.

Investigations, development, and testing of turbomachines such as stream and gas turbines, axial and radial air compressors, and centrifugal pumps require reliable flow-surveying instruments. Flow characteristics of greatest concern include total pressure, static pressure, velocity direction and magnitude, and temperature. Although extremely important, temperature probes are considered to be beyond the scope of this paper. Meyer and Benedict[99] present a brief summary on performance and design characteristics of claw, cylindrical (cantilevered Pitot), spherical, disk averaging, and rake probes. Markowski and Moffatt[71] give corresponding material on micro-Pitot-static, Kiel, cylindrical, and three-dimensional cylindrical probes. Schulze, Ashby, and Erwin[98] compare the performance of several probes for this service and find high-sensitivity yaw indication with simple yaw-element probes when the angle of slant is between 30 and 60 degrees relative to the tube axis, maximum directional sensitivity for the claw-type probes when the included angle between the two yaw-element tubes is 120 degrees, and that several miscellaneous combination probes will provide suitable information.

Velocity Gradient

Limited experiments[55] have demonstrated that when a tube is used in a two-dimensional velocity field, the effective center of the total pressure of a square-ended circular impact tube is displaced from the geometric center toward the region of higher velocity. The experiments covered the range of $0.35 < d/D < 0.75$ and

$$0.1 < \frac{D}{\frac{\rho V^2}{2}} \frac{d\left(\frac{\rho V}{2}\right)^2}{dx} < 1.2$$ with the results being expressed in $\delta/D = 0.131 + 0.82\ d/D$,

where d = internal diameter

D = external diameter

δ = displacement of effective center of total pressure

x = coordinate transverse to velocity.

The air velocities were low and provided essentially incompressible flow conditions. Data were obtained in the wake of an airfoil where the tube was free from wall mutual interference and also in the boundary layer of a model airship hull where mutual interference existed. Results of these tests have been applied generally to other tubes of different nose shape due to the lack of specific data regarding those shapes.

Impact tubes with square-ended flattened oval sections (fish mouth), Fig. 7, have been used for boundary layer velocity-distribution measurements in order to reduce the displacement effect.[87,96,106] Livesey[108] states, without presenting the supporting experimental evidence, that for incompressible flow, the displacement error is a function of the solidity of the cross section of the probe tip and the aspect ratio of that tip. Livesey recommends a displacement correction of $0.15 < \delta/D < 0.18$. On the basis of boundary layer measurements O'Donnell[105] shows that measurements are subject to tube interference if $D/\lambda \geq 0.22$, where λ is laminar boundary layer thickness. Livesey also points out that there is no consistent indication of a displacement error in compressible sub- or supersonic flow.

Blue and Low[101] made laminar boundary layer velocity measurements under identical conditions with a series of flattened oval impact tubes. The thickness ratios varied by $0.20 < d/D < 0.72$, the aspect ratio by $2.5 < L/D < 16.6$, and the solidity correspondingly. These tests made in air with $2 < Ma < 3$ were in the range of no low Reynolds number effects. The results determined with each probe showed that the variations of measured boundary layer momentum thickness, were of greater magnitude than could be explained by correcting for the effective centerline displacement[55] on the basis of presently available data.

Turbulence

Turbulence in the fluid stream may have a decided effect on the flow in a system, such as changing the boundary layer characteristics, including the separation point (if one exists),[111] and producing a pressure reading on a Pitot-static higher than the true mean pressure. On the basis of the theory of isotropic turbulence, Goldstein[53] obtains the expressions for the pressures as

$$\text{Total head} = p + \frac{\rho q^2}{2} + \frac{\rho \overline{(q')^2}}{2}$$

$$\text{Static pressure} \;=\; p_s + \frac{\overline{\rho(q')^2}}{6}$$

where q is the resultant mean velocity and q' the resultant turbulent velocity. Flow in pipes does not exhibit isotropic turbulence, and Fage[54] calculated on the basis of turbulence measurements[42]

$$\text{Static pressure} \;=\; p_s + \frac{\overline{\rho(q')^2}}{4} .$$

(See Grossman[100] and Laufer[102] for additional pipe turbulence data.) For the usual degree of turbulence at sections in pipes of fully developed velocity distribution, the turbulence errors are small and tend to equalize in the velocity determination.[49] For higher degrees of turbulence it is possible for the turbulence errors to reach appreciable magnitudes in terms of the dynamic pressure.[82]

Cavitation

When the local pressure in the vicinity of a body submerged in flowing liquid is reduced sufficiently, cavitation occurs, with resulting changes in pressure distribution about downstream portions of the body. For Pitot tubes of normal shape, no changes in impact-head reading are expected, but if a Pitot-static tube is used, the static pressure may be changed appreciably when cavitation takes place. In studies using water tunnels, a large body of data has been collected on symmetrical bodies subject to cavitation flow. Typical results for a tube with a hemispherical head are shown in Fig. 8, taken by Rouse and McNown[72] in the water tunnel of the Iowa Institute of Hydraulic Research. Additional data are available from the work of the David W. Taylor Model Basin, California Institute of Technology, and Pennsylvania State University.

Multiphase Fluids

If condensation takes place when a condensable vapor exists in the fluid, the velocity and temperature downstream from the condensation region will differ from corresponding properties in the undisturbed air.[67] Care must be used in the interpretation of measurements obtained under such conditions. Pearcey[91] made experimental studies in wind tunnels with water vapor in the air and a Mach number range of 0.5 to 0.8 and found that condensation caused a loss in total head which depended on supersaturation phenomena.

Modified impact tubes may be used to determine impact pressures in two-phase fluid streams. Examples would be the gas-velocity measurement when liquid or fine solid particles are involved in the stream. Difficulties arise due to plugging and reading changes due to the influence of the momentum exchange between gas and particles upstream and within the instrument. The tendency to plug can be reduced by venting the tube at the rear through a nozzle having an area of about 5 percent of the inlet area. Dussourd and Shapiro[114] have theoretically and experimentally tudied the momentum-exchange effects on pressures for a deceleration probe with static aps located in the inside wall of the probe head. Good correlation of theory and experiments was shown to exist in the overpressure recorded with the tube. Practical calbration data are available in the original articles.

5. DYNAMICAL SIMILARITY

eynolds Number

True dynamical similarity requires geometrical similarity in all respects rearding probe- and flow-system boundaries as well as kinematic similarity. If dynamcal similarity exists for the flow about a Pitot tube, the Reynolds number becomes the easure of this condition, i.e., Re = constant. A wide range of experiments has shown o change in Pitot tube pressure-coefficient characteristics at values of Re greater han about 500 and for Pitot-static probes (NPL type) at values of Re greater than aout 2300 with Re based on probe-head external diameter. At Re < 500, the magnitude of he pressure coefficient $C_i = \dfrac{p_i - p_\infty}{\dfrac{\rho V_\infty^2}{2}}$ is increasingly greater than unity as the Reynlds number decreases, actual values depending on the geometry of the probe and impact pening.

Theoretical investigations[50,73,74,79,95] have been made for the purpose of calulating the low Reynolds number effects on the impact tube pressure coefficient in incompressible fluids. One procedure has been to integrate the momentum equation along the upstream stagnation streamline from the stagnation point to the free stream for specified elocity variations in the vicinity of the stagnation streamline. Approximate velocity istributions at appropriate Reynolds numbers have been based on Stokes, Oseen, and poential flow with boundary layer considerations. The geometrical shapes have included pheres, cylinders, and prolate spheroids. The results in terms of the pressure coeficients are given in Table 1.

Impact tubes have been calibrated by several different means to ascertain emirical magnitudes of the viscosity effects. The usual calibration methods are the folowing:

a. The rotating arm equipment where the results are subject to corrections for the fluid-swirl velocity induced by the probe under test and the determination of static pressure.

b. The centerline velocity (maximum) determination in fully developed viscous flow in a circular conduit, the rate of flow through the known cross-sectional area of pipe being determined by other calibrating means.

TABLE 1

THEORETICAL PRESSURE COEFFICIENTS FOR IMPACT TUBES WITH DIFFERENT SHAPES OF PROBE HEADS

Flow	Stokes	Oseen	Low Re
Approximate Re Range	$(Re < 0.1)$	$(0.1 < Re < 5)$	$(10 < Re < 100)$
Cylinder		$\left(\dfrac{1 + \frac{4}{Re}}{1.309 - \ln Re}\right)$ (a)	$\left(1 + \dfrac{4}{Re}\right)$ (a) $\left(1 + \dfrac{4}{Re + 0.457\sqrt{Re}}\right)$ (a)
Sphere	$1 + \dfrac{3}{Re}$ (a)		$\left(1 + \dfrac{6}{Re}\right)$ (a) $\left(1 + \dfrac{6}{Re + 0.455\sqrt{Re}}\right)$ (a) $\left(1 + \dfrac{6}{Re + 0.457\sqrt{Re}}\right)$ (b)
Prolate Spheroid where $C = f_1(\epsilon)$ $D = f_2(\epsilon)$ ϵ = eccentricity of ellipsoid	$\left(1 + \dfrac{3}{Re}\left[\left(1 + \dfrac{\epsilon^2}{10} + \dfrac{109}{1400}\epsilon^4 --\right)\right]\right)$ (c)	$1 + \dfrac{D}{Re}\left(1 + \dfrac{DRe}{8}\right)$ (c)	
Source Shape			$\left(1 + \dfrac{8}{Re}\right)$ (c)

Re based on outside radius perpendicular to flow
(a) Homann[50]
(b) Chambré[73] and Chambré and Smith[79]
(c) Ipsen[95]

c. The known velocity field, where velocity at location of impact tube is known from other calibrating means such as wind tunnel or water tunnel nozzles or the float method.

Table 2 lists the important available calibration tests, and Fig. 9 presents the work in terms of curves omitting the experimental points. MacMillan[107] shows a smaller spread in these curves if Re is based on internal tube diameter.

The calibration work shows that the impact-pressure coefficient rises rapidly at lower Reynolds numbers, even reaching a magnitude of 2 at Reynolds numbers in the order of 4, the actual magnitude depending on the shape of the tip. Pressure coefficients for spherical and source-shaped probe heads depart from unity at larger Reynolds numbers and reach higher values at given low Reynolds numbers than do straight tubes with square-cut or sharpened upstream ends. Some tests have shown pressure coefficients of less than unity in the Reynolds number range of about 100 to 6000; however, in general, the more reliable tests have tended to show no values less than unity.

Supersonic Flow

Wilson[109] investigated the Reynolds number effects on static-pressure measurements in a supersonic flow field for a cone-cylinder type of static probe. The tube head was formed by a 15-degree total included-angle cone with the static holes located about 13 tube outside diameters downstream from the base of the cone. At Mach numbers of 4.13, 4.67, and 6.39 the probe diameter and static-hole diameter had no effect on static-pressure readings for $Re \gtrsim 3.500$ (based on tube OD). There was a trend (not established) for the static pressure to increase at Re below this magnitude.

In the special application of measurement under rarefied-gas-dynamics conditions at low Reynolds numbers with Mach numbers below or above unity, slip-flow phenomena may become important. Lin and Schaaf[83] have developed theoretical values for these conditions, and Sherman[90] includes tests on supersonic flows at low Reynolds numbers, but does not reach the region where slip flow (molecular mean free path same magnitude as characteristic length of flow system) becomes important. Sherman[90] calibrated spherical, source-shaped, and sharpened upstream-end probes throughout a limited range of Mach numbers. The results show characteristics which are similar but take place at different free-stream Reynolds numbers, as compared with subsonic data, the impact-pressure coefficient being a function of probe shape and Reynolds number, with only a trend indicated for change with Mach number.

Mutual Interference

When pressure-measuring tubes are placed in the vicinity of a fluid boundary, the tube calibrations made without such boundaries usually cannot be applied directly. Information about special flow boundaries is very limited and only a few cases are

TABLE 2

IMPACT-PRESSURE CALIBRATIONS

Ref.	Head Shape	d/D	Re Range (VD/μ)
50	Sphere	----	2 - 80
	Cylinder	----	2 - 120
90	Square, sharp	1.0	4 - 400
	Source shape	0.20	4 - 400
103	Square, blunt	0.74	2 - 8000
107	Square, blunt	0.06	25 - 2200
28	Square	----	9 - 55
14	Square	----	40 - 1300
38*	N.P.L. Std	----	3 - 4000
	Hemispherical	0.155	3 - 3000

d = tube hole diameter

D = outside tube diameter

*Data for Pitot-static tube

available. Some data for static-pressure differences with Pitot-static tubes approaching pipe walls are discussed in the sections on the tubes concerned. Comparisons of hot-wire and impact tube with known static pressure for velocity measurement in the boundary layer have shown good correlation as long as the tube diameter is small enough. Care must be exercised when making measurements in the flow passages of turbomachines for the purpose of interpreting the instrument readings obtained.

Free Surface

At times it becomes desirable to use a Pitot probe near the free surface of a liquid. There is a mutual interference in fluid flow between a tube and a solid wall. It would be expected that a Pitot tube measuring a velocity near a free surface would have a mutual interference effect with that surface. This phenomenon does not appear to have been investigated, either on an experimental or a theoretical basis. Parkin, Perry, and Wu,[112] in checking the velocity distribution in a free-surface water tunnel, indicate that discrepancies in the uniform velocity distribution found near the free surface were not significant, since they felt that the Prandtl probe near the surface did not read correctly. They indicate "so far as the writers know, calibration data for a Prandtl probe near the surface are not available."

6. APPLICATIONS

Shielded Total-Pressure Tube

In the determination of the total pressure, it is frequently important to use instruments insensitive to yaw and pitch angles. Although it is possible to correct for effects of angularity of flow with many types of probes, the calibration work required is expensive and often inconclusive due to the different characteristics of the test and calibration flow fields. Kiel[47] introduced a shielded total-pressure tube to meet the requirements of insensitivity to angularity for total-pressure measurements.

