

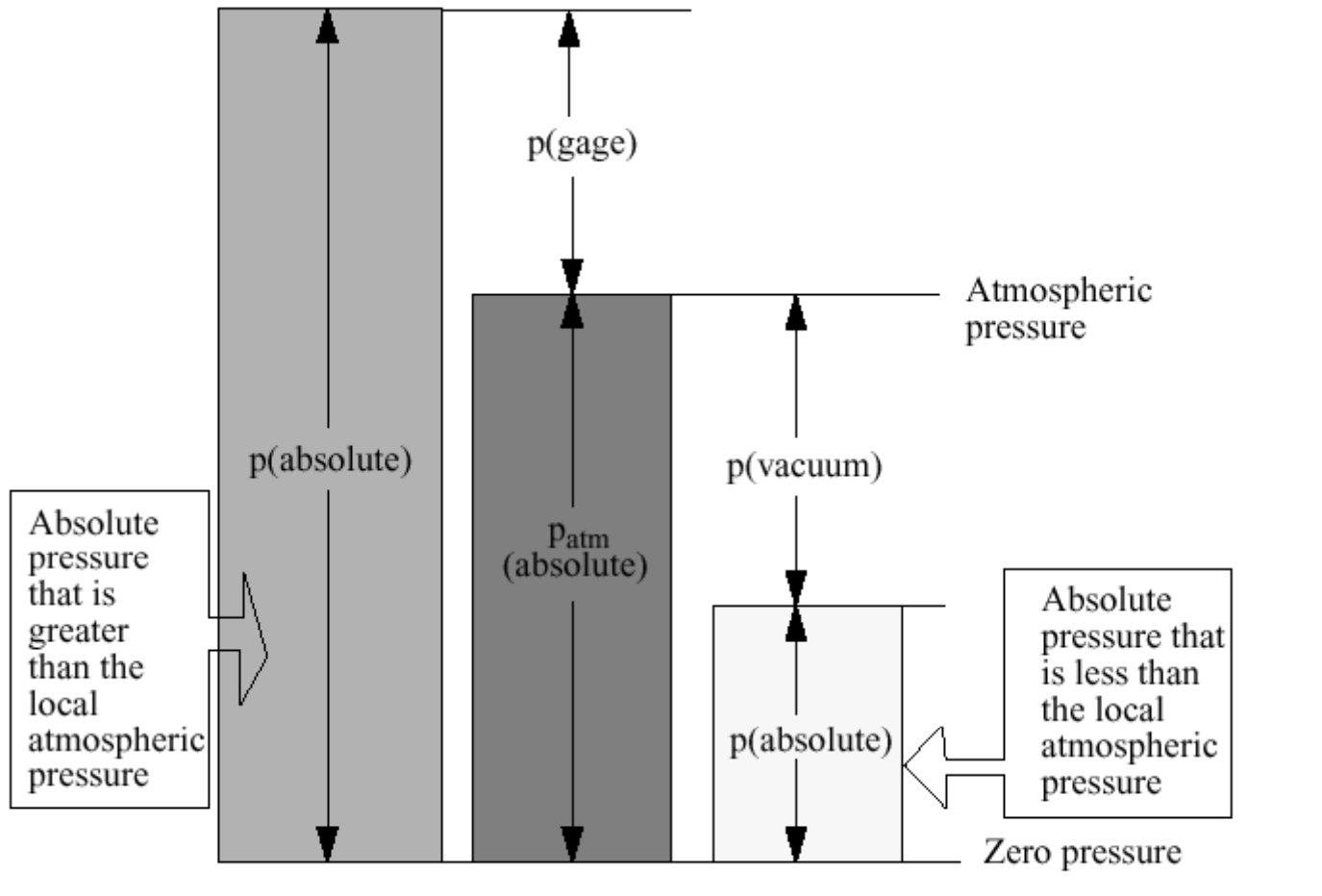
Pressure Measurements

Measurable pressures

- Absolute pressure
- Gage pressure
- Differential pressure
- Atmospheric/barometric pressure

- Static pressure
- Total Pressure

Relationships among the absolute, atmospheric, gage, and vacuum pressures



Pressure Measurement

- Mechanical Pressure Measurement

- Manometer

- Mechanical deflection

$$P = \lim_{A \rightarrow \text{continuum}} \frac{F_{\text{normal}}}{A}$$

- Pressure Sensitive Paint

- Measures the oxygen concentration in a polymer paint layer

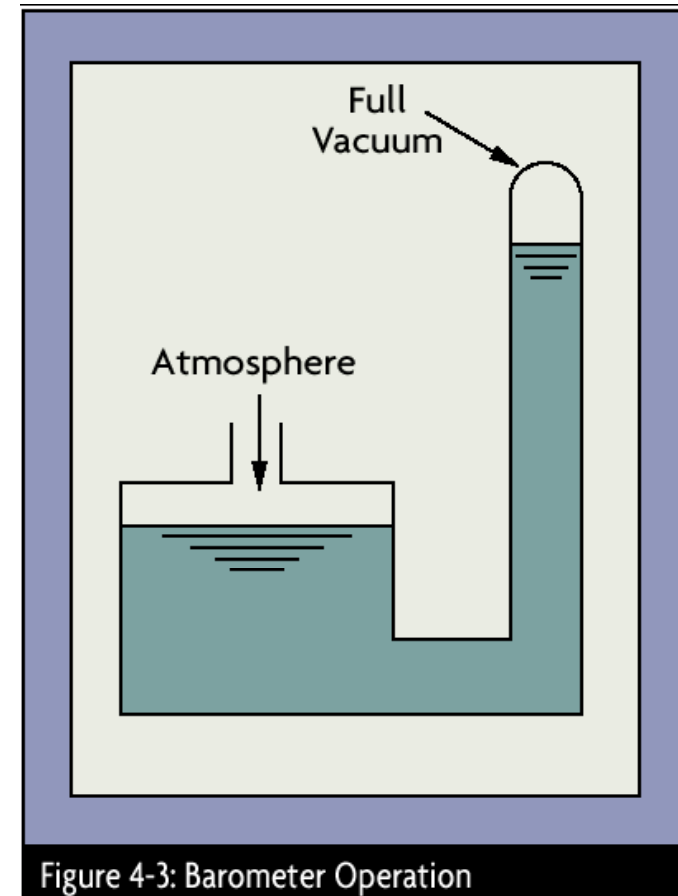
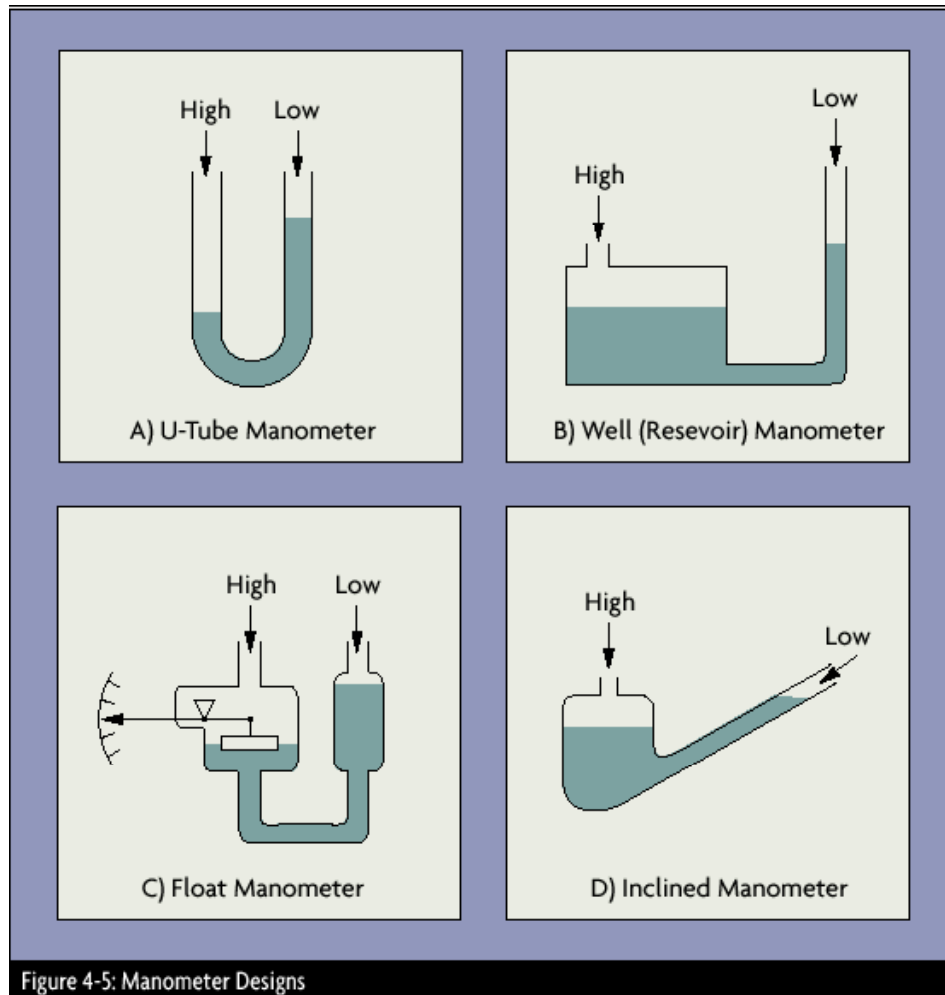
$$p \sim p_{O_2} \sim c[O_2]$$

Static
pressure

Oxygen
Partial
pressure

Henry's Constant x
oxygen concentration

Manometers



Manometer Resolution

$$p_2 - p_1 = (\rho_L gh)$$

- Main use for Manometers is calibration of electronic pressure transducers

Pressure Measurements

The evaluation of the pressure and velocity field is an essential part of experimental aerodynamics.

Total and static pressure have to be measured over a wide range of Mach and Reynolds numbers to define the forces on bodies or walls and the local magnitude and direction of the fluid velocity.

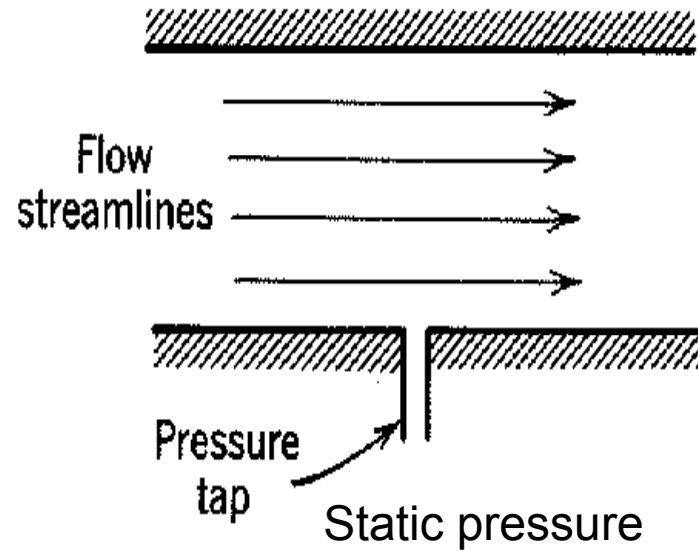
- Static Pressure P_s \rightarrow Wall Pressure P_w

- Total Pressure (Stagnation or Reservoir Pressure)