Gracey, Letko, and Russell[86] investigated thirty-nine total-pressure tubes over an angle-of-attack range of $\pm$ 45 degrees at $Ma < 0.3$. A few typical results are given in Fig. 10. Russell, Gracey, Letko, and Fournier[89] extended the observations to six Kiel type tubes for the range $0.26 < Ma < 0.95$, demonstrating the greater insensitivity of a curved entry (Fig. 11) compared to a straight conical entry (Fig. 10-4). Typical characteristics for Mach number effects are shown in Fig. 11, taken from Gracey, Pearson, and Russell,[94] who investigated a typical shielded total-pressure tube through the transonic region. Gracey, Coletti, and Russell[85] used twenty tubes selected from the thirty-nine[86] previously tested to determine Mach number effects in the supersonic region up to $Ma = 2.4$. The Kiel type probe was the only tube to show a decrease in range of insensitivity as Mach numbers increased. Markowski and Moffatt[71] call attention to the miniaturization of the Kiel tube for use in turbomachinery work without appreciable change in the yaw-insensitive range, resulting in the shape shown in Fig. 12.

Cantilevered Pitot Tubes

Tubes of circular or other constant cross-sectional shape that are inserted into a pipe with an impact-pressure tap faced into the stream are classed as cantilevered Pitot tubes or cylinders. A static-pressure tap or a downstream tap may be included in the tube, or an independent piezometer may be used for static-pressure determination. Standard tips include hemispherical, square-ended, and ellipsoidal shapes with one, two, or three holes in a transverse plane located at various distances from the tip. Fig. 13 shows the magnitude of variations in impact pressure to be expected for different tap locations for hemispherical and ellipsoidal tips. Numachi and Hutizawa[58] present data for square-ended cylinders with approximately the same coefficients for $Z \geqq 2D$.

Cantilevered Pitot tubes are valuable for measuring impact pressure and for determining the direction of velocity in two-dimensional flow, the latter determination being independent of position of holes with respect to pipe walls. The directional properties are satisfactory also when the flows are inclined to the cylinder axis.

The total pressure measured with cantilevered Pitot tubes appears to have constant coefficients for Re greater than about 4×10^3 (see Numachi,[43] Kasai,[51] Kito,[52] Numachi and Hutizawa,[58] and Winternitz[113]). This result appears to hold for hemispherical, square-end, and ellipsoidal heads with holes 0.5 diameter or more from the tip.

The pressure distribution about the cylinder at the transverse plane of the taps is similar to the pressure distribution about a cylinder of infinite length. The distribution is a function of Re and the position of the taps with respect to the pipe walls. Winternitz[113] shows that pressures vary for angles greater than 40 degrees as the taps approach the pipe walls. The "critical angle," where the true static pressure is indicated, reduces from 0.5 to 1 degree for a Re increase of from 10 to 15×10^3. The piezometer hole size compared to tube diameter is important.

Silberman[69] and Winternitz[113] provide information on the total-pressure-coefficient changes on a cantilevered Pitot cylinder when the flow is inclined to the axis of the tube. Within angles of pitch of $\pm$ 20 degrees, the coefficients are lower when the tip is pointing downstream than when pointing upstream at a given inclination. A cosine square law gives coefficients within about 3 percent of experimental values for the range considered. Meyer and Benedict[99] show that there is some variation in coefficients in inclined flow for tubes with a range of from 1- to 3-diameters distance from a square tip to the plane of the static-pressure holes. Markowski and Moffatt[71] describe a cantilevered tube with four holes, one being on the hemispherical portion of the head in the same plane parallel to the head axis and containing the center hole of the normal three-hole tube. With the calibration curves hich they give, it is possible to determine velocities in three dimensions with this ube.

Winternitz[113] calibrated cantilevered Pitot cylinders in a towing tank and n the throat of a wind tunnel. On the basis of agreement of experimental results, t can be inferred that turbulence effects were insignificant within the range $1000 <$ $Re < 12{,}000$ and the variations in turbulence of still water and the wind-tunnel throat. n the other hand, turbulence affects the point of separation of flow from the pe- iphery of the cylinder and changes the pressure distribution for angles greater than he angle at separation. Meyer and Benedict[99] give limited data on the effect of tur- ulence produced by a screen on the static-pressure calibration of a tube with a tap t 40 degrees from the flow direction.

Winternitz[113] used a three-hole cantilevered Pitot tube to measure static ressure in the throat of a circular closed-throat wind tunnel. The Pitot diameter vas 0.311 inch and the tunnel throat 7.5 inches. Using the wind-tunnel piezometer s a standard static pressure, the measured static-pressure difference from the stand- ard varied from +10 to -10 percent of the velocity head at the tunnel centerline, vith the measured value being high near the wall where the tube was inserted.

Cole Pitometer

This instrument, in its various forms, has been used for many years and is specified in the ASME fluid meters report[34] and in its Power Test Codes for Hydraulic Prime Movers.[77] Many articles have appeared in the technical literature, so that reasonably complete information is available for normal applications.[7,10,11,12,23,24,45,46,59]

Transverse Tube

One type of transverse Pitot tube is a straight circular tube of uniform diameter with one or more pressure taps for the determination of the dynamic head in a stream of fluid. When used in a pipe line, the tube passes through stuffing boxes in opposite pipe walls and is free to slide and rotate to place pressure taps at desired locations in the pipe. One form of this instrument is the Collins tube of 5/16-inch diameter with two pressure holes of 0.116-inch diameter placed 180 degrees apart and offset by a distance of 7/16 inch. Calibration data are presented by Christiansen and French[57] and by Cornwell,[62] the latter being more complete. For two-hole instruments similar to the Collins tube, the tube coefficient is less than unity since the downstream pressure is less than static, and a blocking correction (function of tube diameter or pipe diameter) and an overall pipe coefficient are necessary to determine flow in a pipe.

The inside pipe contours at the stuffing boxes are very important for a transverse tube. The type illustrated in the fluid meters report[34] may produce large errors, and recommendations have been made to have the gland welded to the outside of the pipe and let the tube pass through a simple hole in the pipe wall.[57]

Fig. 14 shows measurements made with a transverse tube and a cantilevered Pitot tube in a 6-inch pipe with 20-diameter unobstructed straight pipe upstream. For the same rate of flow as indicated by a calibrated orifice, all curves compare the pressure indicated with the pressure from a standard piezometer placed in the side of the pipe. The shape of the static-pressure curve illustrates the difficulties in the interpretation of such measurements.

Many pressure distributions about circular cylinders crossing a uniform flow field have been reported in the literature. Fig. 15 shows typical pressure distributions at Reynolds numbers above and below the critical Reynolds number range (Reynolds numbers through which the drag coefficient decreases rapidly from about 1.2 to 0.3) determined in air at Mach number of about 0.06. Tests have demonstrated that the potential-flow solution provides information closely approximating actual conditions on the forepart of the cylinder. The departure of theory from experiment depends on the establishment of the adverse pressure gradient associated with boundary layer separation. This separation takes place at larger angles as the Reynolds number increases. Gowen and Perkins[97] have shown that Reynolds number effects on pressure distribution were negligible at Mach numbers above unity to the limit of their tests, i.e., Ma = 2.9.

Short-Head Tube

The dimensions of the short-head tube given in Fig. 1 were selected from the design data of Figs. 3 and 4 to give a velocity coefficient of unity. This procedure was verified by the work of Merriam and Spaulding.[48] The square corner between the head and the stem was to allow measurements to positions one-half tube diameter from the pipe wall.

Comparative calibrations in a three-foot-square closed wind tunnel on five Pitot-static tubes (Prandtl 3/8", ASHVE 1/4", ASHVE 5/16", NAFM 1/4", and short-head 1/2") showed no significant variation in tube-velocity coefficient (all test coefficients within $\pm$ 0.2 percent of standard Prandtl tube). The wind tunnel was checked for constant velocity in magnitude and direction and constant static pressure in the region occupied by the tubes under test. The air velocity varied from 50 to 100 ft/sec.

In an effort to evaluate the velocity-gradient errors and the wall effects when using a Pitot-static tube for quantity rate-flow measurements of water in a pipe, Page[81] made velocity measurements in 4-, 6-, and 8-inch pipes with 1/4-inch- and 1/2-inch-diameter short-head tubes. Pertinent data of the installation are given in Table 3. Volumetrically calibrated free-discharge orifices were used to determine quantity flow rates. The calibration was expressed in terms of

$$Q = C_e A \left[\frac{U'_{ave}}{U_{max}}\right] \sqrt{2g \, \Delta \, h_{\mathrm{C\!\!\!L}}}$$

TABLE 3

DATA ON TEST EQUIPMENT OF PAGE[81]

Nominal pipe size, inches	L/D Straight Upstream	L/D Straight Downstream	f Pipe Friction Factor	Re Range $\times 10^{-5}$	(ϵ/d) Mean	1/4" Dia. Tube d/D	1/2" Dia. Tube d/D
4	138	61	0.0218	2.0-3.0	0.0015	0.062	0.125
6	104	29	0.0253	3.0-4.5	0.0028	0.042	0.083
8	77	23	0.0188	3.5-5.1	0.0008	0.031	0.062

where Q = rate of flow, cfs

C_e = effective coefficient of Pitot-static tube when used in a pipe for measurement of Q

A = cross-section area of pipe, ft^2

U'_{ave} = average velocity determined from Pitot tube traverse, ft/sec

U_{max} = centerline velocity, ft/sec

Δh_{CL} = differential head of Pitot-static tube when placed at pipe centerline, ft.

If the method of equal areas[34] is used to determine U'_{ave} and the Pitot-static tube velocity coefficient is assumed to be unity, the U'_{ave} determined will be greater than the true average velocity in the pipe. Assuming that the velocity distribution will follow the equation

$$1 - r/R = \left[\frac{U}{U_{\mathrm{CL}}}\right]^7$$

where U is the velocity at any radius r, Page[81] has computed the error in indicated average velocity. The results are given in Table 4. His experimental results may be expressed in terms of

$$C_e = \left[1.00 - fL/2D - 1.7(d/D)^2\right] / (1 + m/100)$$

where $fL/2D$ is the correction for pressure gradient between head tip and plane of static-pressure holes, $1.7(d/D)^2$ is correction for blocking, velocity gradient, and wall effects, and $(1 + m/100)$ is correction for error due to taking a finite number of traverse positions to obtain U'_{ave}. Almost all experimental points are within $\pm$ 0.5 percent of the value given by the equation.

Since the impact-pressure tap and the static-pressure tap are frequently at different transverse planes in the pipe, a reduction in static pressure will occur due to the pressure gradient in the pipe. The magnitude of reduction on tube velocity coefficient can be approximated by the quantity $f \frac{L}{2D}$, where f is the friction factor in the expression $h_f = f \frac{L}{D} \frac{V^2}{2g}$, L is the axial distance between impact- and static-pressure taps, and D is the diameter of the pipe. If for orders of magnitude, we consider $f = 0.02$, then the percent reduction in tube velocity coefficient will be $1/D$.

When a Pitot-static head is placed on the centerline of the pipe, the Venturi effect of the volume occupied by the tube head will produce a reduction in measured static head, while the impact head is constant. The effective tube velocity

TABLE 4

CALCULATED RESULTS OVER INDICATION OF AVERAGE VELOCITY WHEN USING STANDARD PROCEDURE FOR METHOD OF EQUAL AREAS AND A ONE-SEVENTH POWER-LAW VELOCITY DISTRIBUTION. PAGE.[81]

Number in equal areas in traverse	Average indicated velocity (U'_{ave}) too large by percent
2	2.27
4	1.4
6	0.91
8	0.67
10	0.53
20	0.25

coefficient will be less than unity by the amount of $(d/D)^2$; e.g., at (d/D) of 0.1 the coefficient becomes 0.99 and for (d/D) of 0.2 the coefficient becomes 0.96.

If the head is at a position other than the centerline, it is probable that the Venturi effect will be the same if a sufficient number and size of static holes are used around the circumference of the head. If the static taps are not adequate, it is possible that the reduction in measured static pressure might be different due to mutual interference on flow produced between the Pitot-static head and the pipe wall. No experimental data on this point are known.

The ratio $\frac{U_{ave}}{U_{max}}$, where $Q = AU_{ave}$, is known as the pipe factor (P.F.), a quantity that is a function of Re, pipe roughness, and the degree of establishment of fully developed velocity distribution (i.e., sufficient upstream straight pipe so that velocity traverse is the same at downstream points and the test traverse section). The relative roughness ϵ/D is determined from Moody's pipe-friction charts[65] by measuring pipe-friction factor and Reynolds number. Through application of the mixing-length theory of turbulence to data from Moody's pipe-friction charts, Fig. 16 can be obtained.[49,76] If Re and ϵ/D are known, the pipe factor can be determined from Fig. 16, and it is only necessary to measure the centerline velocity and use

$$Q = C_e A (P.F.) V_{\mathrm{℄}}$$

where $C_e = 1.00 - fL/2D - (d/D)^2$ if straight pipe sections allow fully developed velocity distributions to form.

To investigate static-pressure determination with a Pitot-static tube, a piezometer tap was installed in a six-inch pipe, 7.1 inches upstream from the hole in the pipe for the tube stem. This distance was chosen on the basis of data from Hubbard[60] to insure that the piezometer reading is independent of the tube position. The indicated static pressure was determined at several radii using short-head tubes of two different sizes. The data were corrected for pipe friction between the piezometer tap and plane of static taps in the tube and results expressed in terms of percent of velocity head and shown in Fig. 17. The calculated difference for head-blocking effect at the centerline is 1.0 percent, while the curves show about 1.4 percent of velocity head. Examination of Fig. 17 reveals characteristics of indicated static pressure when measured with a Pitot-static tube. The mutual interference between the tube head and stem and the pipe wall produces the observed distortions for the geometry investigated.

Three-Dimensional Flow

The measurement of magnitude and direction of velocity at a point in a fluid is accomplished frequently with a probe providing five readings. One form of this type of probe is a sphere having a central hole and four holes distributed equally around the sphere and spaced at the same angular distance from the center hole.[36,40,80,115] From experimental calibrations and pressures measured at the five holes, the velocity in a three-dimensional flow may be determined. Similar results may be obtained from a claw-type probe having the corresponding five pressure determinations. An understanding of the probe performance results from considerations of pressure distributions about a sphere when it is placed in a uniform flow field. The claw probe depends on indications of impact pressure by a square-ended tube when a yaw deflection of velocity with respect to the tube axis exists. Some mutual interference between adjacent tubes of the claw makes calibration under operating conditions desirable.