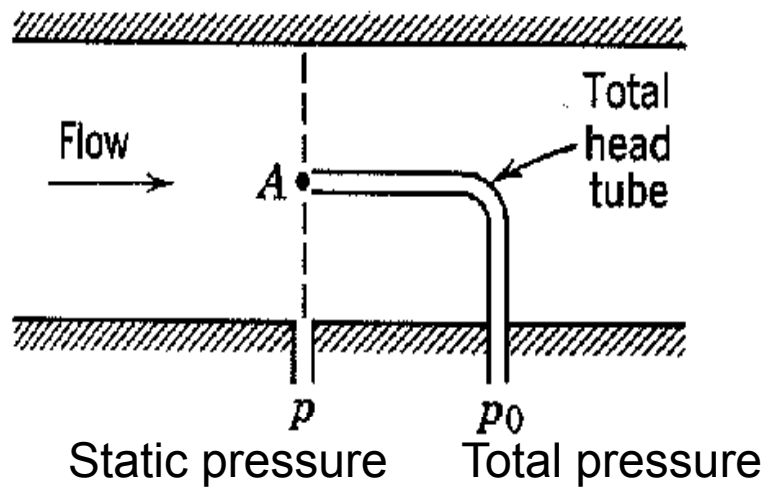
$$P_T = P_s + P_{\text{Dynamic}}$$

$$P_T = P_s + \underbrace{\frac{1}{2} \rho V^2}_{q}$$

Pressure Measurements



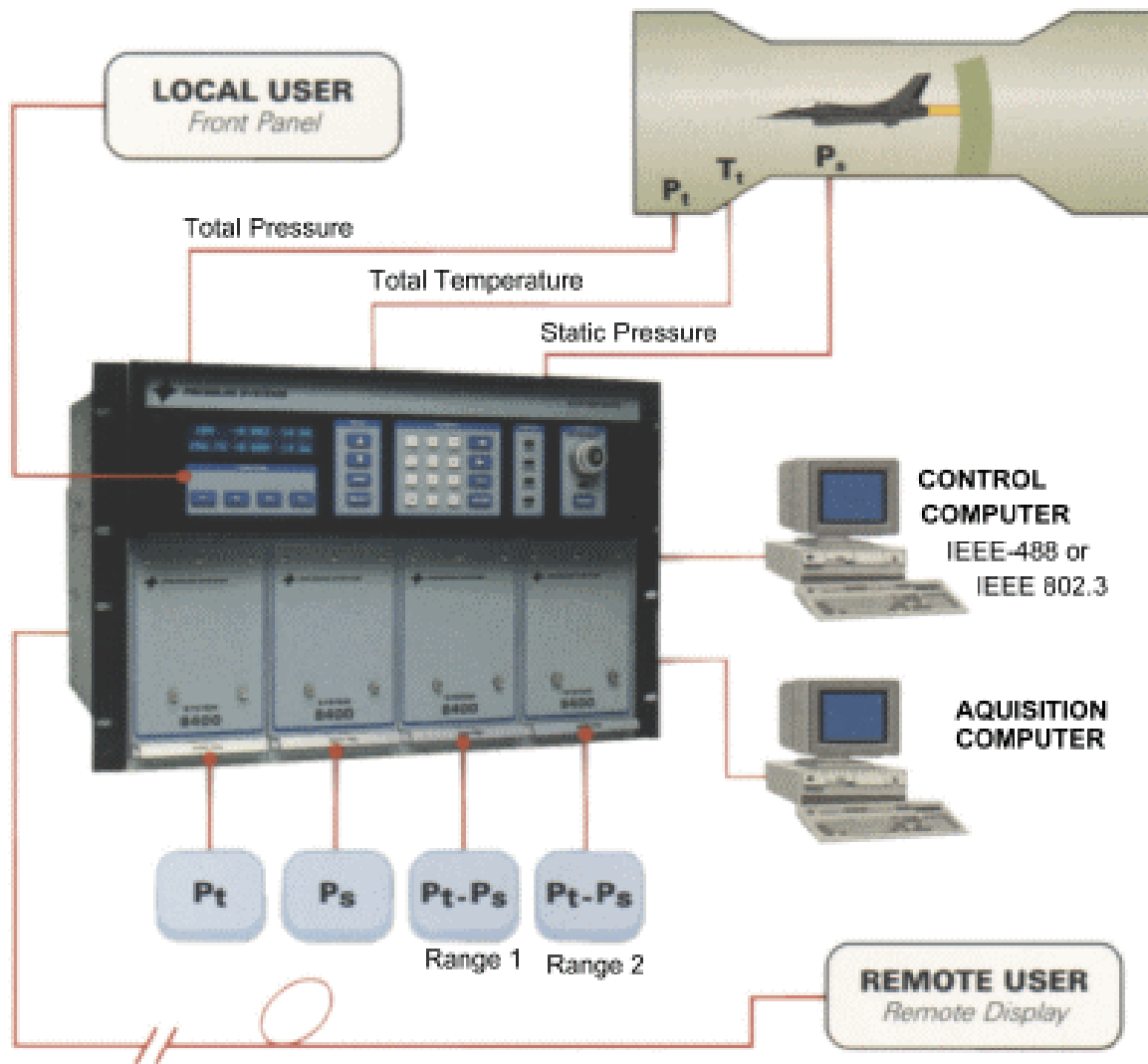
Wall pressure tap for static pressure measurement.



Simultaneous measurements of total and static pressures

Static Pressure Measurements

Static Pressure Measurements



**HIGH PERFORMANCE PRESSURE
BASED DATA ACQUISITION
SYSTEM**

FLEXIBLE

Configurable for a wide range of applications

MODULAR

Input units, expansion racks, slave units, remote processors

FAST

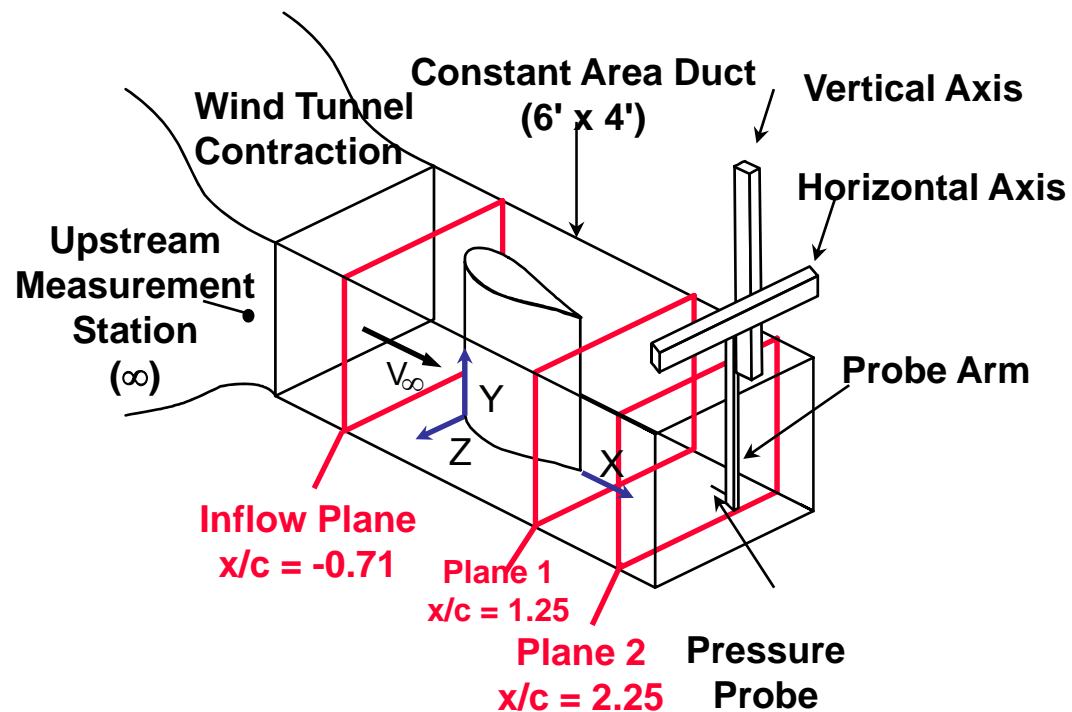
Up to 200000 measurements per second

Static Pressure Measurements

An orifice in the wall is the most commonly used device to measure the value of the static pressure of a fluid.

The orifice can be located on the tunnel wall or on the surface of a body submerged in the fluid.

The measurement of the static pressure away from a wall is done by means of a static pressure probe.



Wall Static Pressure Measurements

Wall Static Pressure Measurements

Best results are obtained with small, sharp edged holes, perpendicular to a wall, which is parallel to a laminar flow.

Hole diameters below 0.5 mm result in large response times and the holes are easily blocked by dust in the flow.

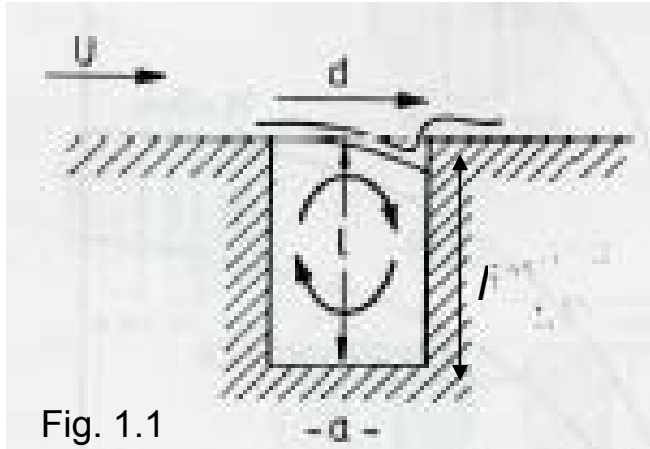
Large holes, however, are less accurate by the amount of distortion they introduce in the flowfield.

The main sources of errors are:

- Eddies developing in the cavity
- Fluid turbulence
- Mach number effects
- Stagnation of the fluid in the holes depending on orifice geometry and burrs

Wall Static Pressure Measurements

- Eddies in cavities



The shear stress of the boundary layer passing over the static pressure hole induces recirculating flows in the cavity, which in turn entrains relatively high momentum fluid from the free stream into the static pressure hole.

This results in a static pressure in the passage which is higher than the pressure on the surface.

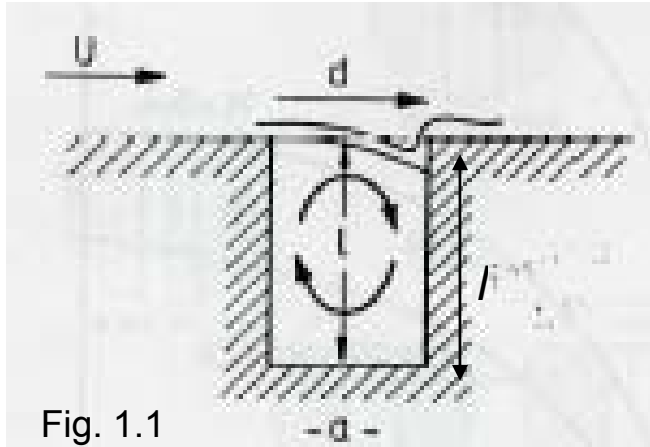
$$\Delta p = P_{sp} - P_s > 0$$

Measured static pressure

Real pressure on the surface

Wall Static Pressure Measurements

- Eddies in cavities



Shaw (1960) shows the variation of $\Delta P = P_{sp} - P_s$ relative to the wall shear stress τ_w for different values of l/d , in function of the Reynolds number Re_d . This Reynolds number is defined by d/v and the friction velocity $\sqrt{\tau_w / \rho}$.

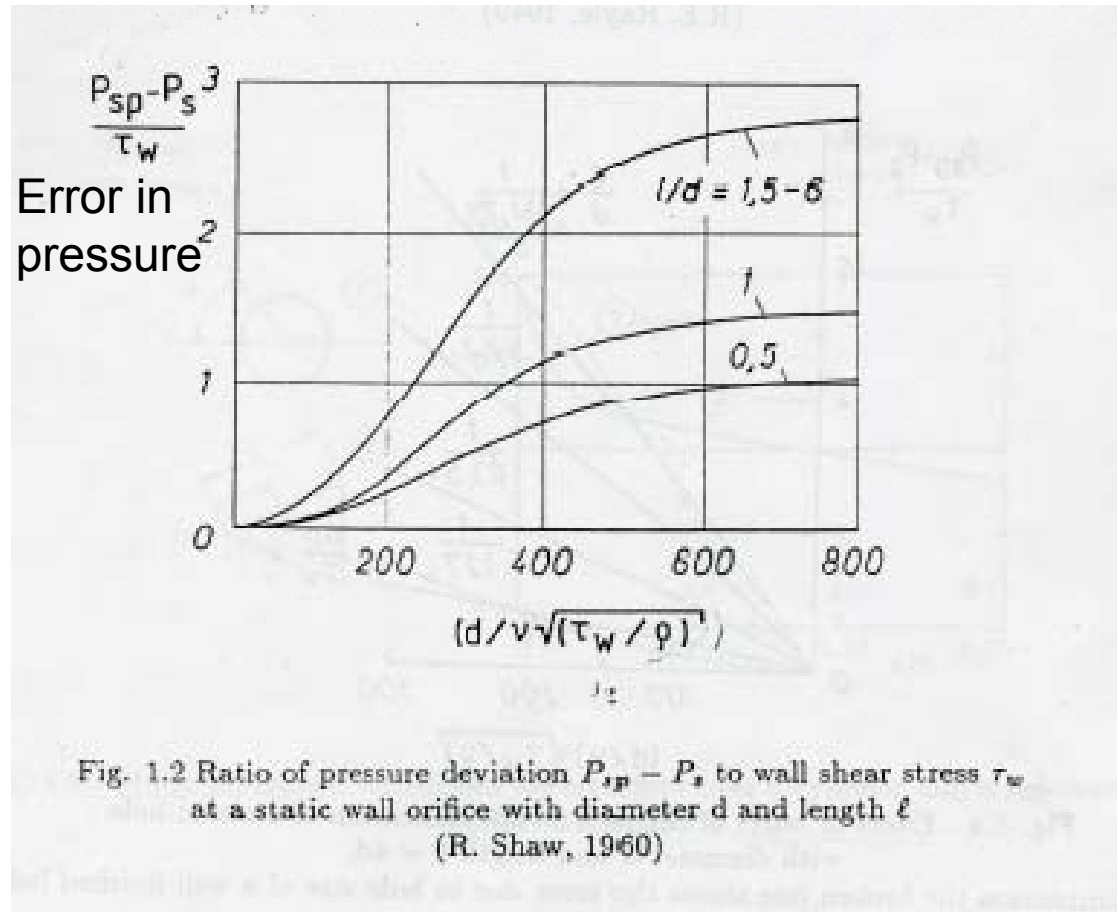
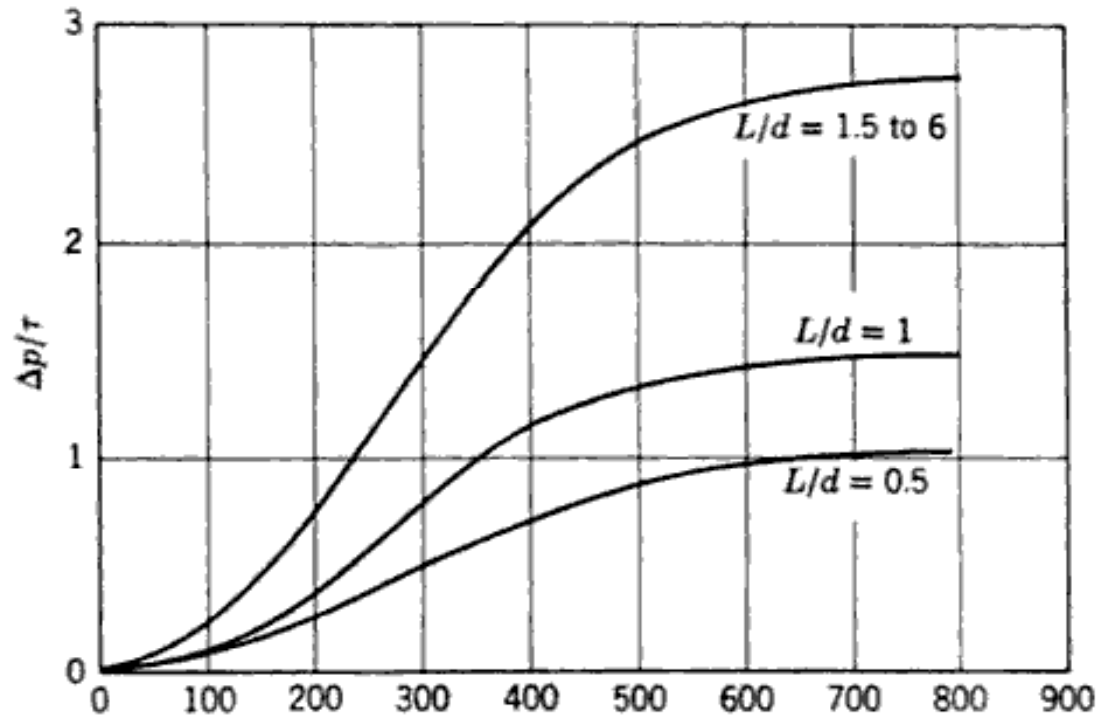