Special-Purpose Probes

In designing probes for special purposes, the general considerations are modified to meet the particular requirements. For example, Bentzel[44] developed a probe with a pressure indicator to measure very low velocities in hydraulic models of civil engineering applications. Several manufacturing firms have compiled design and performance data for specific applications of Pitot tubes of various forms.[117,119-126] Summaries of particular interest have been made for the field of turbojet-engine investigations into flow characteristics in compressors and turbines.[118] Considerable information on special-purpose probes appears in the technical literature, but space limitations prevent an adequate presentation in this paper.

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SUMMARY

Many forms of Pitot and Pitot-static tubes have been calibrated and used for a wide variety of applications. Several of the more common forms of probes are described, and their pressure performance is discussed in detail for normal and for a few special flow conditions.

Experimental calibrations for a Pitot-static tube with a short tip, especially designed for measurements of quantity rate of flow of liquids in pipes, demonstrates the suitability of the probe. Necessary corrections to probe calibrations in a large cross-section uniform flow field for use in pipes are developed, presumably to account for effects of velocity gradients and mutual interference of flow between the pipe wall and the probe.

Quantitative information, presented in the form of curves, provides readily available data for designers and users to determine desirable forms for given applications and to interpret pressure measurements made with specific probes. Additional data may be obtained from the limited bibliographic references or from other references from the large amount of technical information that has been published.

REFERENCES

1 "Description d'une machine pour mesurer la vîtesse des eaux courantes et le sillage des vaisseaux," by H. Pitot, Mémoires, Académie des Sciences, Paris, 1732, pp. 363-376.

2 "Mémoires sur le mouvement de l'eau dans les tuyaux," by H. Darcy, Comptes Rendus, Académie des Sciences, Paris, vol. 38, 1854, p. 407.
Discussion by Messrs. Poncelet, Combes, and Morin, ibid., pp. 1109-1121.

3 "Relative à quelques modifications à introduire dans le tube Pitot," by H. Darcy, Annales des Pontes et Chaussées, ser. 3, vol. 1858, 1st part, pp. 351-359.

4 "Water Measurements in Connection with a Test of a Centrifugal Pump at Jourdan Avenue Drainage Station, New Orleans, La.," by W. M. White, J. Assn. Engrg. Socs., vol. 25, no. 4, 1900, pp. 167-171.

5 "The Pitot Tube: Its Formula," by W. M. White, J. Assn. Engrg. Socs., vol. 27, no. 2, 1901, pp. 34-77.

6 "Tests of Centrifugal Pumps," by W. B. Gregory, Trans. ASME, vol. 22, 1901, pp. 262-274.

7 "Discussion on Flow of Water in Pipes," by E. S. Cole, Trans. ASCE, vol. 47, 1902, pp. 197-369.
Discussion of "Experiments at Detroit, Mich., on the Effect of Curvature upon the Flow of Water in Pipes," by G. S. Williams, C. W. Hubbell, and G. H. Fenkell, ibid., pp. 1-197.

8 "Measurement of Air Velocity and Pressure," by A. F. Zahm, Physical Rev., vol. 17, 1903, pp. 410-423.

9 "The Pitot Tube," by W. B. Gregory, Trans. ASME, vol. 25, 1904, pp. 184-212.

10 "The Pitometer and Its Uses," by E. M. Blake, New Engl. Water Works Assn. J., vol. 20, 1906, pp. 152-162.

11 "The Pitometer," by J. D. Underwood, Proc. Engrs. Soc. West. Penn., vol. 22, 1906, pp. 445-458.

12 "The Pitometer and Water Works Losses," by E. S. Cole, Proc. Amer. Water Works Assn., 1907, pp. 136-156.

13 "The Pitometer," by E. S. Cole, J. Franklin Inst., vol. 164, 1907, pp. 425-441.

14 "On the Value of the Pitot Constant," by J. D. Fry and A. M. Tyndall, Phil. Mag., ser. 6, vol. 21, 1911, pp. 348-366.

15 "Notes on the Pitot Tube," by J. Airey, Engrg. News, vol. 69, 1913, pp. 782-783.

16 "Origin and Theory of the Pitot Tube," by A. E. Guy, Engrg. News, vol. 69, 1913, pp. 1172-1175.

17 "Pitot Tubes for Gas Measurement," by W. C. Rowse, Trans. ASME, vol. 35, 1913, pp. 633-691.

18 "Measurement of the Velocity of Flowing Water," by L. F. Moody, Proc. Engrs. Soc. West. Penn., vol. 30, 1914, pp. 280-323.

19 "Pitot-Tube Formulas," by B. F. Groat, Proc. Engrs. Soc. West. Penn., vol. 30, 1914, pp. 324-381.

20 "Investigation of the Direction and Velocity of Flow in the Neighbourhood of the Tail Plane of B.E. 2," by E. F. Relf, Gt. Brit., ACA, R and M 156, pt. 4, 1914, 4 p. + 4 figs.

21 "The Pitot Tube and Other Anemometers for Aeroplanes," by W. H. Herschel, NACA TR 2, pt. 1, 1915, 24 p.

22 "The Theory of Pitot and Venturi Tubes," by E. Buckingham, NACA TR 2, pt. 2, 1915, 10 p.

23 "Graphic Recorder for Cole Pitometer," by E. S. Cole, Engrg. News, vol. 73, 1915, p. 875.

24 "Rerating a Pitometer," by C. G. Gillespie, Engrg. Rec., vol. 72, 1915, p. 144.
Also in Engrg. and Contracting, vol. 43, 1915, p. 275.

25 "The Design of a Sensitive Yawmeter," by J. R. Pannell and R. Jones, Gt. Brit., ACA, R and M 445, 1918, 6 p. + 4 pl.

26 "Altitude Effect on Air Speed Indicators," by M. D. Hersey, F. L. Hunt, and H. N. Eaton, NACA TR 110, 1920, 27 p.

27 "The Altitude Effect on Airspeed Indicators - II," by H. N. Eaton and W. A. MacNair, NACA TR 156, 1922, 44 p.

28 "On the Use of Very Small Pitot-Tubes for Measuring Wind Velocity," by M. Barker, Proc. Roy. Soc., London, (A), vol. 101, 1922, pp. 435-445.

29 "A Direction and Velocity Meter for Use in Wind Tunnel Work" by T. Lavender, Gt. Brit., ACA, R and M 844, 1923, 2 p. + 2 pl.

30 "The Design of Pitot-Static Tubes," by E. Ower and F. C. Johansen, Gt. Brit., ARC, R and M 981, 1925, 12 p. + 11 p. of figs.

31 "Pressure of Air on Coming to Rest from Various Speeds," by A. F. Zahm, NACA TR 247, 1926, 7 p.

32 "Influence of the Orifice on Measured Pressures," by P. E. Hemke, NACA TN 250, 1926, 7 p. + 8 p. of figs.

33 "Flow and Drag Formulas for Simple Quadrics," by A. F. Zahm, NACA TR 253, 1926, 23 p.

34 "Fluid Meters: Their Theory and Application," ASME, Special Research Committee on Fluid Meters, pt. 1, 1927 (4th ed. 1937); pt. 2, 1931; pt. 3, 1933.

35 "Differential Pressures on a Pitot-Venturi and a Pitot-Static Nozzle over 360° Pitch and Yaw," by R. M. Bear, NACA TR 264, 1927, 9 p.

36 "Improved Instrument for the Simultaneous Determination of the Static Pressure, the Magnitude, and the Direction of the Velocity of Fluids," by B. G. Van der Hegge Zijnen, K. Akad. Wetensch., Amsterdam, Proc., Sec. of Sciences, vol. 32, 1929, pp. 658-668.

37 "Einfluss der Zähigkeit bei Geschwindigkeitsmessungen mit Staudruck Multiplikatoren," by H. Peters, Zeitsch. Flugt. und Motorluftschiffahrt, vol. 22, no. 11, 1931, pp. 321-323.
Translation: "Effect of Viscosity in Speed Measurements with Double-Throat Venturi Tubes," NACA TM 633, 1931, 5 p. + 2 p. of figs.

38 "On the Determination of the Pitot-Static Tube Factor at Low Reynolds Numbers, with Special Reference to the Measurement of Low Air Speeds," by E. Ower and F. C. Johansen, Gt. Brit., ARC, R and M 1437, 1931, 28 p. + 9 p. of figs.

39 "Piezometer Investigation," by C. M. Allen and L. J. Hooper, Trans. ASME, vol. 54 (Hyd-54-1), 1932, 11 p.

40 "Über die Messung von Geschwindigkeit und Druck in einer dreidimensionalen Strömung," by F. Krisam, Zeitsch. Flugt. und Motorluftschiffahrt, vol. 23, 1932, pp. 369-373.
Translation: "Speed and Pressure Recording in Three-Dimensional Flow," NACA TM 688, 1932, 13 p. + 3 pl.

41 "The Measurement of Air Flow," by E. Ower, 2nd ed., rev. and enl., Chapman and Hall, Ltd., London, 1933, viii, 243 p.

Chap. III, "Design of Pitot and Static Tubes" (pp. 16-35).
Chap. V, "Measurements of Flow and Resistance with Pitot-Static Tubes" (pp. 56-71).

42 "Statistical Measurements of Turbulence in the Flow of Air through a Pipe," by H. C. H. Townend, Proc. Roy. Soc., London, (A), vol. 145, 1934, pp. 180-211.

43 "Über zylindrische Staurohre zur Messung von Geschwindigkeit, Richtung und statischem Druck der Wasserströmungen," by F. Numachi, pts. 1 and 2, Tôhoku Imp. Univ., Sendai, Japan, Technology Rep., vol. 11, 1934, pp. 307-364.
For pt. 3 see reference 58.

44 "New Velocity-Measuring Device Developed in Waterways Laboratory," by C. E. Bentzel, Engrg. News-Rec., vol. 112, 1934, pp. 508-509.

45 "The Pitot Tube in Current Practice," by E. S. Cole, Civil Engr., vol. 5, 1935, pp. 220-222.

46 "Pitot Tube Practice," by E. S. Cole, Trans. ASME, vol. 57 (Hyd-57-8), 1935, pp. 281-294.

47 "Gesamtdruckgerät mit grosser Unempfindlichkeit gegen Schräganströmung," by G. Kiel, Luftfahrtforschung, vol. 12, 1935, pp. 75-79.
Translation: "Total-Head Meter with Small Sensitivity to Yaw," NACA TM 775, 1935, 6 p. + 3 p. of figs.

48 "Comparative Tests of Pitot-Static Tubes," by K. G. Merriam and E. R. Spaulding, NACA TN 546, 1935, 46 p. + 14 p. of figs.

49 "The Effect of Turbulence on the Drag of Flat Plates," by G. B. Schubauer and H. L. Dryden, NACA TR 546, 1935, 7 p.

50 "Der Einfluss grosser Zähigkeit bei Strömung um den Zylinder und um die Kugel," by F. Homann, Zeitsch. angew. Math. und Mech., vol. 16, 1936, pp. 153-164.
Translation: "The Effect of High Viscosity on the Flow Around a Cylinder and Around a Sphere," Univ. of Calif., Berkeley, Inst. of Engrg. Res., Rep. HE-150-88, 1931, 16 + 7 p.
Translation also published as: NACA TM 1334, 1952, 29 p.

51 "On the Exit Velocity and Slip Coefficient of Flow at the Outlet of the Centrifugal Pump Impeller, with Some References to the Characteristics of the Pump," by T. Kasai, Kyushu Imp. Univ., Fukuoka, Japan, Faculty of Engrg., Memoirs, vol. 8, no. 1, 1936, 89 p.

52 "Experimental Study on a Propeller Pump," by S. Kito, Tokyo Imp. Univ., Faculty of Engrg., Journal, vol. 20, no. 12, 1936, pp. 283-384 + 30 pl.

53 "A Note on Measurement of Total Head and Static Pressure in a Turbulent Stream," by S. Goldstein, Proc. Roy. Soc., London, (A), vol. 155, 1936, pp. 570-575.

54 "On the Static Pressure in Fully-Developed Turbulent Flow," by A. Fage, Proc. Roy. Soc., London, (A), vol. 155, 1936, pp. 576-596.

55 "The Behaviour of a Pitot Tube in a Transverse Total-Pressure Gradient," by A. D. Young and J. N. Maas, Gt. Brit., ARC, R and M 1770, 1936, 16 p.

56 "Errors in Pressure Readings Due to Wrong Gauge Connections," by R. W. Angus, _J. Amer. Water Works Assn._, vol. 29, 1937, pp. 458-468.

57 "Characteristics of Transverse Pitot Tubes," by J. E. Christiansen and O. C. French, _Agric. Engrg._, vol. 18, 1937, pp. 21-24

58 "Über zylindrische Staurohre zur Messung von Geschwindigkeit, Richtung und statischem Druck der Wasserströmungen," by F. Numachi and S. Hutizawa, pt. 3, Tôhoku Imp. Univ., Sendai, Japan, Technology Rep., vol. 12, 1938, pp. 543-559.
For pts. 1 and 2 see reference. 43.

59 "Pitot Tubes in·Large Pipes," by Edward S. Cole and E. Shaw Cole, Trans. ASME, vol. 61, 1939, pp. 465-473.

60 "Investigation of Erros of Pitot Tubes," by C. W. Hubbard, Trans. ASME, vol. 61, 1939, pp. 477-492.

61 "Investigations in a Horizontal 6-inch Pipe with Transverse Impact Tubes, by L. S. Jue, Special Graduate Student Report, Univ. of Calif., Berkeley, 1939.

62 "Measurement of Water in Pipe Lines with Transverse Pitot Tubes," by W. A. Cornwell, M.S. Thesis, Univ. of Calif., Berkeley, 1940.

63 "The Effect of Compressibility on Static Heads," by C. N. H. Lock, A. E. Knowler, and H. H. Pearcey, Gt. Brit., ARC, R and M 2386 (Jan. 1943; Publ. 1950), 13 p.

64 "Application of Pitometer to Water Distribution Systems," by E. S. Cole, _New Engl. Water Works Assn. J._, vol. 58, 1944, pp. 74-83.

65 "Friction Factors for Pipe Flow," by L. F. Moody, Trans. ASME, vol. 66, 1944, pp. 671-684.

66 "The Impact Tube," by B. Hodkinson, Proc. Instn. Mech. Engrs., vol. 151, 1944, pp. 257-263.

67 "Pitot Pressures in Moist Air," by G. I. Taylor, Gt. Brit., ARC, R and M 2248, 1945, 5 p.

68 "Hydraulic Measurements: A Manual for Engineers," by H. Addison, John Wiley and Sons, New York, 1946.
Chap. 5, "Measurement of Velocity" (pp. 81-89).

69 "The Pitot Cylinder," by E. Silberman, Univ. of Minn., St. Anthony Falls Hydraulic Lab. Circular No. 2, 1947, 18 p.

70 "Pitot Tube Calibration Tests," by C. K. Ferguson, Special Graduate Student Report, Univ. of Calif., Berkeley, 1948, 12 + 34 p.

71 "Instrumentation for the Development of Aircraft Power Plane Components Involving Fluid Flow," by S. J. Markowski and E. M. Moffatt, Quart. Trans. SAE, vol. 2, 1948, pp. 104-116.

72 "Cavitation and Pressure Distribution, Head Forms at Zero Angle of Yaw," by H. Rouse and J. S. McNown, State Univ. of Iowa, Stud. Engrg. Bul. 32, 1948, 70 p.

73 "The Theory of the Impact Tube in a Viscous Compressible Gas," by P. L. Chambré, Univ. of Calif., Berkeley, Inst. of Engrg. Res., Rep. HE-150-50, 1948, 6 + 5 p.

74 "Wind-Tunnel Testing Problems in Superaerodynamics," by Hsue-Shen Tsien, J. Aero. Sci., vol. 15, 1948, pp. 573-580.

75 "The Theory of the Impact Tube at Low Pressures," by P. L. Chambré and S. A. Schaaf, J. Aero. Sci., vol. 15, 1948, pp. 735-737.

76 "Pipe Factors for Quantity Rate Flow Measurements with Pitot Tubes," by R. G. Folsom and H. W. Iversen, ASME Advance Paper 48—A-35, 1948, 18 p.
Abstracted in Mech. Engrg., vol. 70, 1948, pp. 1019-1020.

77 "Hydraulic Prime Movers," ASME Power Test Codes, 18-1949, ASME, 1949, 29 p.
Sections on Pitot Tube Traverse and Cole Pitometer Methods.

78 "Flow Measurement and Meters," by A. Linford, E. and F. N. Spon, London, 1949, 95 p.

79 "The Impact Tube in a Viscous Compressible Gas," by P. L. Chambré and H. R. Smith, Univ. of Calif., Berkeley, Heat Transfer and Fluid Mechanics Inst. Publ., June 1949, pp. 271-278.

80 "Flow Around Bends in an Open Flume," by A. Shukry, Proc. ASCE, vol. 75, 1949, pp. 713-741
Discussion, ibid., pp. 1391-1396.

81 "Performance Characteristics of Pitot Tubes in Water Pipes," by W. A. Page, M.S. Thesis, Univ. of Calif., Berkeley, 1949.

82 "Impact Tube Measurements in Isothermal Air Jets," by J. F. Taylor and E. W. Comings, Proc. Midwestern Conference on Fluid Dynamics, 1950, pp. 204-215.

83 "The Effect of Slip on Flow Near a Stagnation Point and in a Boundary Layer," by T. C. Lin and S. A. Schaaf, Univ. of Calif., Berkeley, Inst. of Engrg. Res., Rep. HE-150-76, 1950.
Also: NACA TN 2568, 1951, 28 p.

84 "The Three-Quarter Radius Pitot Tube Flow Meter," by J. H. Preston, Engr., vol. 190, 1950, pp. 400-402.

85 "Wind-Tunnel Investigation of a Number of Total-Pressure Tubes at High Angles of Attack - Supersonic Speeds," by W. Gracey, D. E. Coletti, and W. R. Russell, NACA TN 2261, 1951, 48 p.

86 "Wind-Tunnel Investigation of a Number of Total-Pressure Tubes at High Angles of Attack - Subsonic Speeds," by W. Gracey, W. Letko, and W. R. Russell, NACA TN 2331, 1951, 69 p.

87 "On Reflection of Shock Waves from Boundary Layers," by H. W. Liepmann, A. Roshko, and S. Dhawan, NACA TN 2334, 1951, 100 p.

88 "Effects of Pressure-Rake Design Parameters on Static-Pressure Measurement for Rakes Used in Subsonic Free Jets," by L. N. Krause, NACA TN 2520, 1951, 20 p.

89 "Wind-Tunnel Investigation of Six Shielded Total-Pressure Tubes at High Angles of Attack - Subsonic Speeds," by W. R. Russell, W. Gracey, W. Letko, and P. Fournier, NACA TN 2530, 1951, 25 p.

90 "New Experiments on Impact Pressure Interpretation in Supersonic and Subsonic Rarefied Airstreams," by F. S. Sherman, Univ. of Calif., Berkeley, Inst. of Engrg. Res., Rep. HE-150-99, 1951, 30 + 46 p.
Also: NACA TN 2995, 1953, 30 + 40 p.

91 "The Effect of the Condensation of Atmospheric Water Vapour on Total Head and Other Measurements in the N.P.L. High Speed Tunnels," by H. H. Pearcey, Gt. Brit., ARC, R and M 2249, 1951, pp. 1-35.

92 "The Pitot-Venturi Flow Element," by H. W. Stoll, Trans. ASME, vol. 73, 1951, pp. 963-969.

93 "Small Pitot Tubes with Fast Pressure Response Time," by W. S. Bradfield and G. E. Yale, Univ. of Minn., Rosemount Res. Cent.
Condensed in J. Aero. Sci., vol. 18, 1951, pp. 697-698.

94 "Wind-Tunnel Investigation of a Shielded Total-Pressure Tube at Transonic Speeds," by W. Gracey, A. O. Pearson, and W. R. Russell, NACA RM L51K19, 1952, 8 p.

95 "Viscosity Correction to Impact Pressure on Prolate Spheroid," by D. C. Ipsen, Univ. of Calif., Berkeley, Inst. of Engrg. Res., Rep. HE-150-89, 1952 15 + 3 p.

96 "Direct Measurements of Skin Friction," by S. Dhawan, NACA TN 2567, 1952, 60 p.

"The Effect of High Viscosity on the Flow Around a Cylinder and Around a Sphere," by F. Homann, NACA TM 1334, 1952, 29 p.
Translation of reference 50.

97 "Drag of Circular Cylinders for a Wide Range of Reynolds Numbers and Mach Numbers," by F. E. Gowen and E. W. Perkins, NACA RM A52C20, 1952, 26 p.

98 "Several Combination Probes for Surveying Static and Total Pressure and Flow Direction," by W. M. Schulze, G. C. Ashby, Jr., and J. R. Erwin, NACA TN 2830, 1952, 64 p.

99 "Instrumentation for Axial-Flow-Compressor Research," by C. A. Meyer and R. P. Benedict, Trans. ASME, vol. 74, 1952, pp. 1327-1336.

100 "Measurement of Turbulent Velocity Fluctuations by Method of Electromagnetic Induction," by L. M. Grossman and A. F. Charwat, Rev. Sci. Instruments, vol. 23, 1952, pp. 741-747.

101 "Factors Affecting Laminar Boundary Layer Measurements in a Supersonic Stream," by R. E. Blue and G. M. Low, NACA TN 2891, 1953, 49 p.

102 "The Structure of Turbulence in Fully Developed Pipe Flow," by J. Laufer, NACA TN 2954, 1953, 55 p.

103 "Influence of Viscous Effects on Impact Tubes," by C. W. Hurd, K. P. Chesky, and A. H. Shapiro, J. Appl. Mech., vol. 20, 1953, pp. 253-256.

104 "Pitot-Venturi Flow Element Water Service Report," by H. W. Stoll, Trans. ASME, vol. 75, 1953, pp. 969-974.

105 "Experimental Investigation at a Mach Number of 2.41 of Average Skin-Friction Coefficients and Velocity Profiles for Laminar and Turbulent Boundary Layers and an Assessment of Probe Effects," by R. M. O'Donnell, NACA TN 3122, 1954, 38 p.

106 "Experimental Velocity Profiles for Adiabatic Supersonic Flow of Air in a Tube," by J. Kaye, G. A. Brown, and J. J. Dieckmann, M.I.T. Report. Condensed in J. Aero. Sci., vol. 21, 1954, pp. 203-205.

107 "Viscous Effects on Pitot Tubes at Low Speeds," by F. A. MacMillan, Engrg. Lab., Cambridge (Aeronautical Research Council, Fluid Motion Sub-Committee), Report F.M. 2081, 1954, 8 p.

108 "Design of Total Pressure Probes for Minimum Interference with Measured Flow," by J. L. Livesey, J. Aero. Sci., vol. 21, 1954, p. 641.

109 "An Experimental Investigation of Reynolds Number Effects on Supersonic Static Probes," by L. N. Wilson, Univ. of Toronto, UTIA TN-3, 1954, xii, 24 p.

110 "Pressure Probe Response in Fluctuating Flow," by R. E. Kronauer and H. P. Grant, Proc., 2nd U.S. National Congress of Applied Mechanics, 1954, pp. 763-769.

111 "Boundary Layer Theory," by H. Schlichting, tr. by J. Kestin, McGraw-Hill Book Co., New York, 1955, xx, 535 p.

112 "Pressure Distribution on a Hydrofoil Running near the Water Surface," by B. R. Parkin, B. Perry, and T. Y. Wu, C.I.T., Hydrodynamics Lab., Report No. 47-2, 1955, vi, 38 p.

113 "Cantilevered Pitot Cylinder," by F. A. L. Winternitz, The Engineer, vol. 199, 1955, pp. 729-732.

114 "A Deceleration Probe for Measuring Stagnation Pressure and Velocity of a Particle-Laden Gas Stream," by J. L. Dussourd and A. H. Shapiro, M.I.T., Dept. Mech. Engrg., Gas Turbine Lab., Report DIC 5-6985, based on Sc.D. Thesis, 1955.

115 "A Three-Dimensional Spherical Pitot Probe," by J. E. Ash and J. C. Lee, ASME Paper No. 55-SA-56, 1955, 9 p.

116 "Streamlined Pitot-Tube Bar for Measuring Water Flow in Large Pipes," by F. Numachi, H. Murai, and S. Abe, ASME Paper No. 55-SA-25, 1955, 16 + 9 p.

117 "Instructions for Installing and Operating Indicating Flow Meters, Type T, with Flow Nozzles, Pitot Tubes and Orifice Tubes (Instructions 86512A)," 2nd ed., General Electric Co., Schenectady, N. Y., 1925, 19 p. + 11 fold. diagrams in pocket.

118 "Design Manual for Air and Gas Flow Measurement Probes, Volume I—Pressure," by C. B. Haughton, Jr., and E. P. Newborg, General Electric Co., Aircraft Gas Turbine Engineering Div., West Lynn, Mass., Bul. R51GT41, Sept. 1951, various pagination.

Index and Corrections to this bulletin, issued by authors Dec. 1951, Bul. DF51GT379.

119 "Calibration and Use of the Spherical Search Tube," by B. S. Kudravetz, Westinghouse Report AGT-338.

120 "The Averaging Pressure Probe," by H. Gladston, Westinghouse Report AGT-477.

121 "The Effect of Hole Geometry on the Total Pressure Recovery of Cylindrical Pressure Probes," by F. A. Gagliardi and G. A. Cederborg, Westinghouse Report AGT-1088.

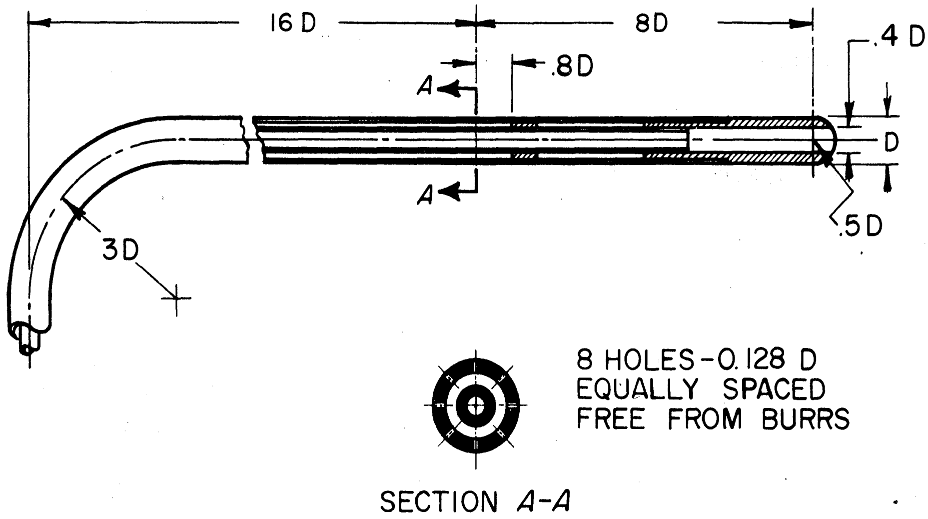
122 "A Note on the Accuracy of the Averaging Pressure Probe," by F. F. Ehrich, Westinghouse Report AGT-1157.

123 "The Directional Pressure Probe-Claw Type," by R. P. Benedict, Westinghouse Report AGT-1196.

124 "The Directional Pressure Probe-Cylindrical Type," by R. P. Benedict and W. E. Gunson, Westinghouse Report AGT-1210.

125 "The Development of the Disc Probe," by W. N. Gilmer, Westinghouse Report AGT-1295.

126 "The Cylindrical Pressure Probe Accuracy as Affected by Angle of Attack, Mach Number, and Hole Geometry," by E. F. Hammond, Westinghouse Report AGT-781.