Fig. 1.2 Ratio of pressure deviation $P_{sp} - P_s$ to wall shear stress τ_w at a static wall orifice with diameter d and length ℓ (R. Shaw, 1960)

Short holes (small l/d) limit the recirculation, which results in small errors. The maximum errors are obtained at $l/d=1.5$. Further increase of l/d has no effect. The errors also increase with Reynolds number to reach an asymptotic value at $Re_d=800$.



$$R_d^0 = \left(\frac{d}{\nu}\right) \left(\frac{\tau g_c}{\rho}\right)^{1/2} = \frac{V \cdot d}{\nu}$$

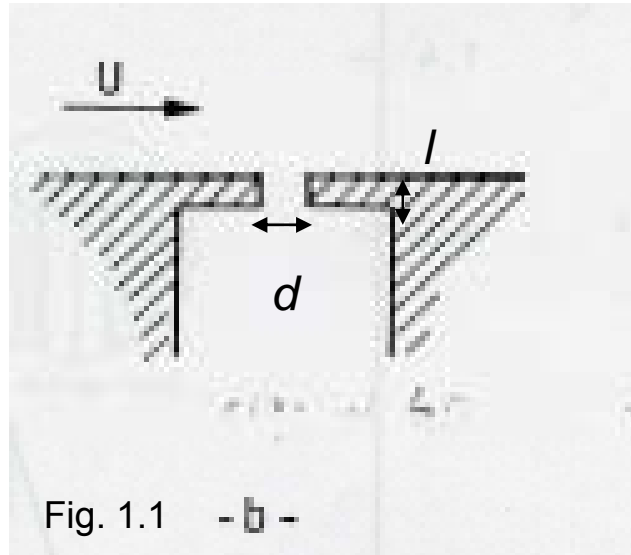
[Ref. Shaw]

Wall tap errors for incompressible turbulent flows for $0.025 < d < 0.175$.

✓ Static pressure tap size error is usually expressed as a function of the wall shearing stress τ since it is believed to arise because of a local disturbance of the boundary layer, that is, the wall shear stress enters the correlation since it characterizes the flow velocity gradient [i.e. $\tau = \mu(dV_p/dy)_{y=0}$, that is $\tau \propto \rho V^2/2g_c$]

✓ The dimensional curves of Shaw (above figure) indicate that L/d should be > 1.5 to avoid tap error dependence on L/d . Thus most experimenters keep L/d between 1.5 and 15.

Wall Static Pressure Measurements



$$\Delta p < 0$$

The short holes with underlying cavity can result in negative values of Δp

Wall Static Pressure Measurements

Mach number effect and influence of the hole diameter

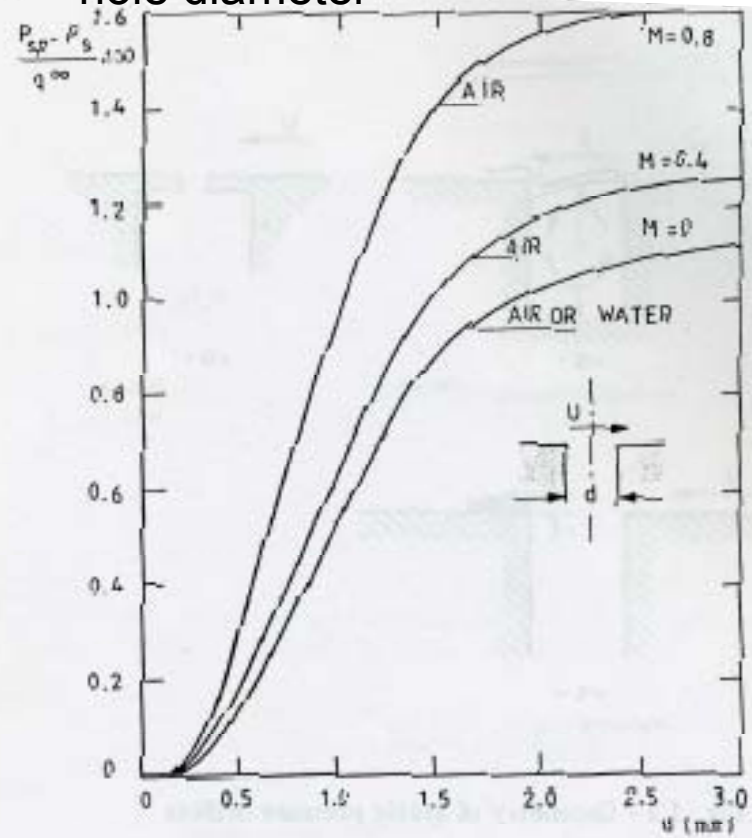
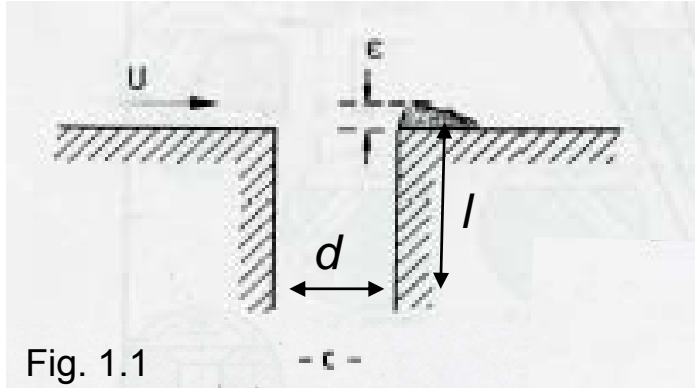


Fig. 1.3 - Effect of hole size and Mach number on the static pressure error registered by a square-edged hole
(R.E. Rayle, 1949)

The results indicate an increasing static pressure error for increasing hole diameter and Mach number.

Wall Static Pressure Measurements

Effect of burrs:



Solid lines indicate the influence of burrs, of height ϵ , adhering downstream edge of the hole.

Dashed line indicates the error due to the hole size of a well finished hole with $l/d=4$ (as shown in Fig. 1.2)

A burr on the upstream face of the hole will result in a lower reading.

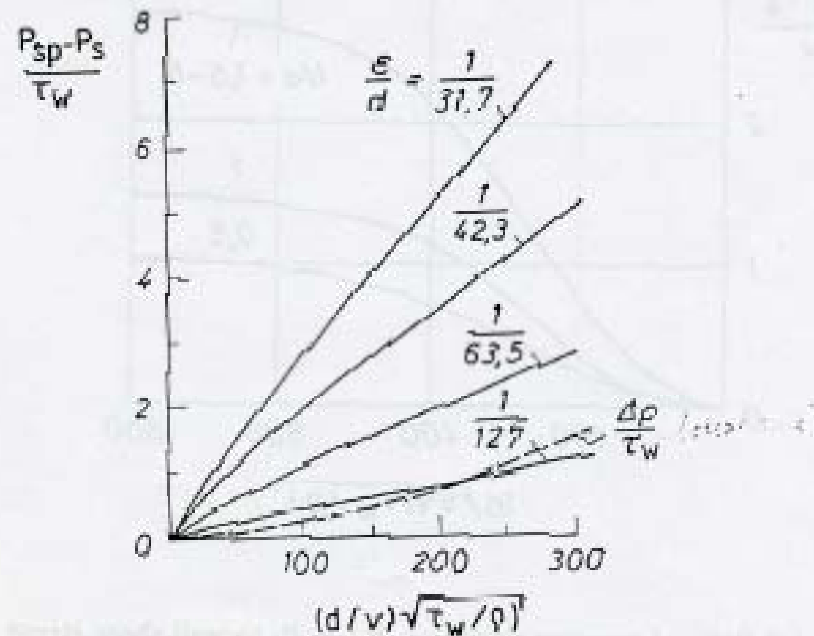
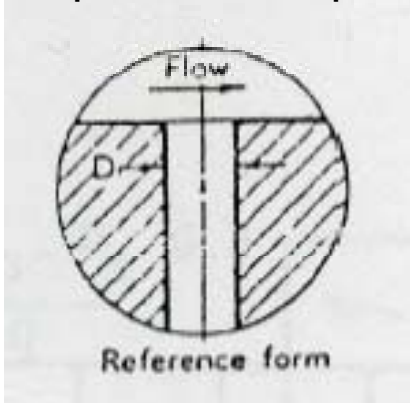


Fig. 1.4 - Effect of burrs of height ϵ on the indication of a static hole with diameter d and length $\ell = 4d$.

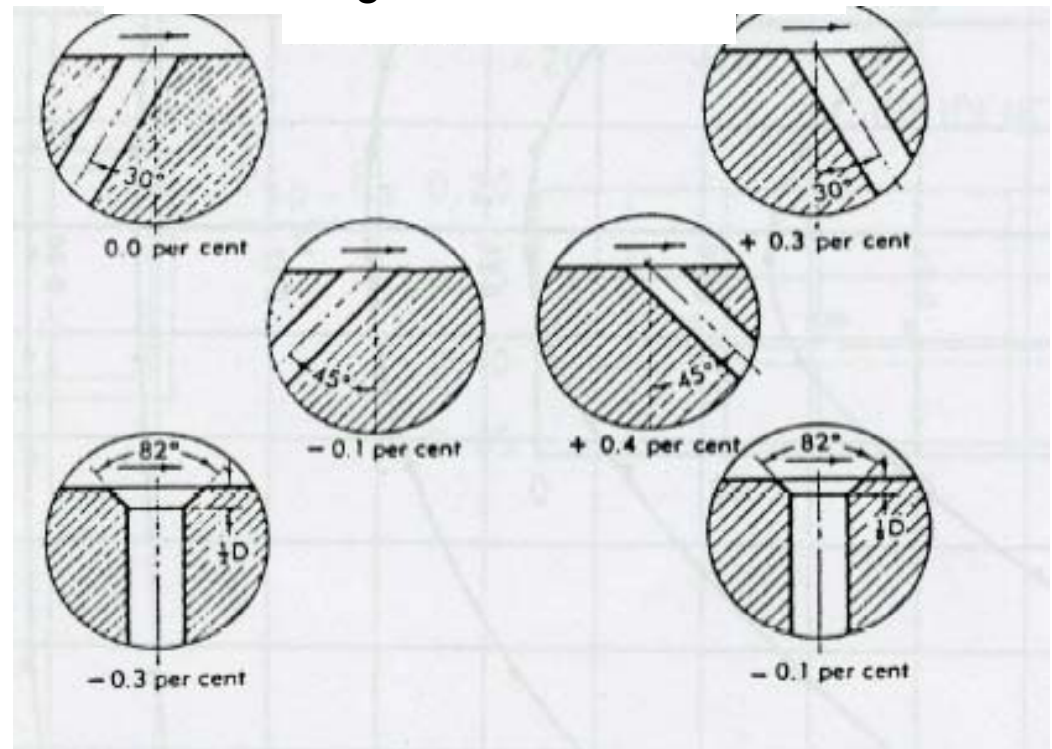
For comparison the broken line shows the error due to hole size of a well finished hole (R. Shaw, 1960)

Wall Static Pressure Measurements

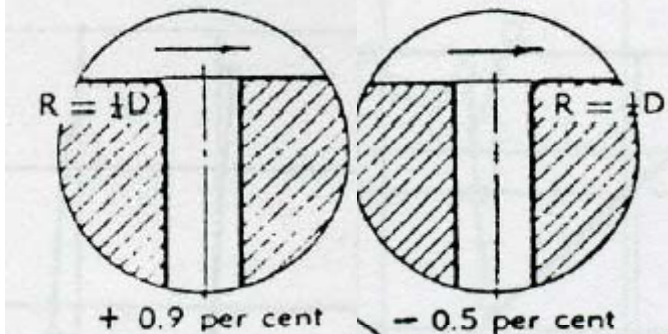
The effect of orientation of the hole centerline to the surface and roundoff of the orifice shape on static pressure measurement error $(P_{sp}-P_s)/q$