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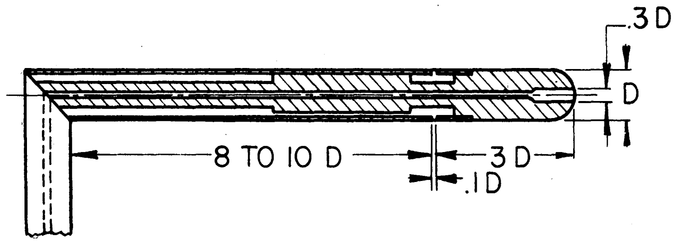

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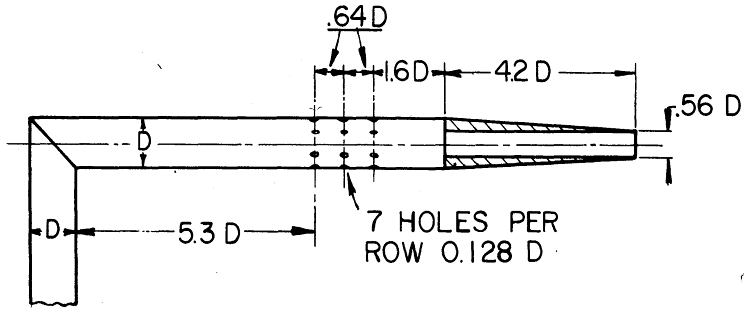

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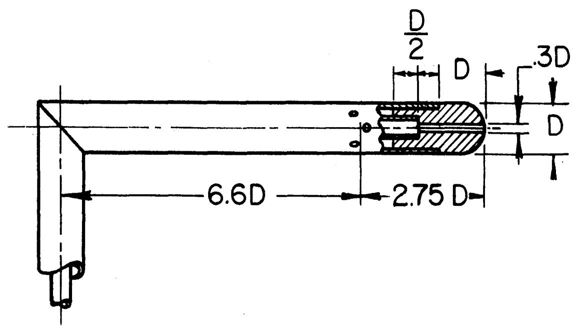

SHORT TIP

Fig. 1. Generalized dimensions of some typical Pitot-static tubes.

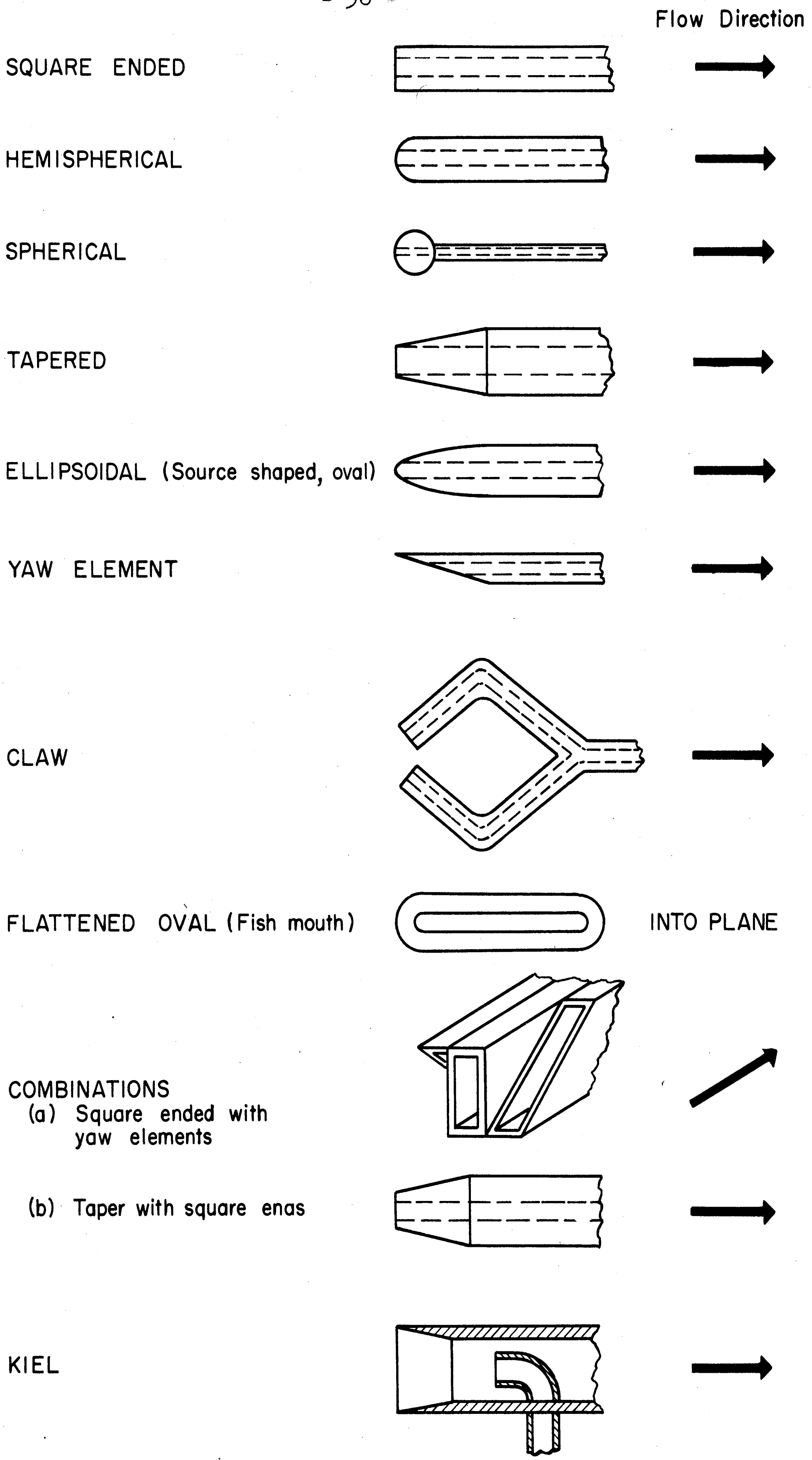

Fig. 2. Typical head shapes for Pitot tubes.

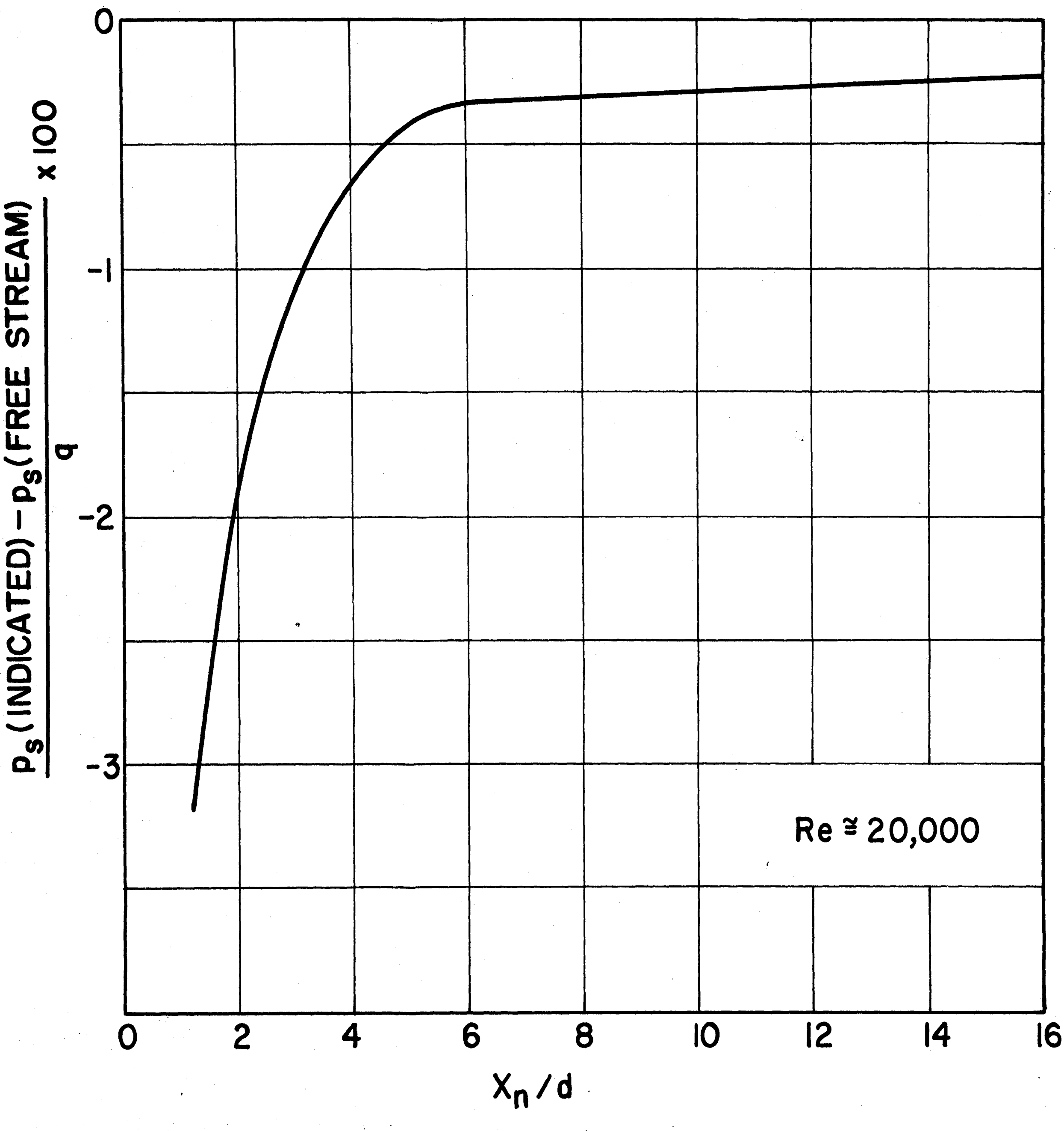

Fig. 3. Indicated static pressure along tube body with hemispherical tip. (X_n = diameters from base of nose along tube body.) Ower and Johansen.[30]

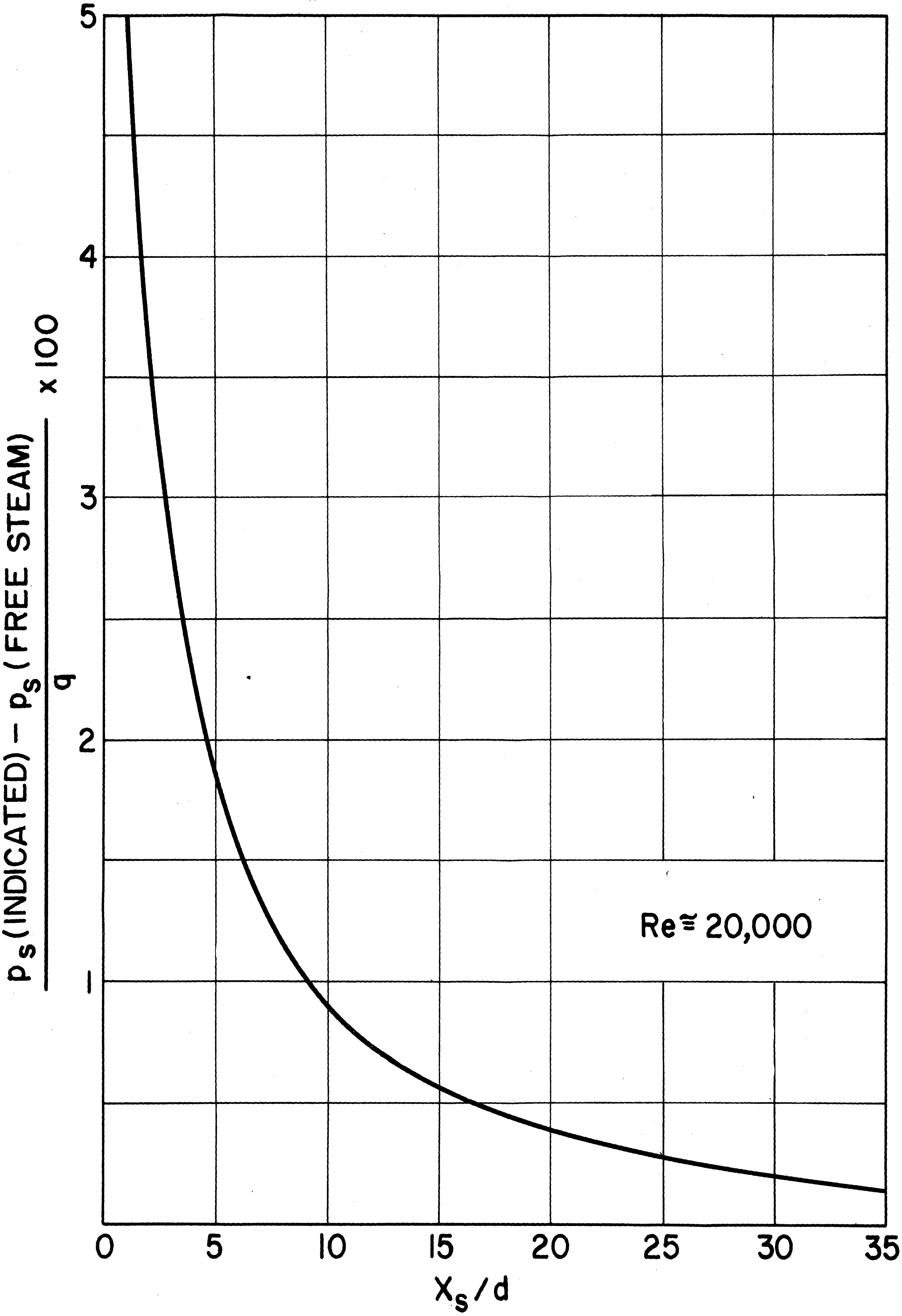

Fig. 4. Influence of stem position on observed static pressure. (X_s = stem distance aft of static holes.) Ower and Johansen.[30]