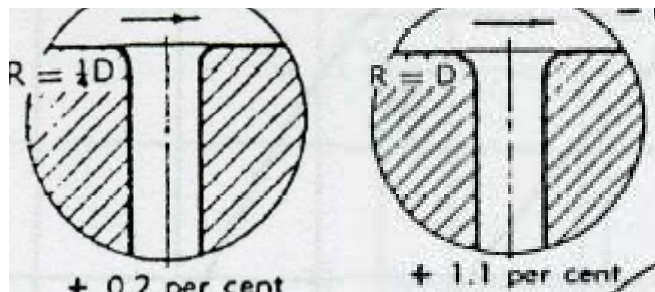
Other orientations and geometries

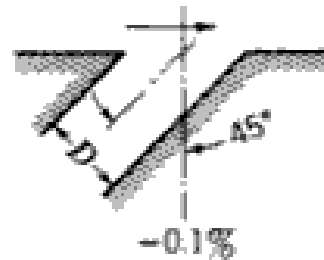
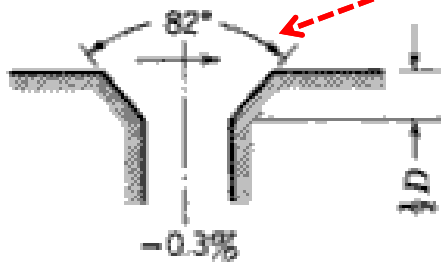
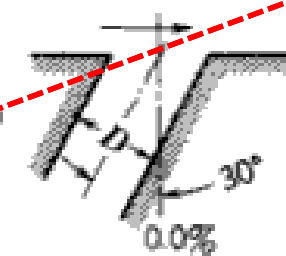
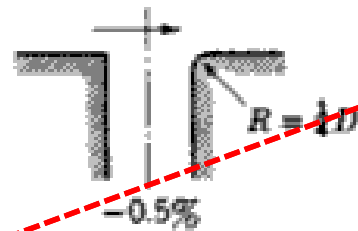
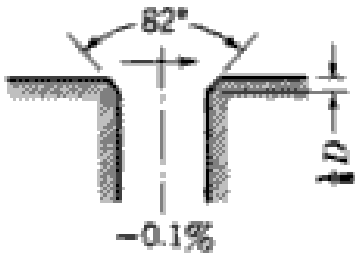
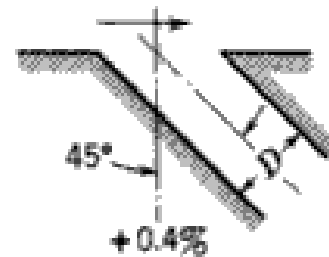
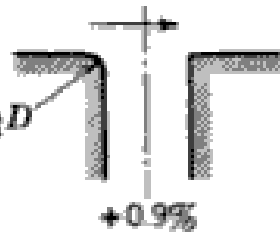
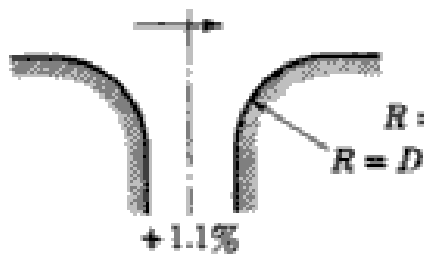
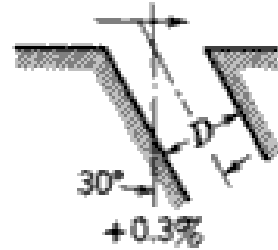
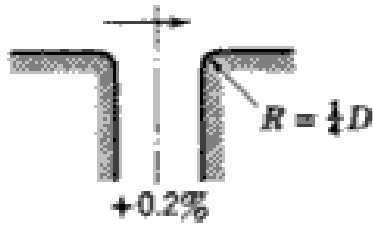
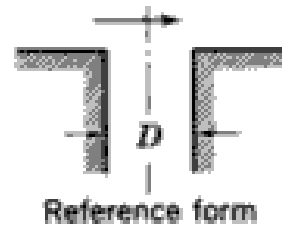


Filet at one side of orifice with $R=1/4D$



Fillets at both side of orifice with $R=1/4D$ and $R=D$





Although square-edged holes yield small positive errors, radius-edged holes introduce additional positive errors, and chamfer-edged holes introduce small negative effects.

At the upstream edge of a square tap, the fluid separates cleanly. (In effect, the fluid fails to note the removal of the constraining boundary.) Thus there are only minor deflections of the streamlines into a square tap. However, by fluid viscosity, a slight forward motion is imparted to the fluid in the hole. It is the **arresting of this motion by the downstream wall of the tap that accounts for the pressure rise.**

On the contrary, flow over a tap with a rounded edge does not immediately separate; but instead is guided into the hole with the resulting recovery of a portion of the dynamic pressure.

Finally, although the flow does separate at the upstream edge of a countersunk tap, it also accelerates at the sloping downstream edge of the tap, this latter effect induces a pressure suction (negative pressure difference) in the countersunk tap.

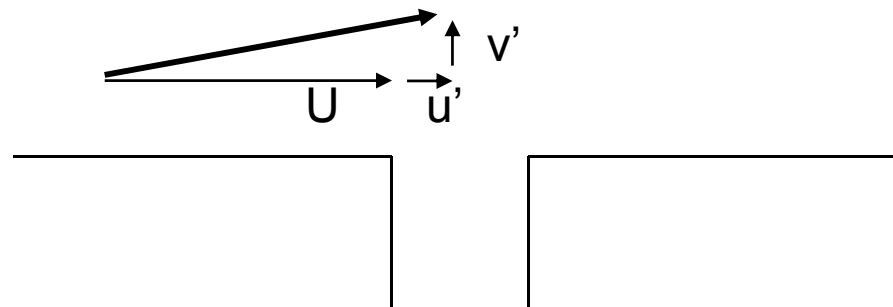
Wall Static Pressure Measurements

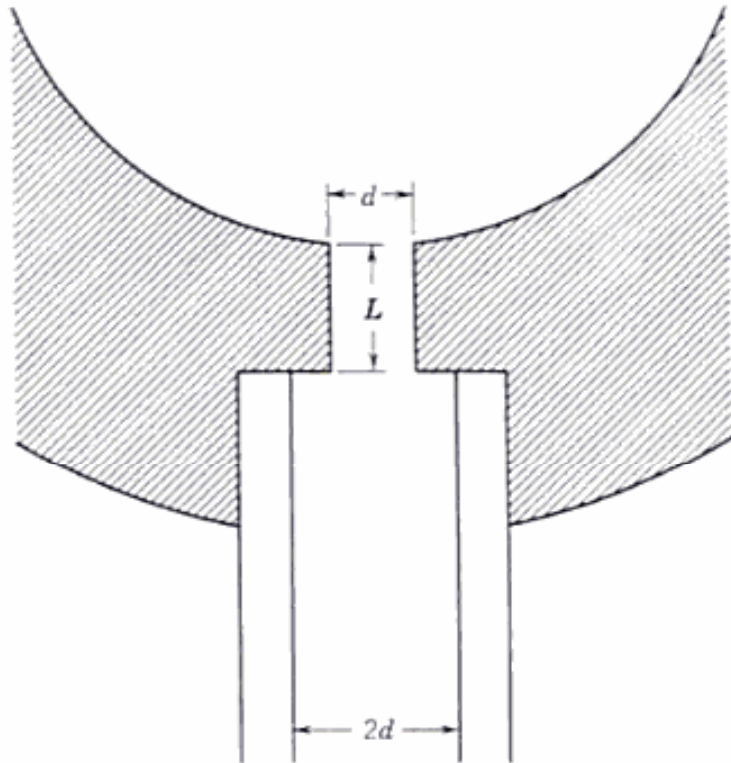
Effect of flow turbulence:

The influence of flow turbulence results from the fluctuation v' of the velocity component perpendicular to the wall.

Order of error is

$$\frac{v'^2}{U^2} = 0.25\% - 0.5\% \text{ of dynamic pressure}$$





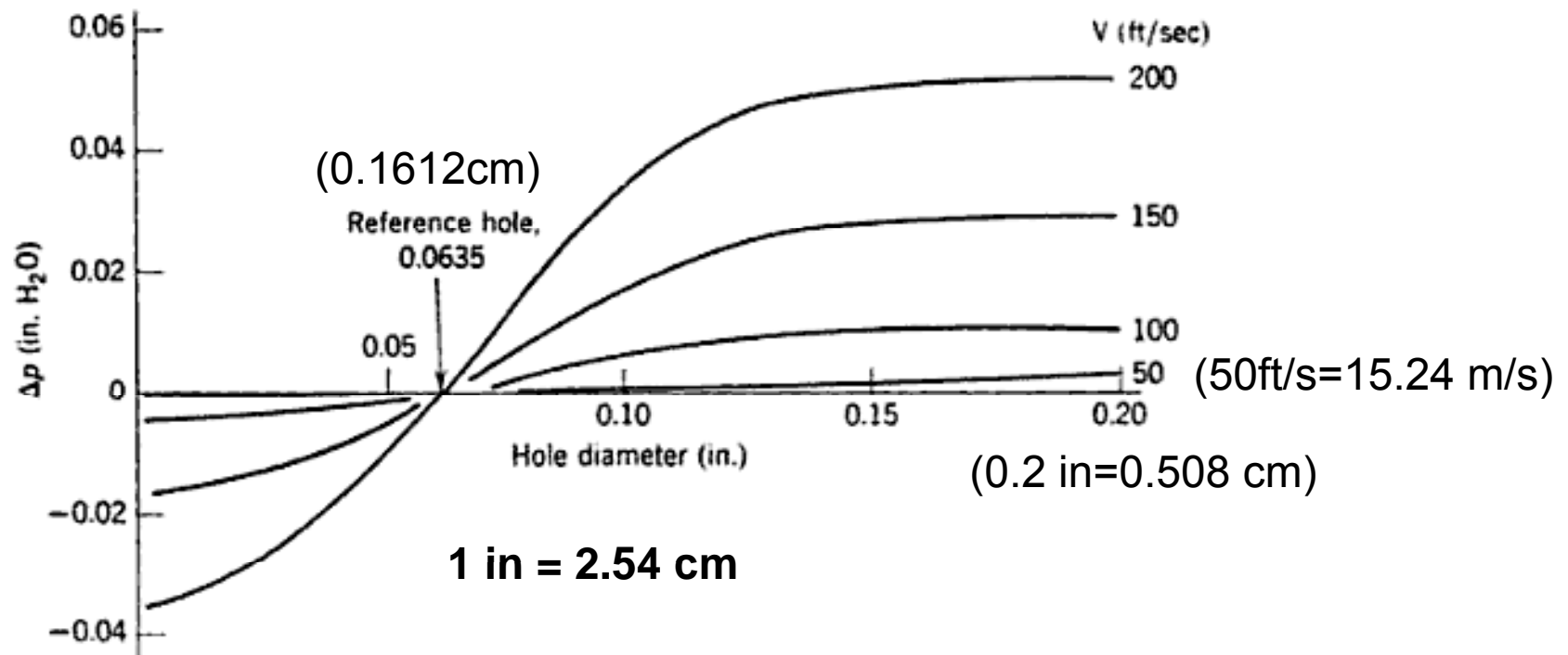
A recommended static pressure wall-tap geometry $1.5 < L/d < 6$

It is generally assumed that infinitely small square edged holes installed normal to flow boundaries give the correct static pressure.

Now it seems a relatively simple matter to drill a small hole perpendicular to a flow boundary and hence to sense the static pressure. But in reality, small holes are difficult to machine, they are exceedingly difficult to keep burr-free, and small holes are slow to respond to pressure changes.

Due to this, experimentalist apply a correction to the reading of a finite diameter pressure tap rather than having infinitely small holes.

1 foot = 0.3048 m



Typical experimental determination of hole size effect for $1.5 < L/d < 6$ [ref. Shaw]

The effect of hole size is almost always evaluated experimentally with respect to an arbitrary small diameter reference tap. Such results are then extrapolated to zero hole size to obtain absolute errors.

Static Pressure Probes

Static Pressure Probes

Static pressure probes are used to measure the static pressure of the flow in locations away from the walls. Typical probe geometries are:

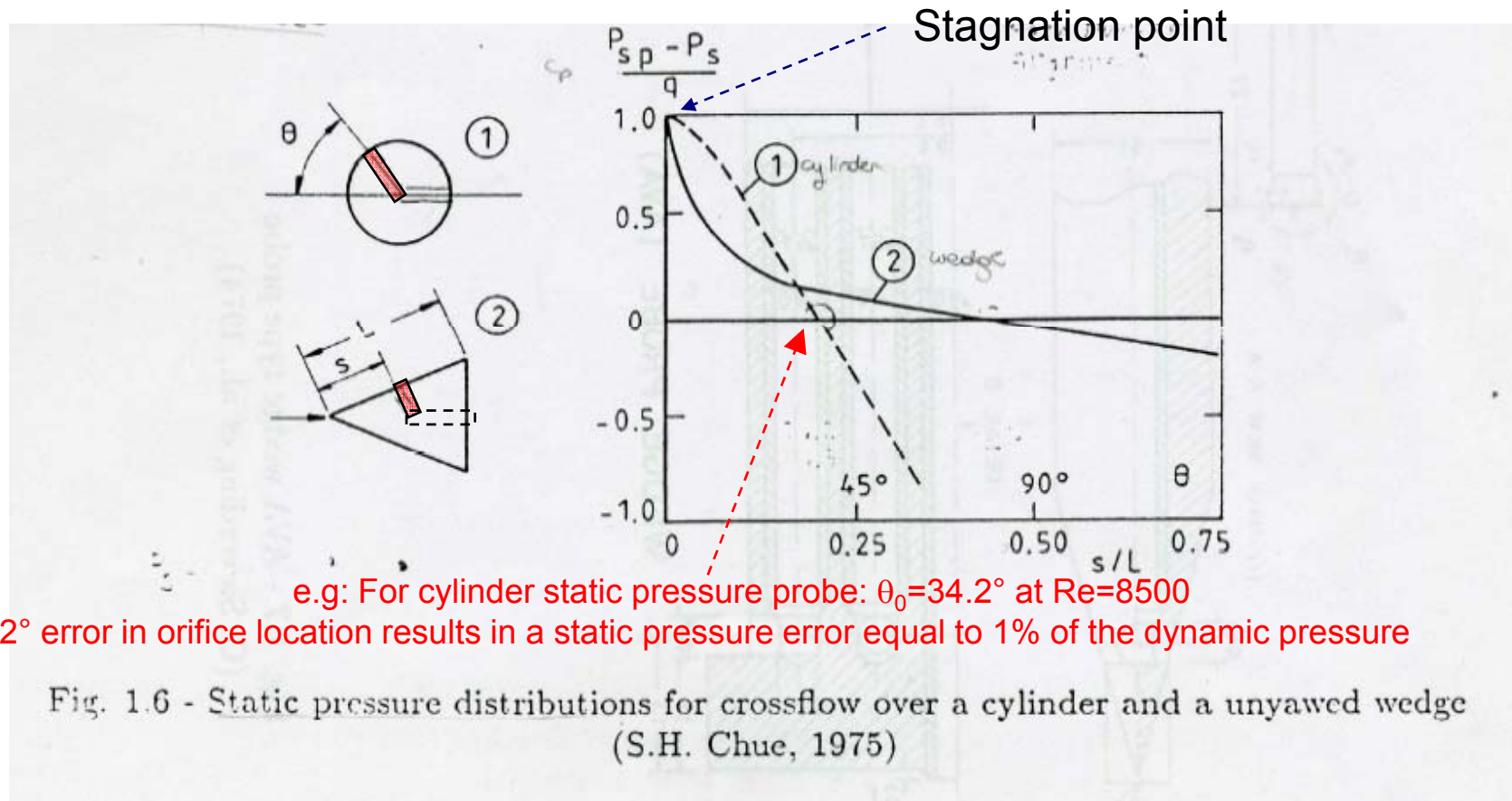
- A cylindrical tube perpendicular to the flow with static pressure orifices
- A wedge aligned with the flow with static pressure orifices located on both sides or downstream of a step
- A disk parallel to the flow with a static pressure orifice on one side and the probe stem on the other side
- A cylindrical tube placed parallel to the flow with static pressure orifices located on the conical nose or on the cylindrical tube.

The choice of the probe depends on the available space, the application (Reynolds and Mach number) and on the required accuracy.

Static Pressure Probes

A. Static pressure cylinder: The flow perpendicular to an infinite cylinder results in a pressure decrease from the stagnation point to the lateral points.

Two intermediate positions (on top and on bottom sides) can be defined where the measured pressure equals the free stream static pressure. The position of these points depends on the Re and Mach number.



Static Pressure Probes

B. Static pressure wedge: The static pressure distribution along a wedge is shown also on Fig. 1.6. A correct static pressure measurement can be made at $s/l=0.37$.

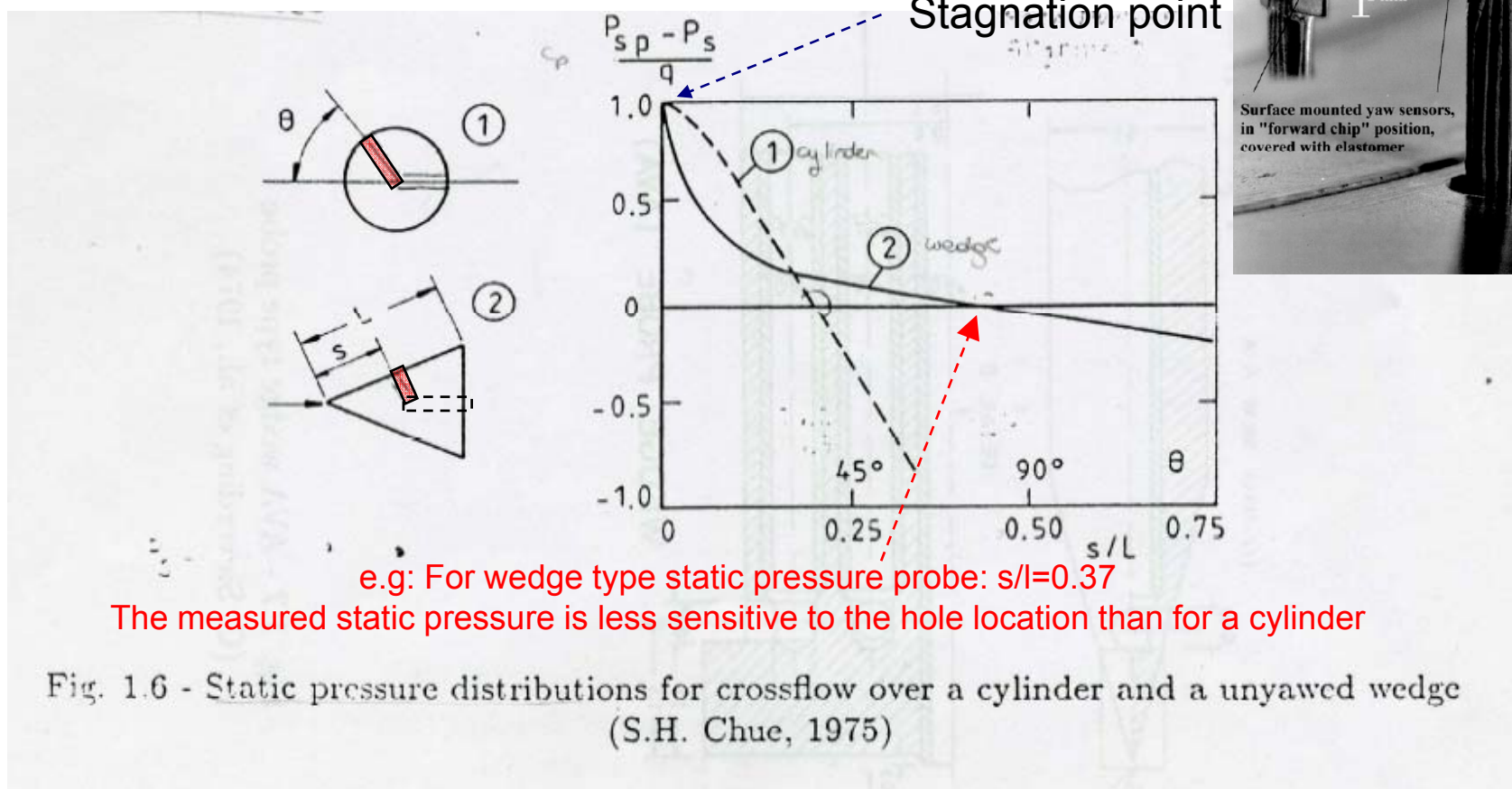
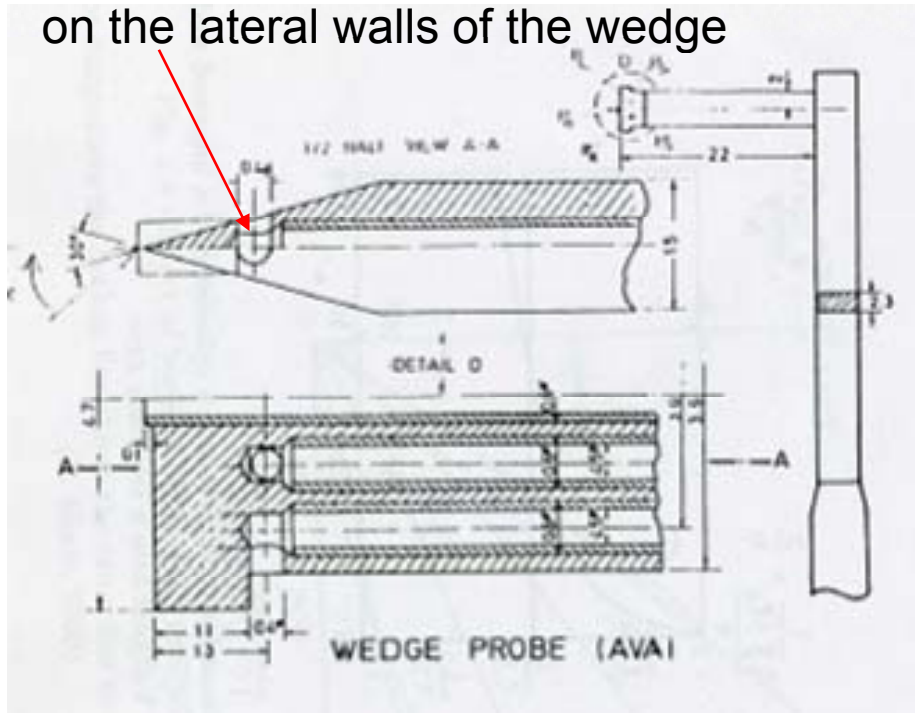


Fig. 1.6 - Static pressure distributions for crossflow over a cylinder and a yawed wedge (S.H. Chue, 1975)

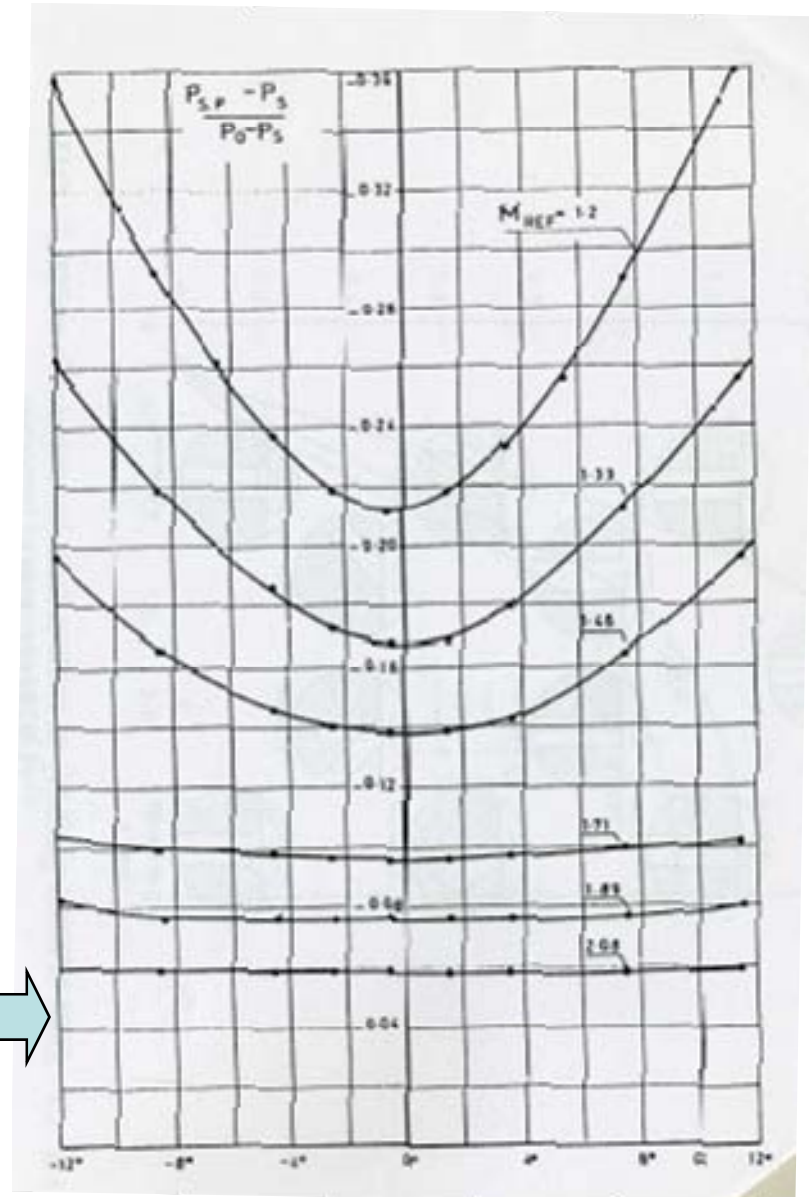
Static Pressure Probes

B. Static pressure wedge:

Static pressure orifices are located on the lateral walls of the wedge



Impact of non-alignment and Mach number on static pressure measurement: The calibration curves at supersonic Mach numbers show the differences between the measured and exact static pressure when the probe is not aligned with the flow ($\alpha \neq 0$)



Static Pressure Probes

C. Disk probes:

Disk probes have found little application because of their sensitivity to incidence as shown on the calibration curve.

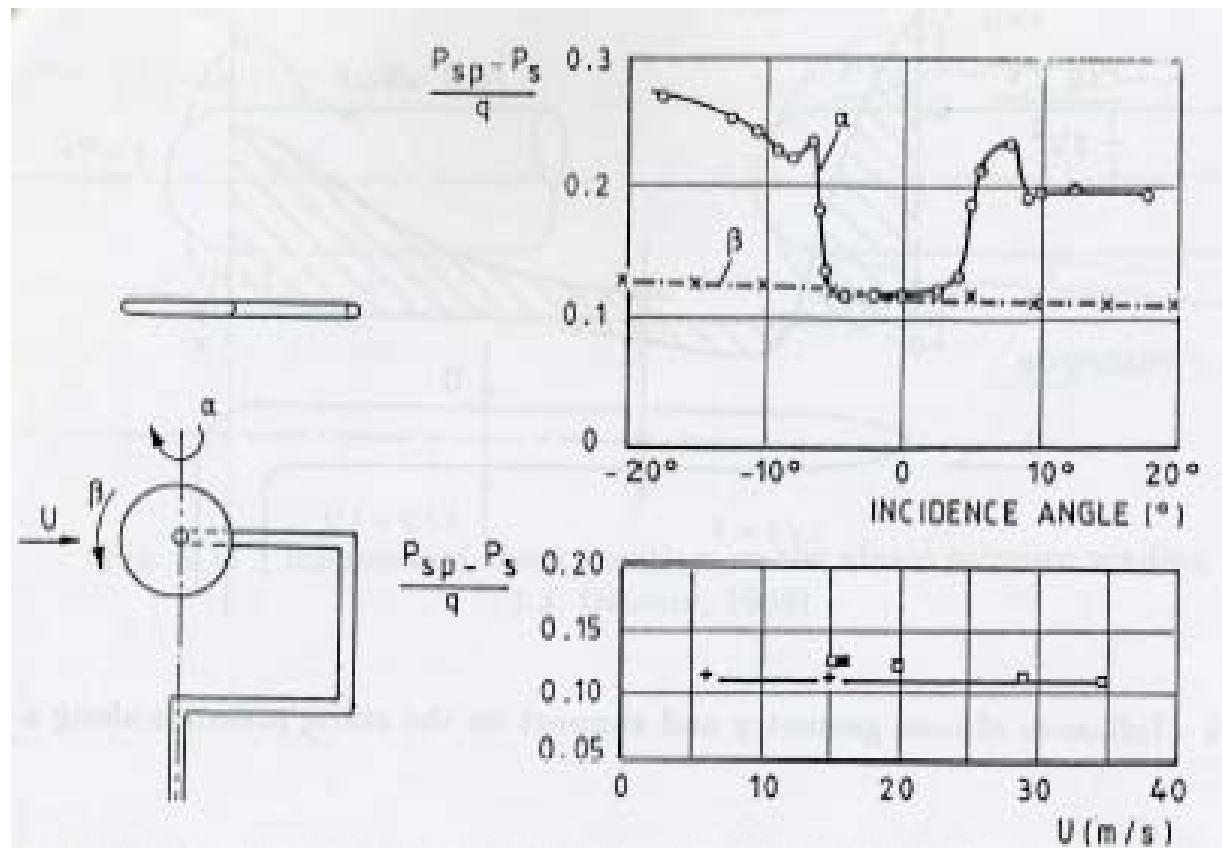


Fig.1.8 - Disk probe and calibration curves for α and β rotation and for different speeds

Static Pressure Probes

D. Static pressure tube:

The static pressure measured by orifices on a cylindrical tube parallel to the flow (Prandtl tube) is influenced by the nose and the stem (support).