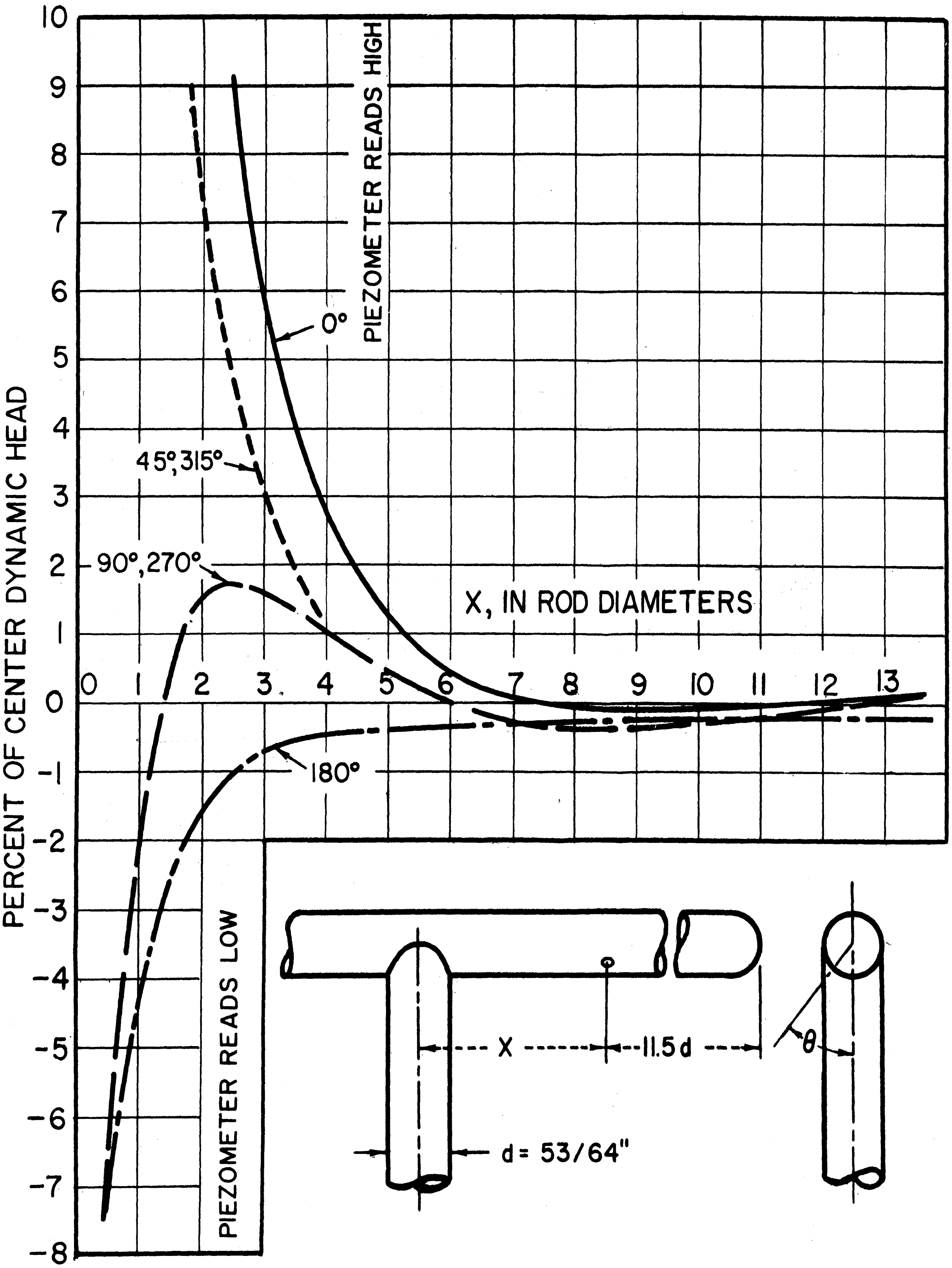

Fig. 5. Effect of stem location on reading from static-pressure piezometer in Pitot-static tube with hemispherical head. Hubbard.[60]

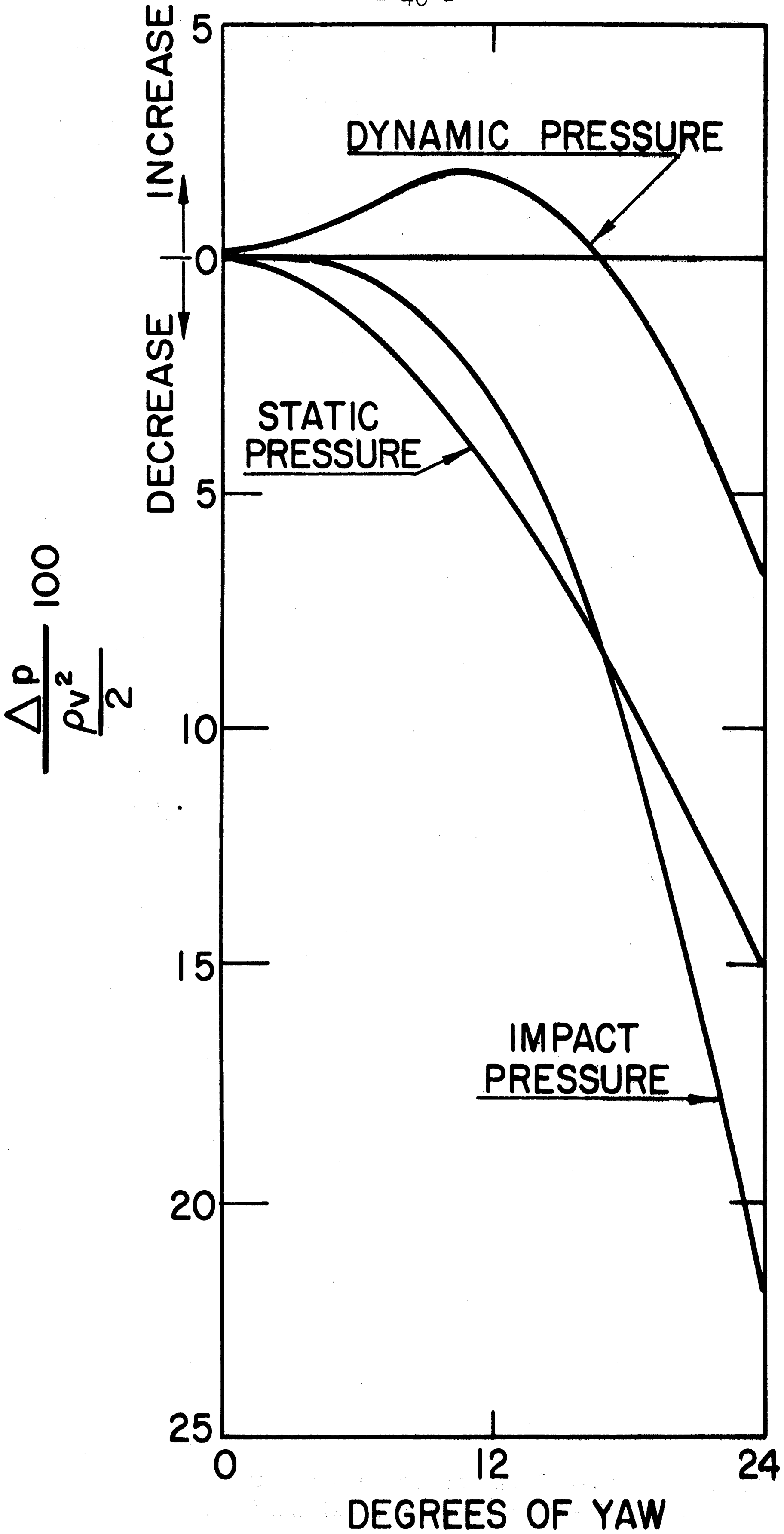

Fig. 6. Pressure readings under conditions of yaw for a Prandtl Pitot-static tube (hemispherical tip). Merriam and Spaulding.[48]

NORMAL RANGE

$$0.3 < \frac{d}{D} < 0.6$$

$$3.0 < \frac{L}{D} < 5.5$$

Fig. 7. Impact tube for boundary layer measurements.

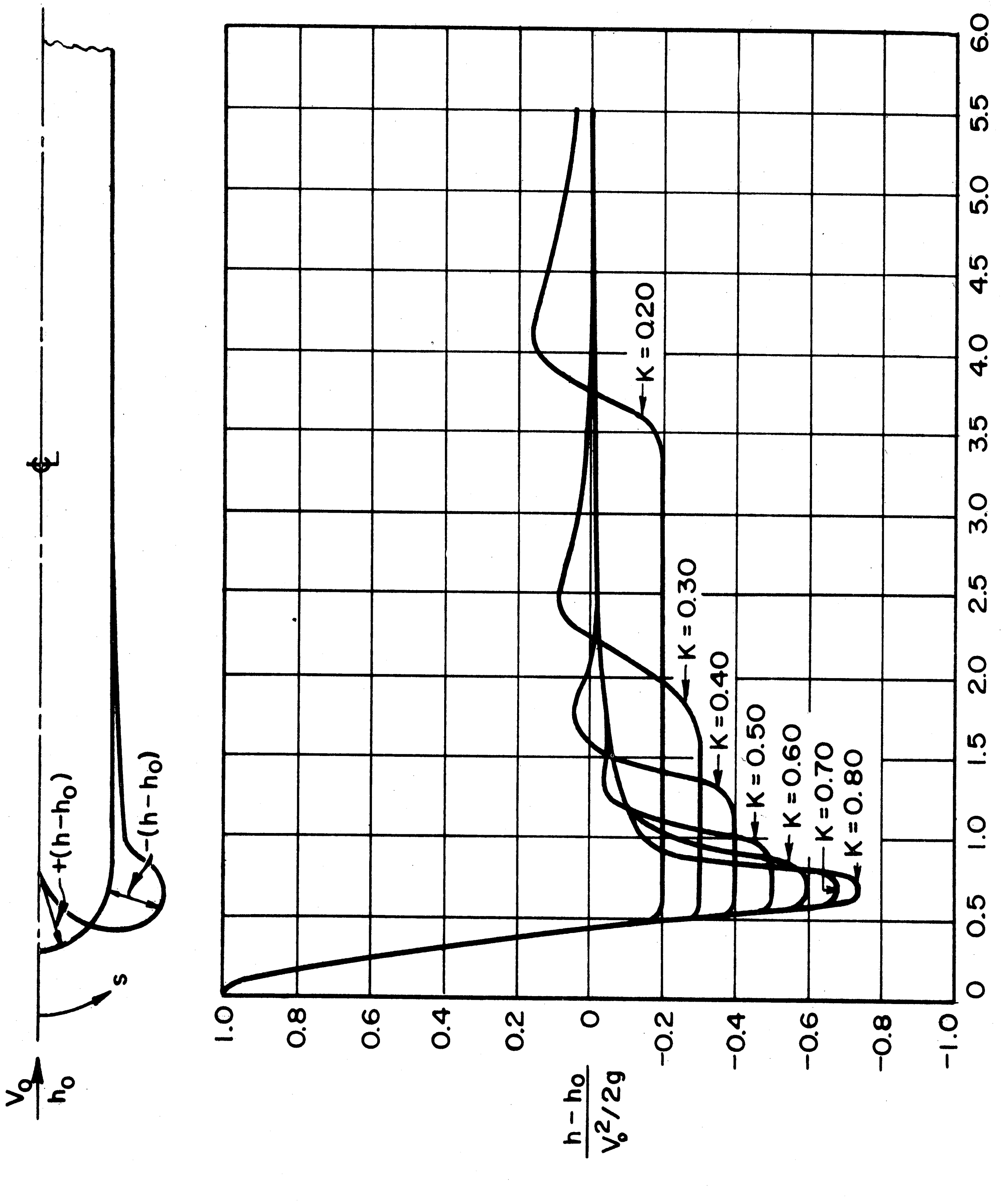

Fig. 8. Effect of cavitation upon the pressure distribution on a cylindrical body with a hemispherical head. ($K = \dfrac{h_o - h_v}{V_o^2/2g}$, where h_v = vapor-pressure head, d = diameter of cylindrical body.) Rouse and McNown.[72]

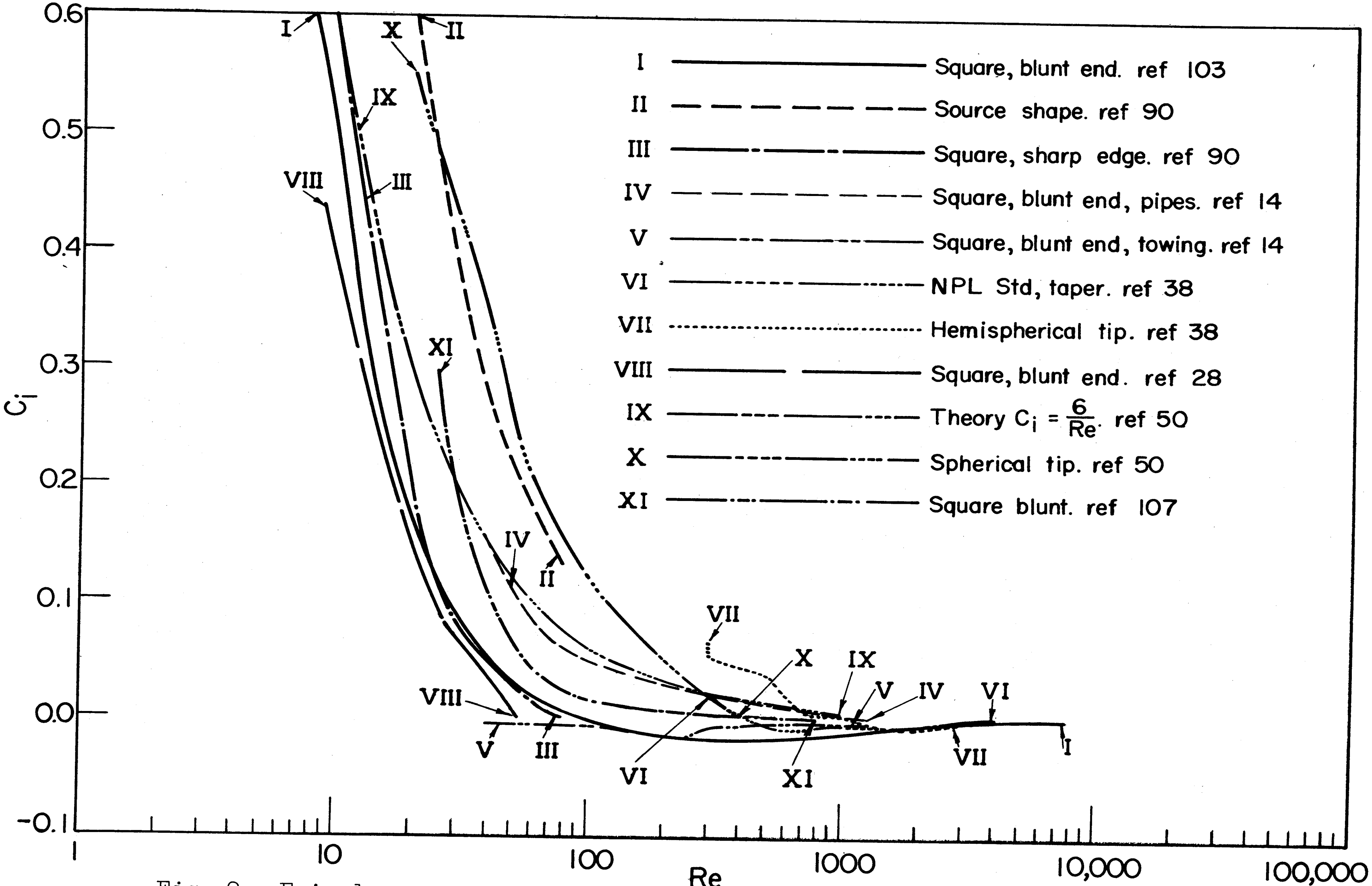

Fig. 9. Faired curves of pressure coefficients at low Reynolds numbers.