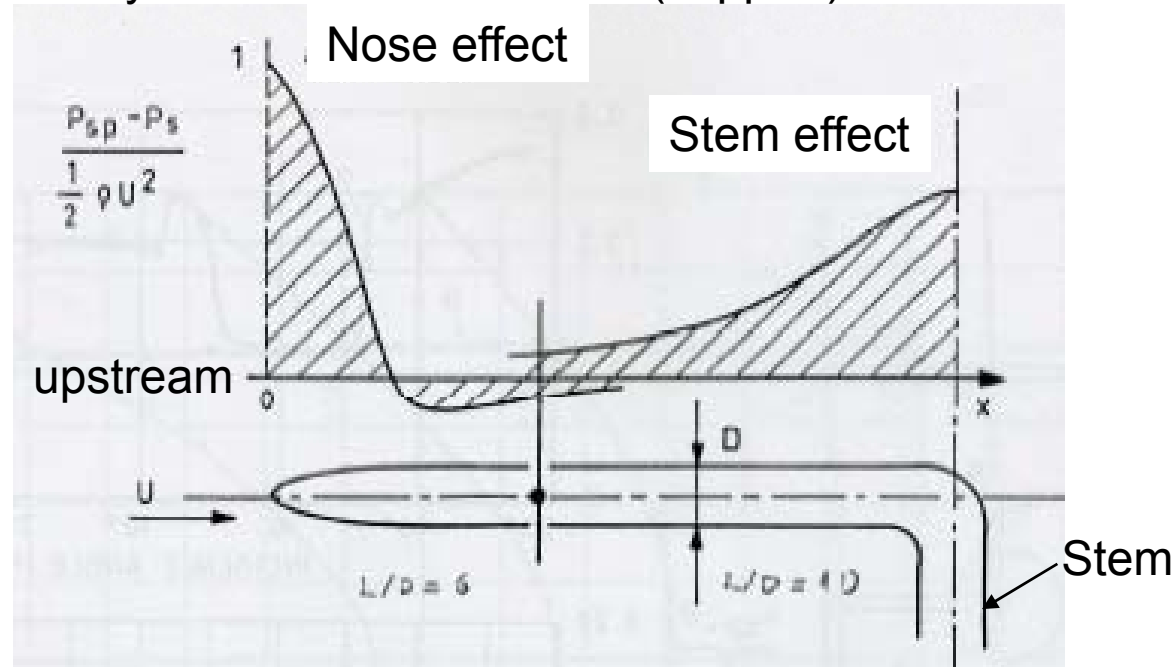


Fig. 1.9 Influence of nose geometry and support on the static pressure along a tube

Nose effect:

- The flow accelerates in the nose region from zero velocity in the stagnation point to a velocity above the free stream value.
- The static pressure decreases from the stagnation value to a value below the free stream and then slowly increases to a free stream value.
- It is recommended to locate the static pressure orifice at a minimum 6 to 10 tube diameters downstream of the leading edge depending on the Mach number.

Static Pressure Probes

D. Static pressure tube:

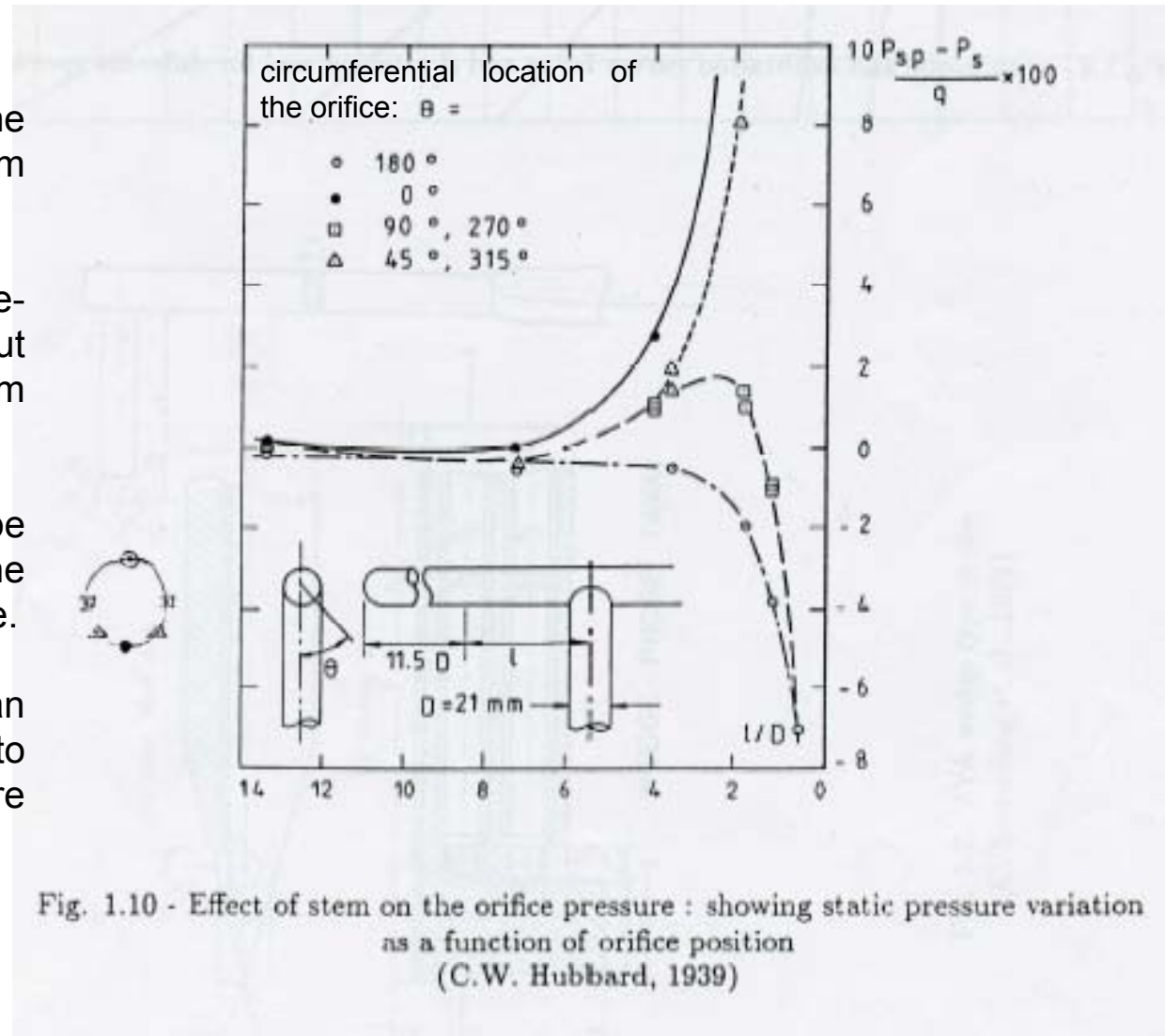
Stem (support) effect:

The stagnation of the fluid on the probe stem has an upstream influence.

This results in higher than free-stream pressure and results about 10 diameters upstream of the stem before the pressure is uniform.

The upstream influence of the probe stem is depending on the circumferential location of the orifice.

The fact that the stem causes an overpressure can be used to compensate the underpressure created by the nose of the probe.



Static Pressure Probes

- At increasing freestream Mach number, a subsonic critical value M_c will be reached at which locally a region of supersonic velocity develops near the nose.

- The shock downstream of the supersonic zone can be in front of the static pressure orifices, which results in a static pressure corresponding to a subsonic flow.

- At increasing Mach number the shock moves to a position downstream of the static orifices and a low static pressure, corresponding to supersonic flow, will be measured ($\alpha=0$ curve on Fig. 1.12).

- The static pressure measured at an incidence is completely different ($\alpha=20^\circ$ curve on Fig. 1.12). Correct static pressure measurements are therefore very difficult for free stream Mach numbers.

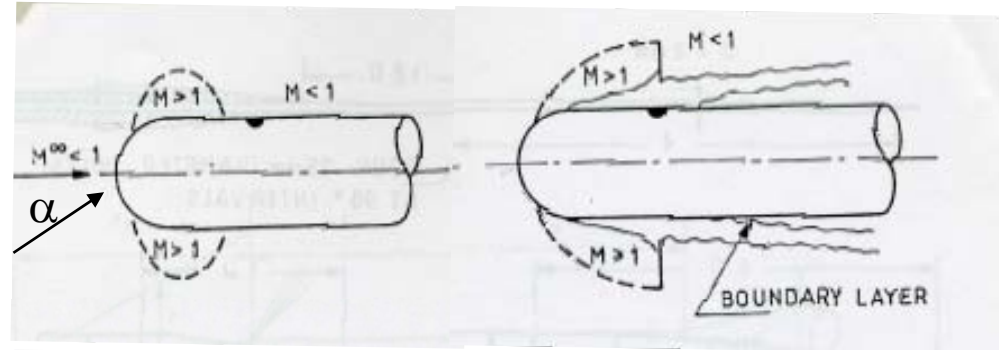


Fig. 1.11 - Influence of shock position on the static pressure reading (J.J. Ginoux, 1964)

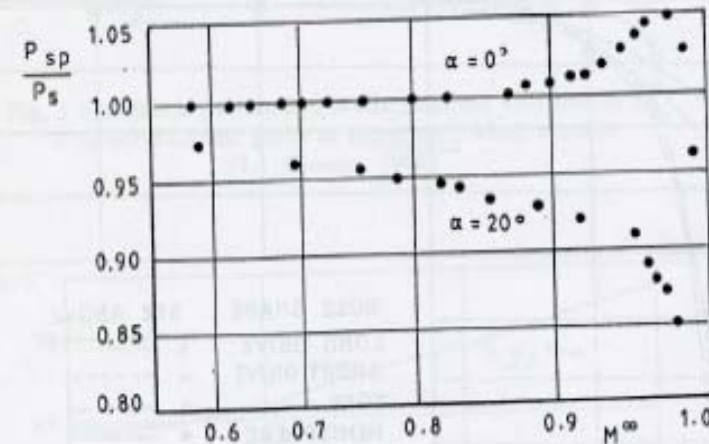
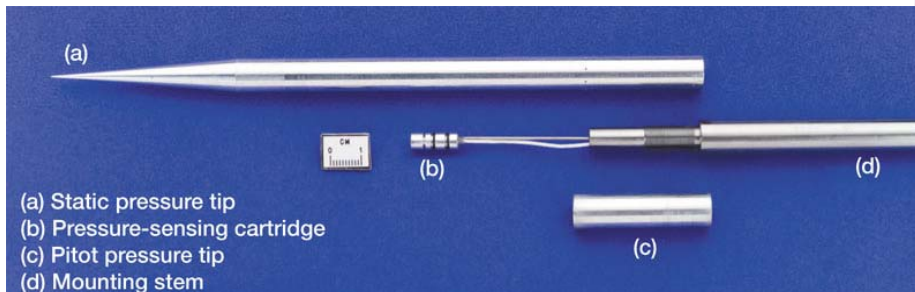
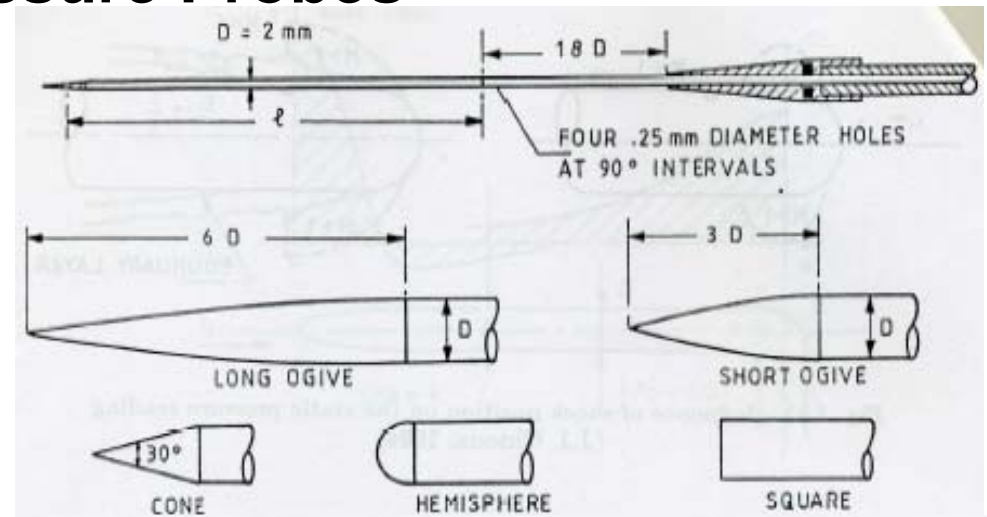


Fig. 1.12 - Variation of static pressure reading with free stream Mach number at $\alpha = 0^\circ$ and $\alpha = 20^\circ$ (J.J. Ginoux, 1964)

Static Pressure Probes

Influence of probe geometry and location of orifices:

- The size of the supersonic flow region near the probe leading edge can be reduced by changing the shape of the probe nose.
- Elliptical nose shapes are used at low Mach numbers.
- Sharp, long conical noses are used at supersonic Mach numbers.



NASA: Dynamic Pressure Probes Developed for Supersonic Flow-Field Measurements

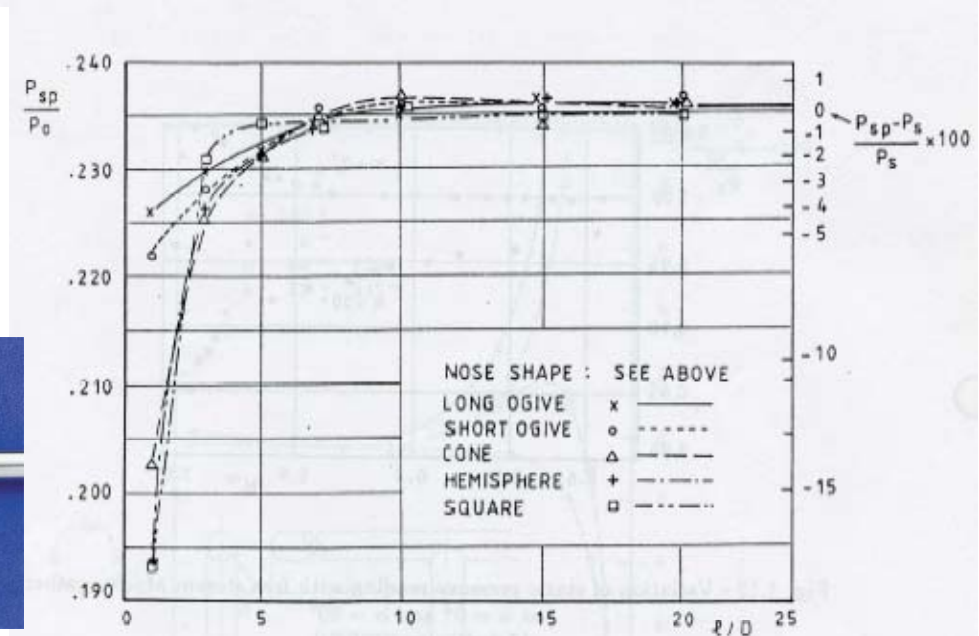


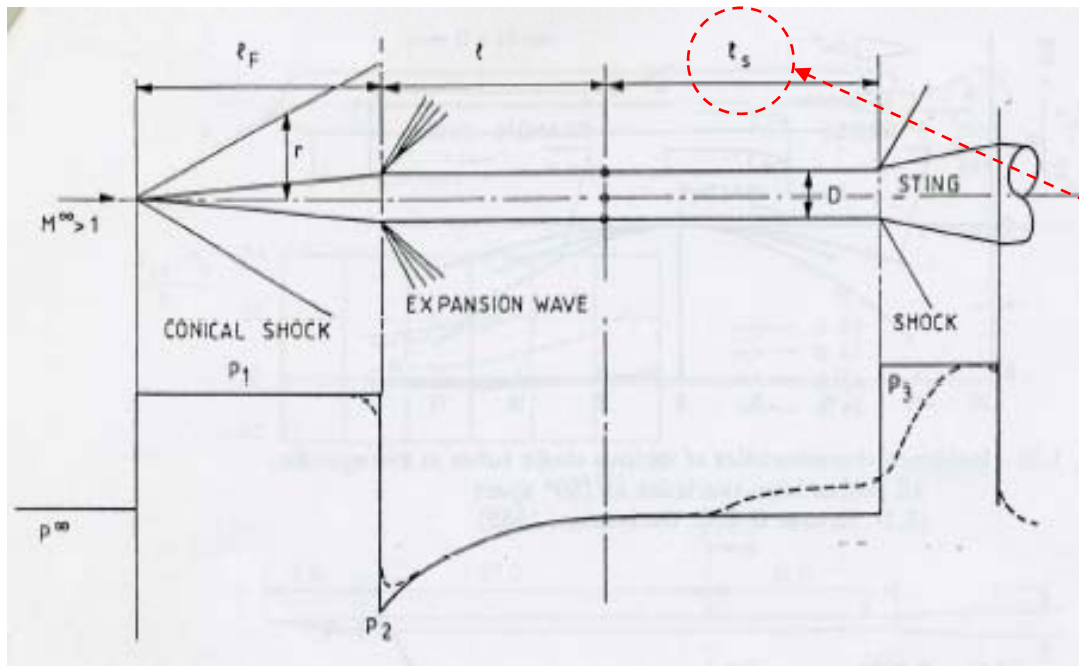
Fig. 1.13 - Influence of probe geometry and location of the orifice on the static pressure reading at M = 1.6 (D.W. Holder et al., 1950)

Static Pressure Probes

Supersonic flow:

Shock pattern and static pressure distribution on a cone-cylindrical probe at supersonic Mach number.

The shock wave, created by the downstream stem, interacts with the boundary layer and the pressure p_3 propagates upstream.



— Theoretical pressure distribution
 - - - - - Real static pressure distribution

The minimum distance at which to place the stem to avoid interaction with the pressure orifice as a function of Mach number and probe diameter.

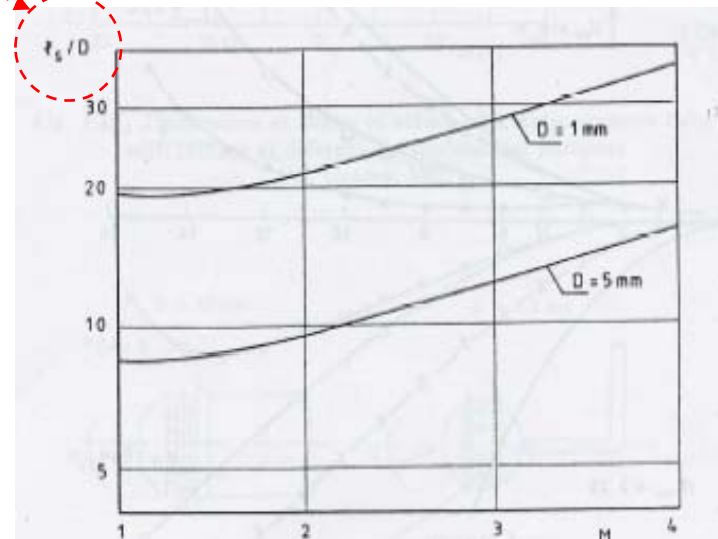


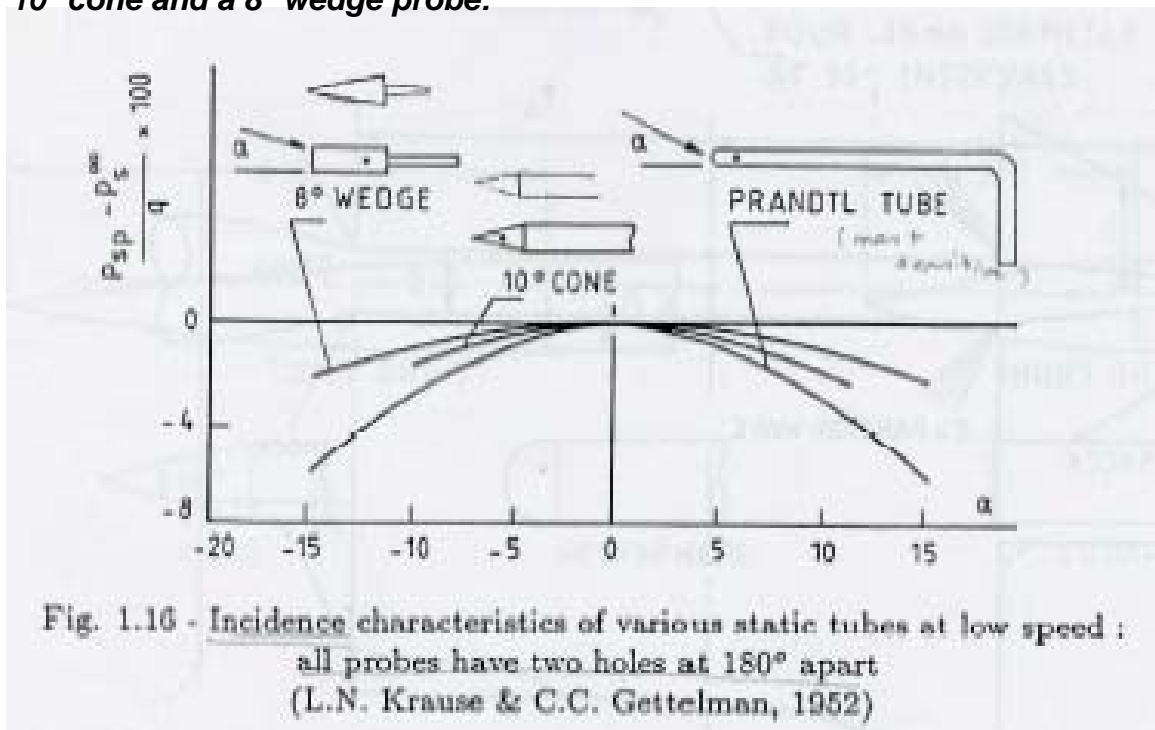
Fig. 1.15 - Required length of static probe to avoid support interference through the boundary layer (J.A. Hill et al., 1956)

Static Pressure Probes

Measurement errors:

The flow direction is sometimes unknown and this makes it difficult to set the pressure probes parallel to the stream. In some cases the probe may be fixed and not adjustable to the flow direction. As a consequence one tries to design probes that are not too sensitive to the flow direction.

The influence of pitch angle on the static pressure measurement for a Prandtl tube, a 10° cone and a 8° wedge probe:



Prandtl tube is the most sensitive to misalignment.

The 8° wedge is the least sensitive.

Static Pressure Probes

Measurement errors:

The influence of incidence angle has been measured by Ginoux with a static pressure tube having one single orifice.

Fig. 1.17 shows the variation of the measured static pressure as a function of incidence angle α and the angular position θ of the static pressure hole.

A large sensitivity to incidence is observed. Correct results within 1% error can be obtained only when $\alpha < 3^\circ$.

A static orifice at $\theta = 40^\circ$ is insensitive to positive values of α up to 10° .