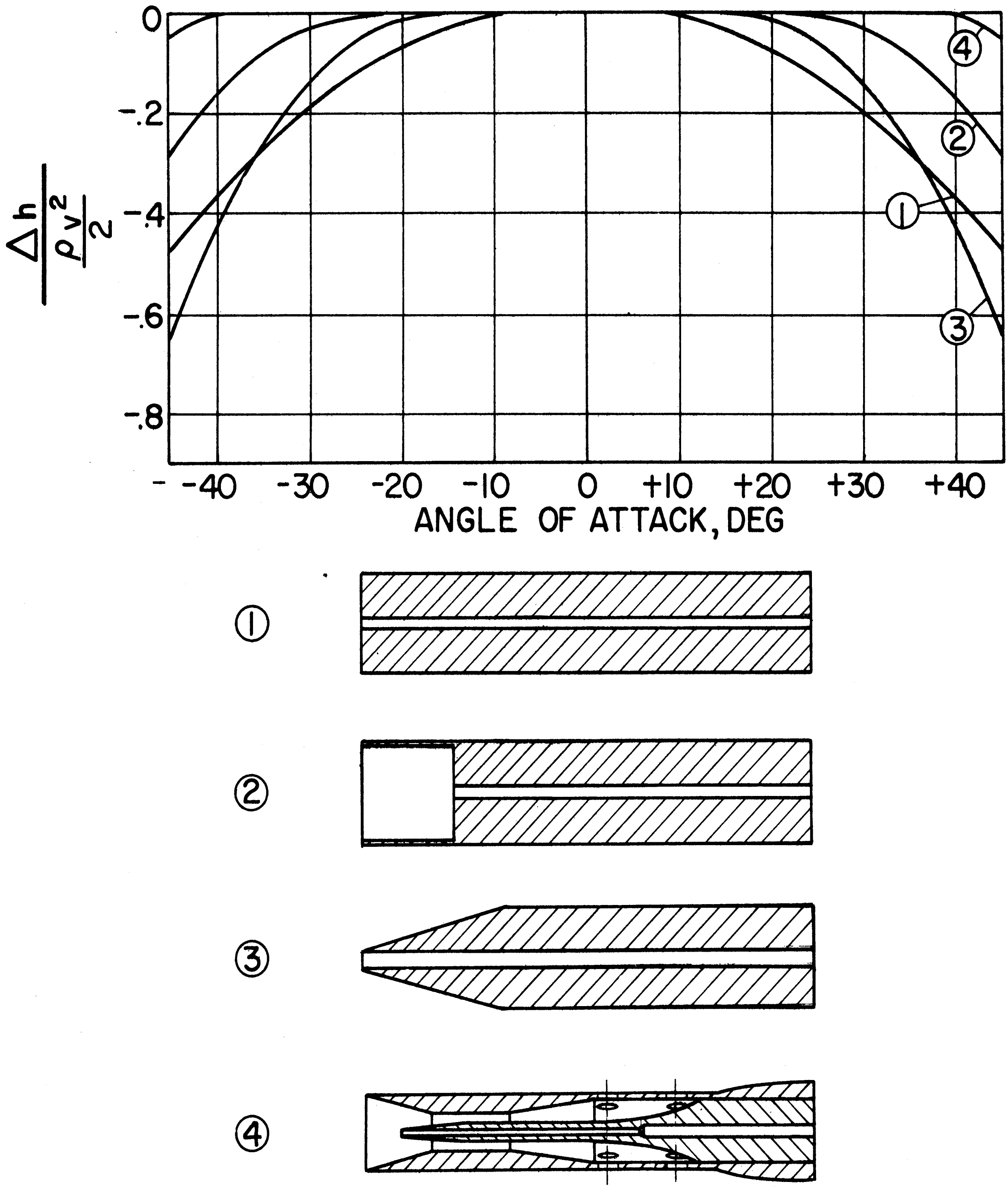

Fig. 10. Total-pressure tubes at large angles of yaw. Gracey et al.[86]

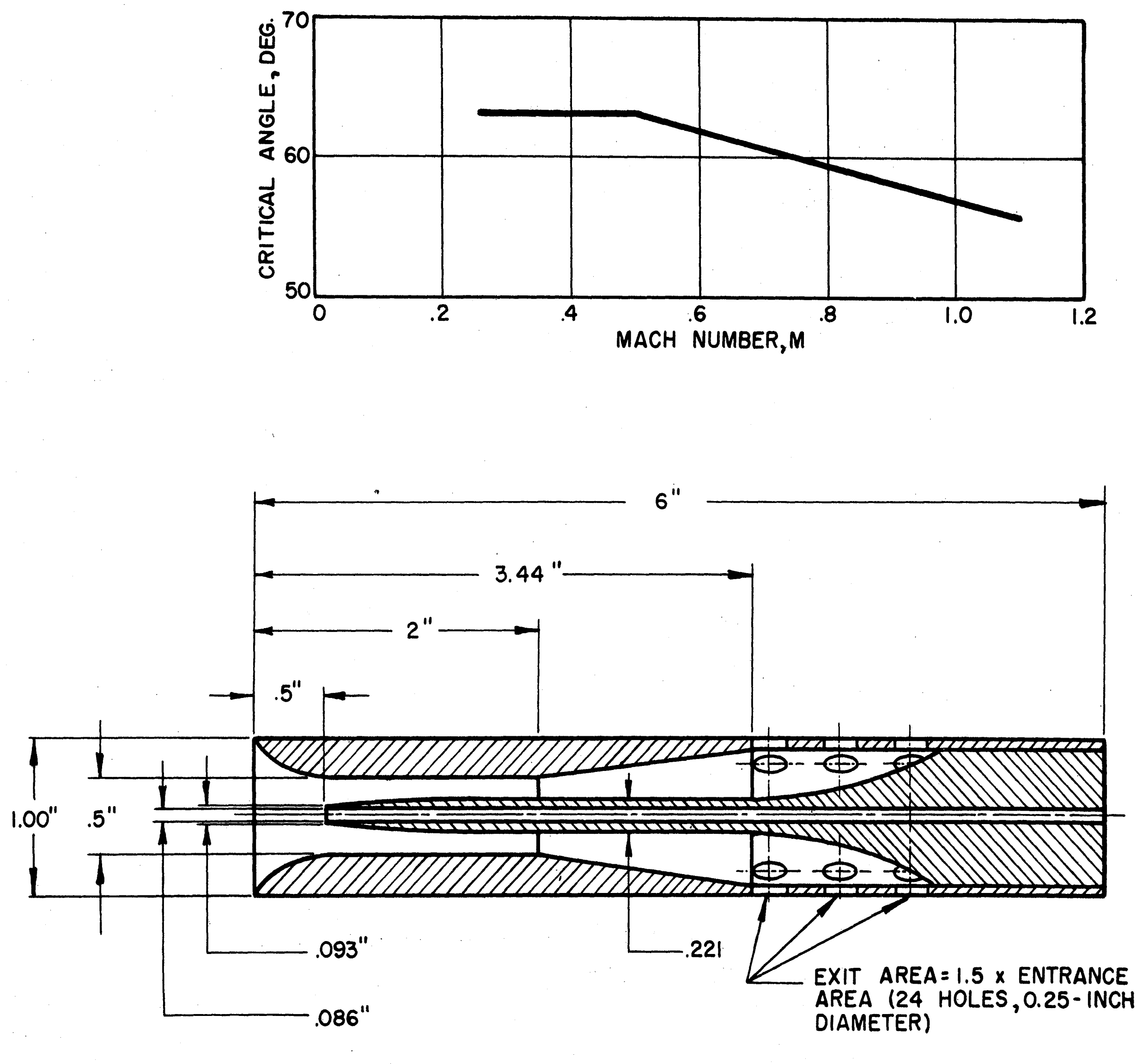

Fig. 11. Yaw performance of a typical shielded total-pressure tube at various Mach numbers. (Critical angle is the angle of attack of tube head where the total-pressure error reaches a value of one percent of the impact pressure.) Gracey et al.[94]

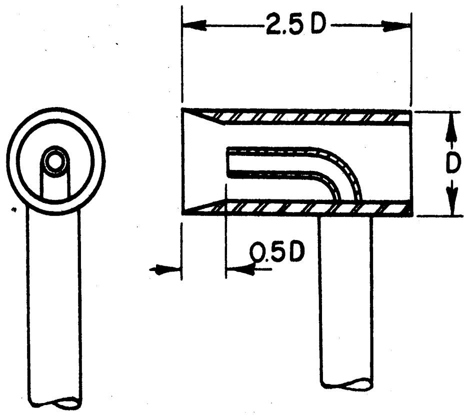

Fig. 12. Typical miniature shielded impact tube.
Markowski and Moffatt.[71]

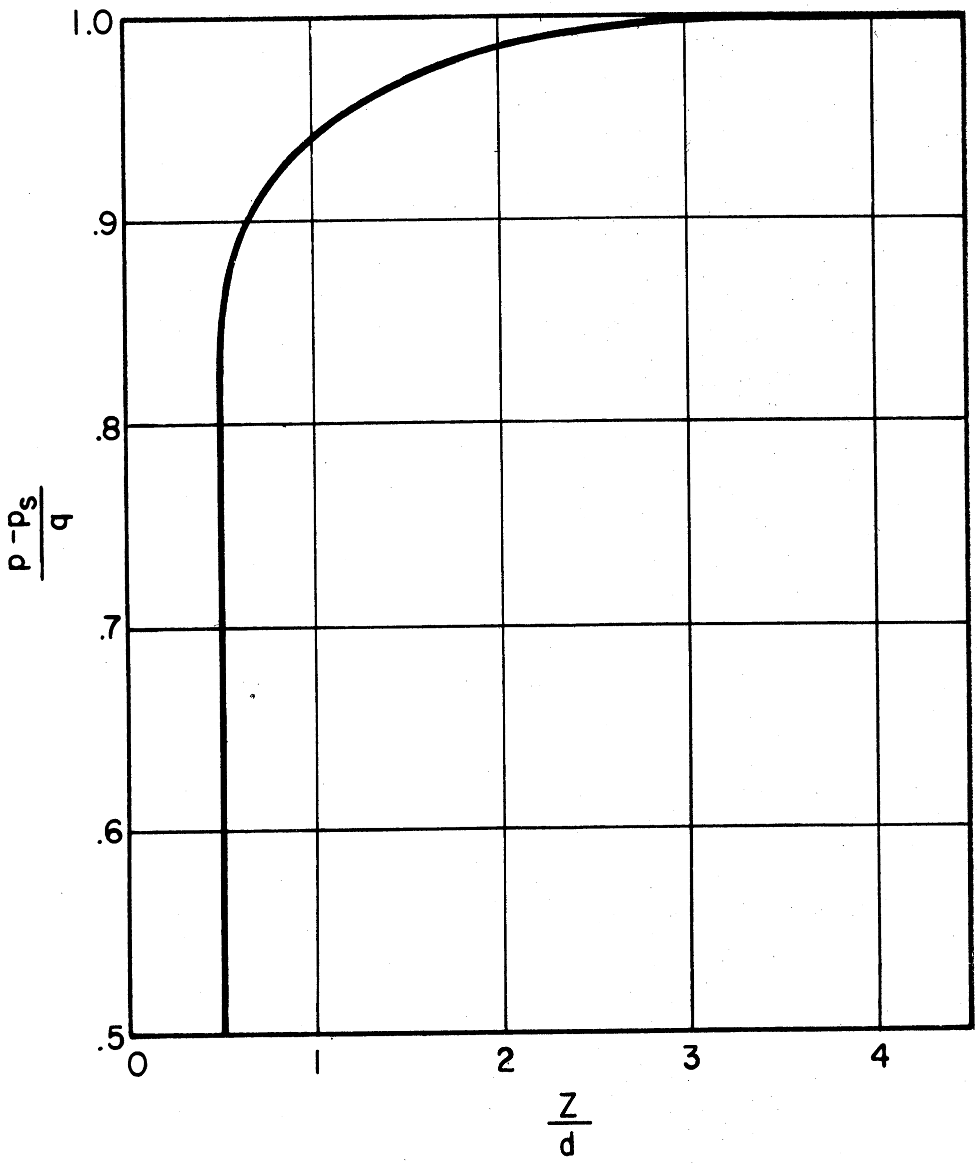

Fig. 13. Pitot-cylinder impact coefficient $\left(\frac{p - ps}{q}\right)$ as a function of piezometer distance from the tip $\left(\frac{Z}{D}\right)$ from hemi- and ellipsoidal tips. (Data from Silberman[69] and Winternitz.[113])

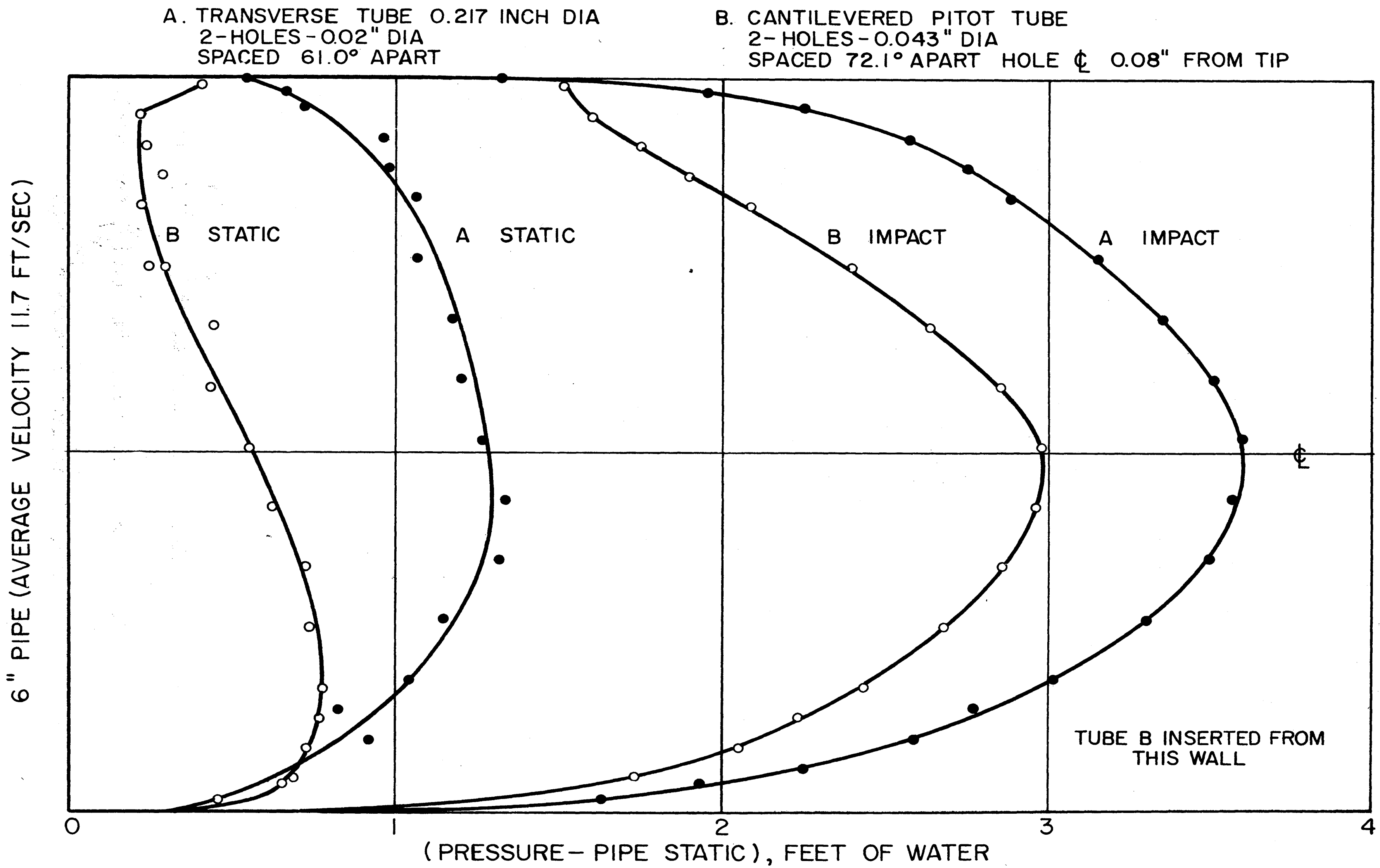

Fig. 14. Impact and static-pressure indications across a pipe with average velocity of water of 11.7 ft/sec for a transverse tube and a cantilevered Pitot tube. Jue.[61]

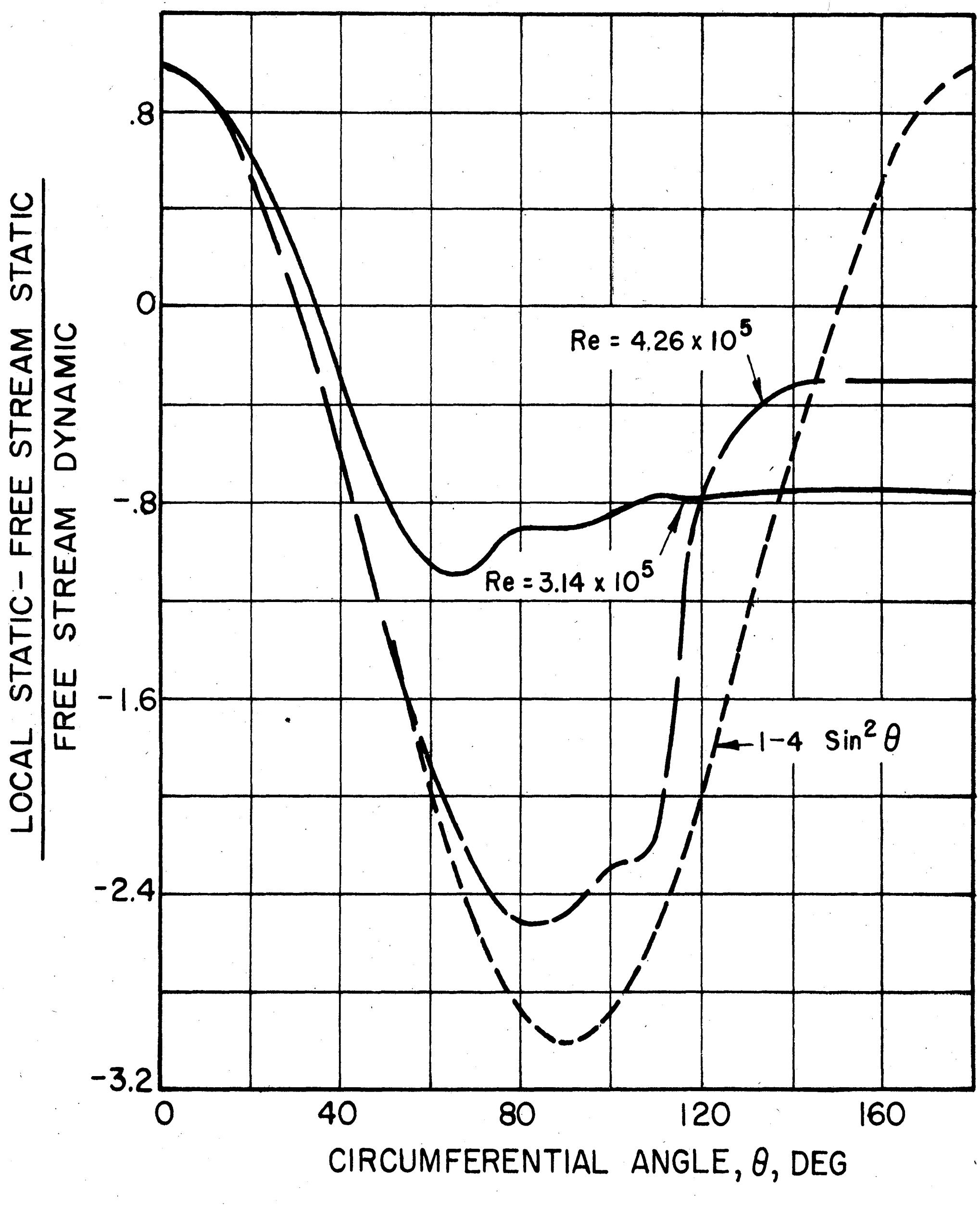

Fig. 15. Typical pressure distributions about a long circular cylinder in a uniform flow field. Gowen and Perkins.[97]

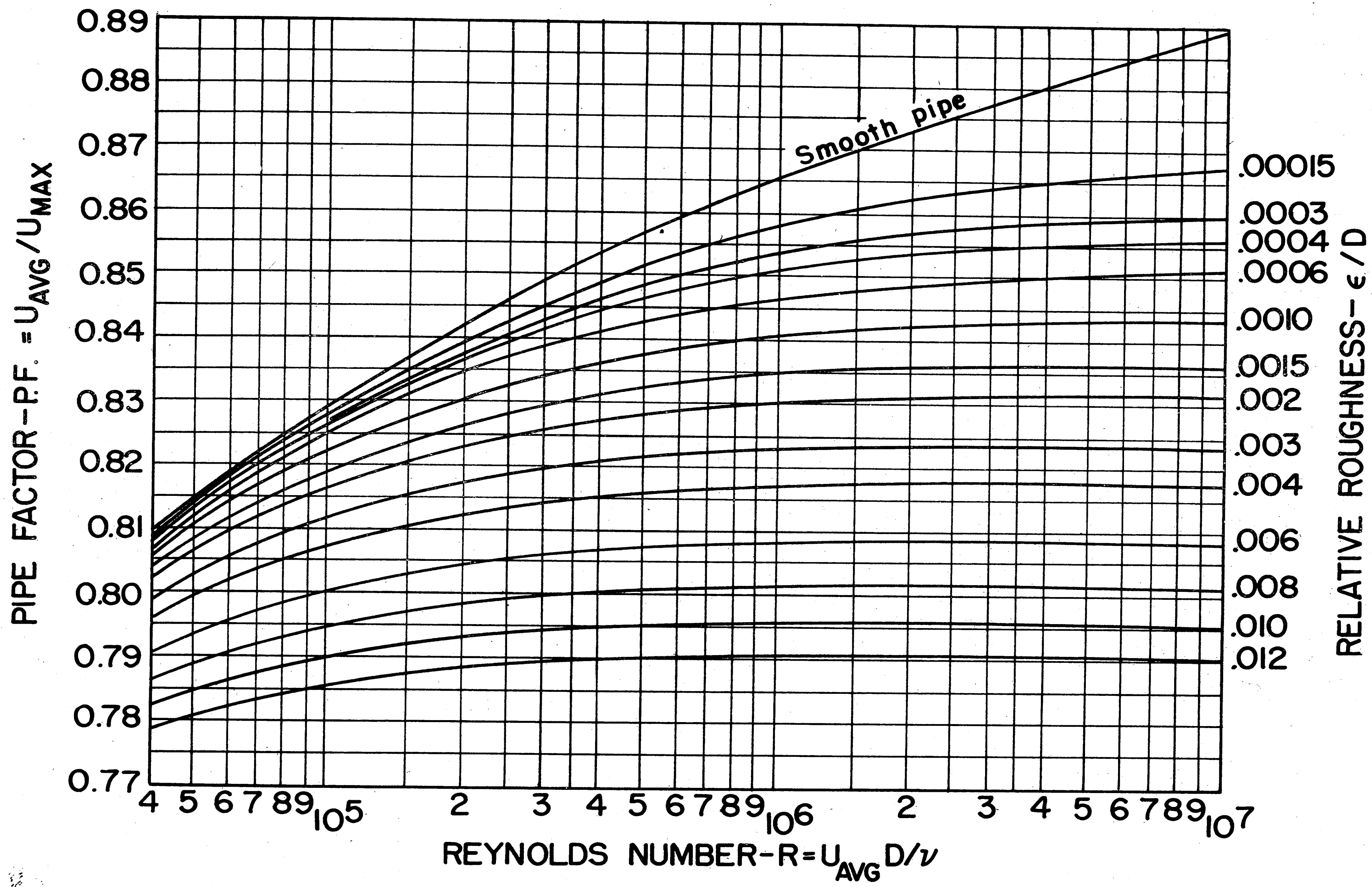

Fig. 16. Pipe factors for turbulent flow with a stabilized velocity distribution. Schubauer and Dryden,[49] Folsom and Iversen.[76]

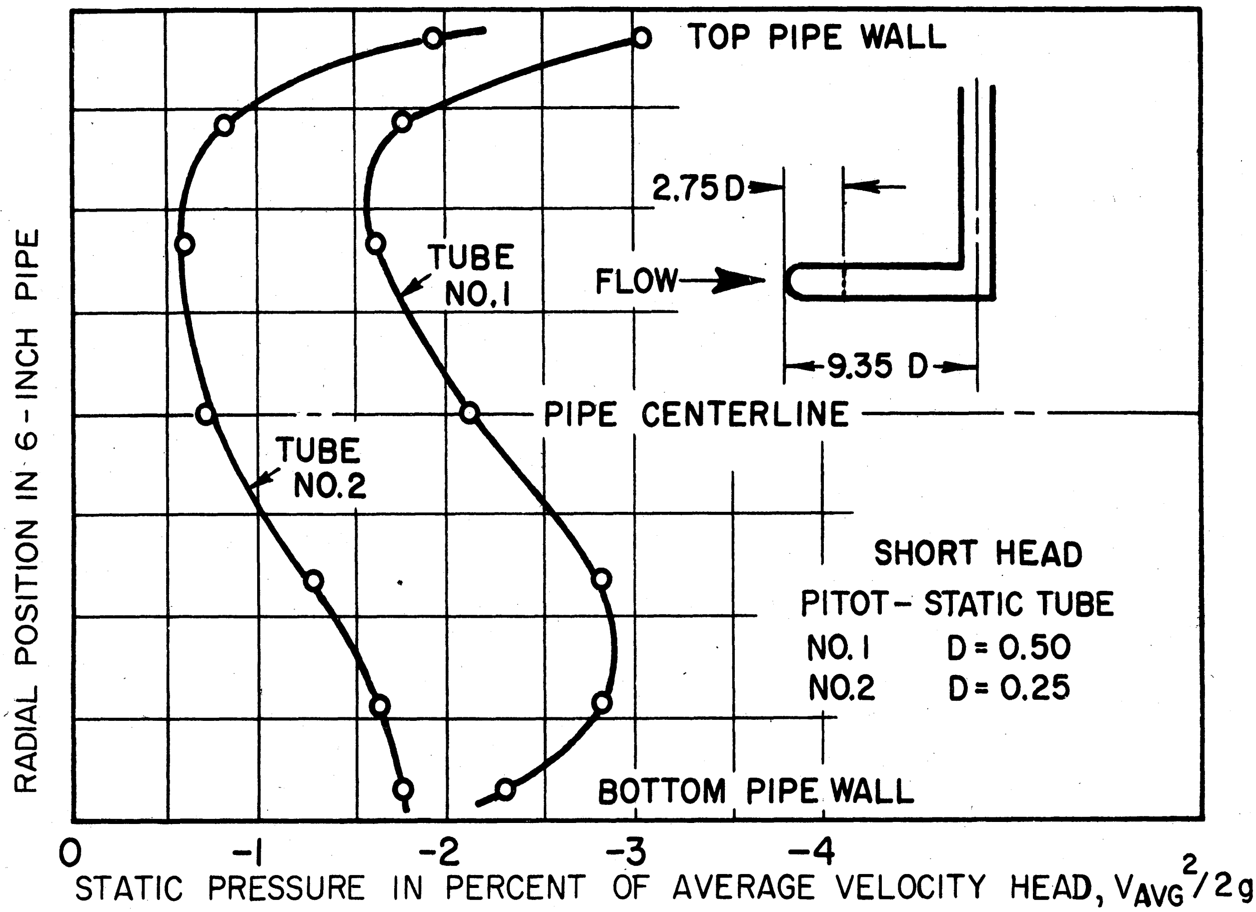

Fig. 17. Static-pressure measurements in water flow with short-head Pitot-static tubes of different size in a 6-inch pipe. Ferguson.[70]