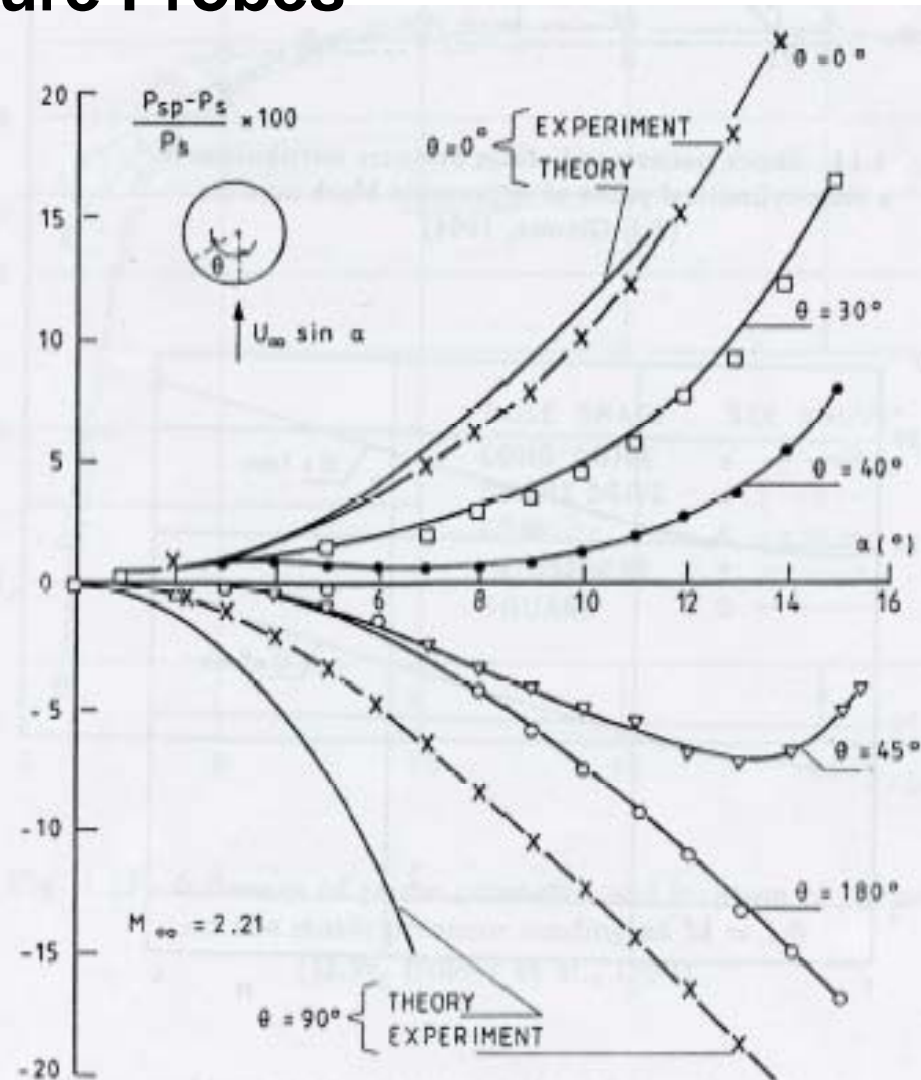
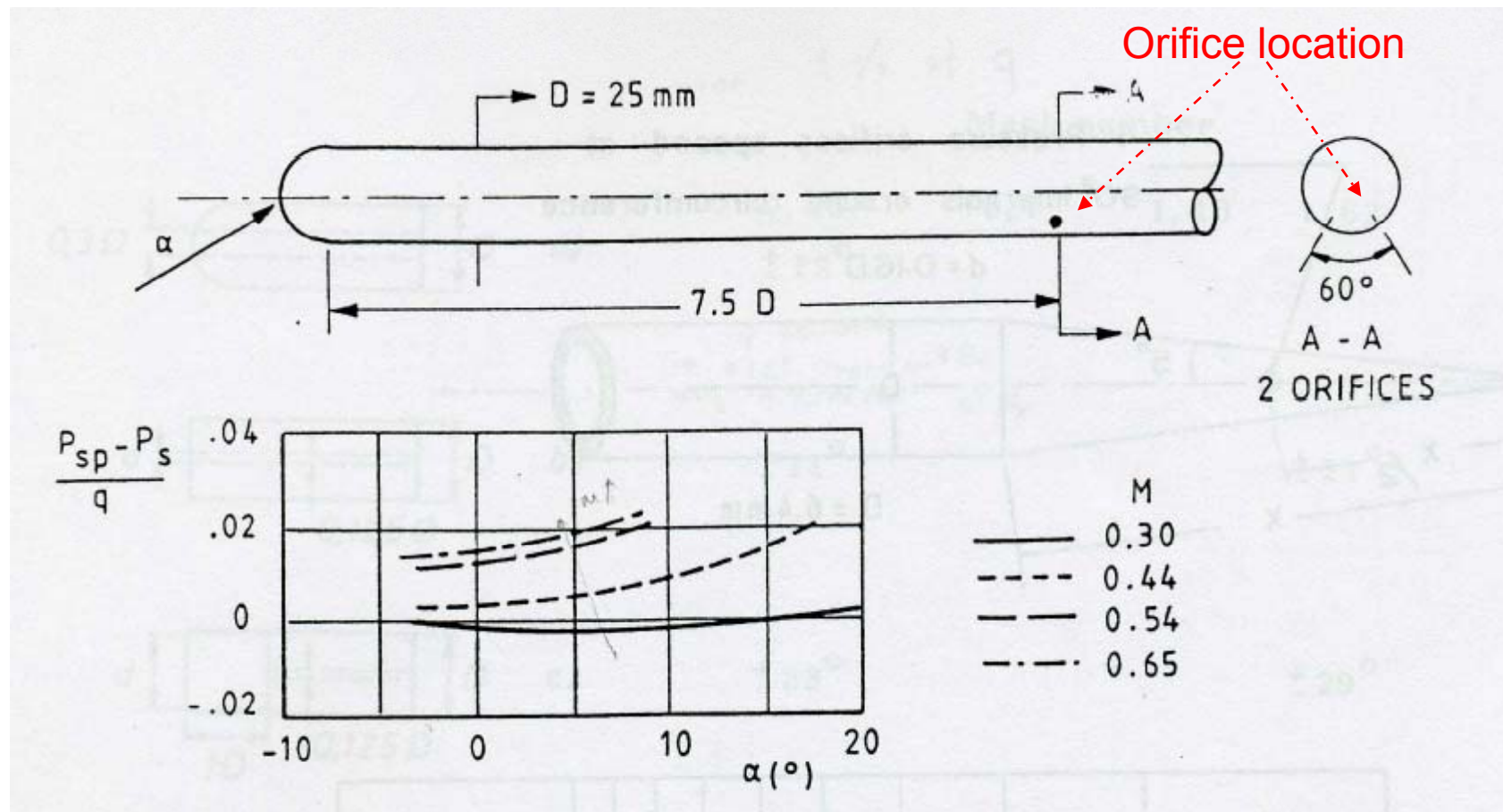


Fig. 1.17 - Effect of incidence on static pressure reading for different circumferential positions of the orifice (J.J. Ginoux, 1964)

Static Pressure Probes

Measurement errors:

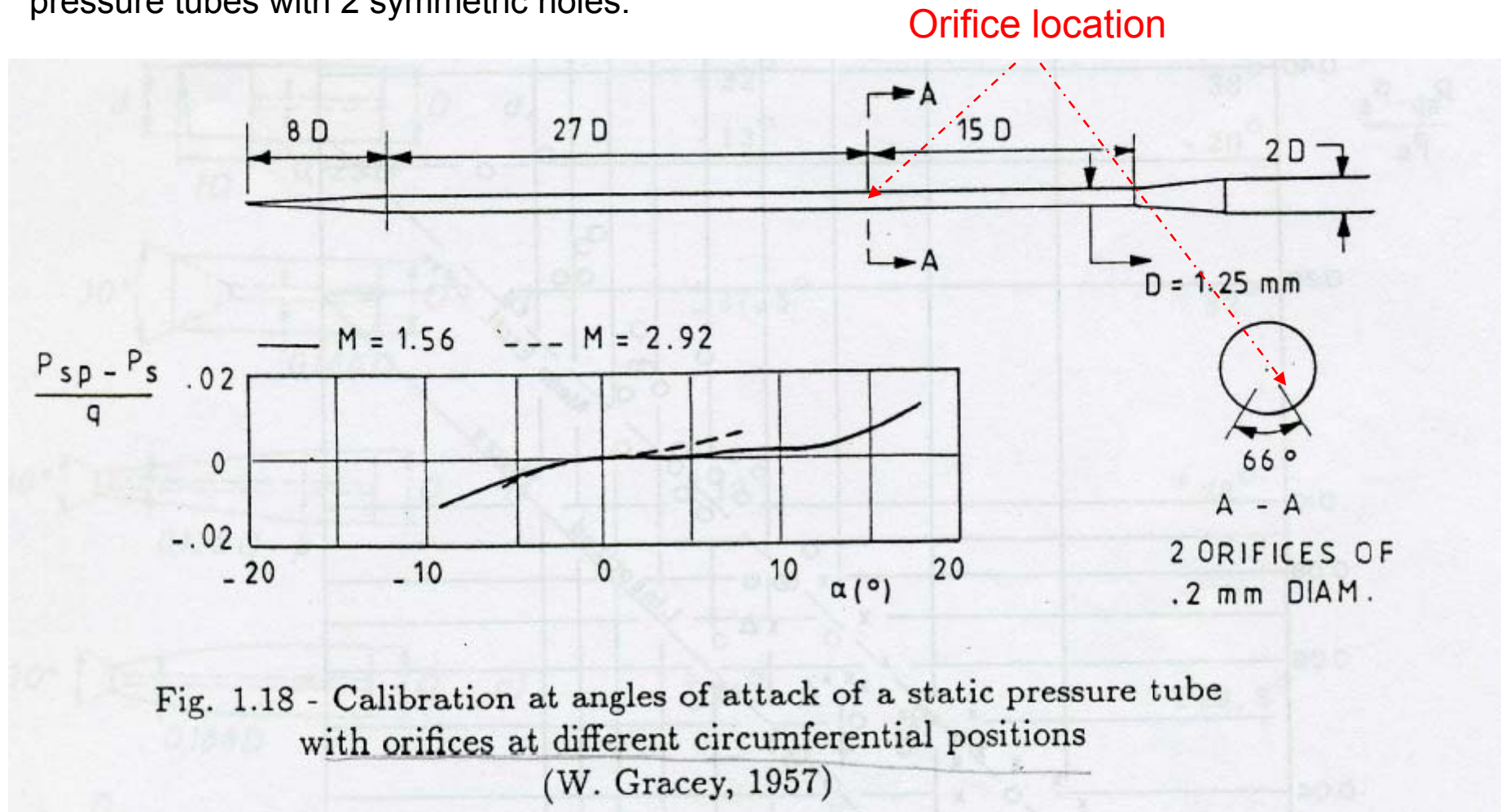
The dependence of the incidence error on free stream Mach number for static pressure tubes with 2 symmetric holes:



Static Pressure Probes

Measurement errors:

The dependence of the incidence error on free stream Mach number for static pressure tubes with 2 symmetric holes:



Static Pressure Probes

Measurement errors:

Incidence insensitive probes have been developed for low speed flows ($M \ll 1$). Static pressures can be measured with errors less than 2% of the dynamic pressure for $\pm 20^\circ$ of incidence angle.

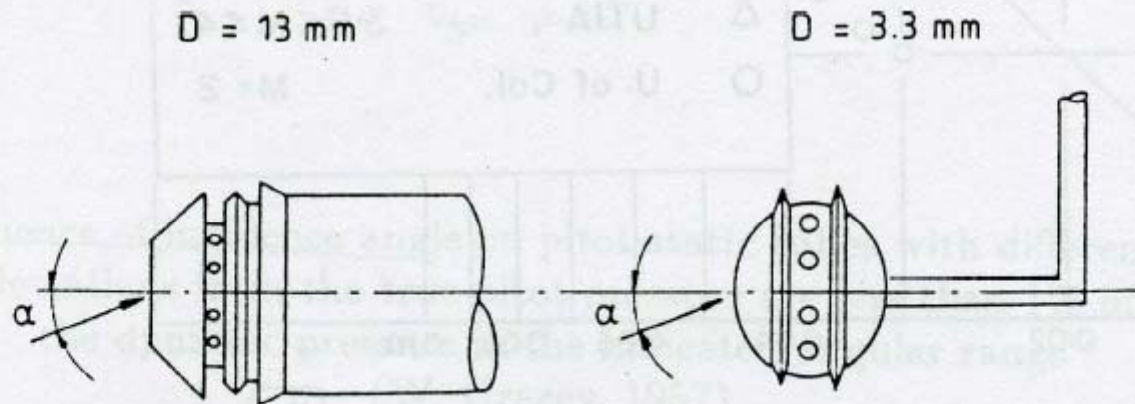


Fig. 1.19 - Static pressure probes with small influence of pitch and yaw angle variation

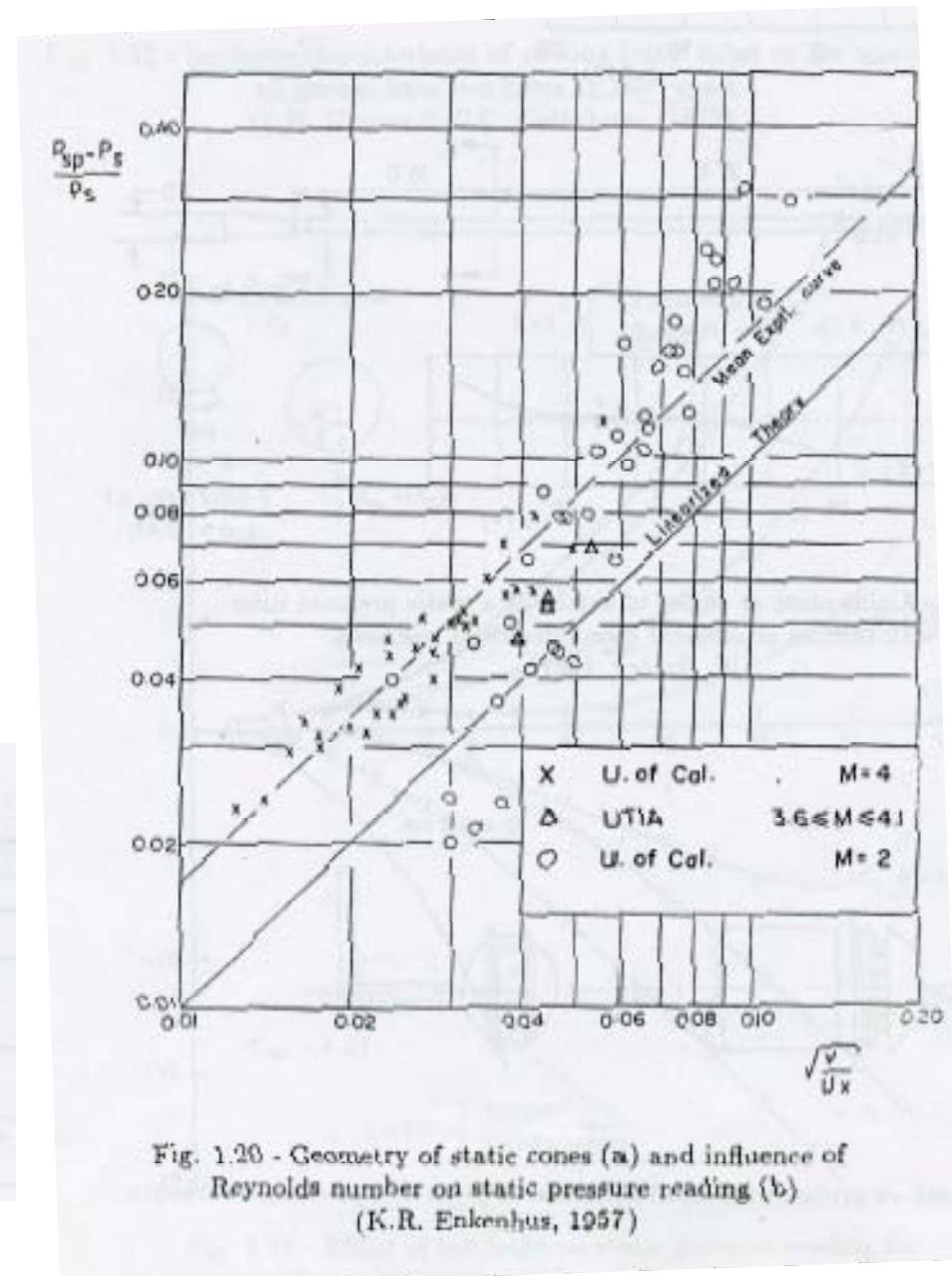
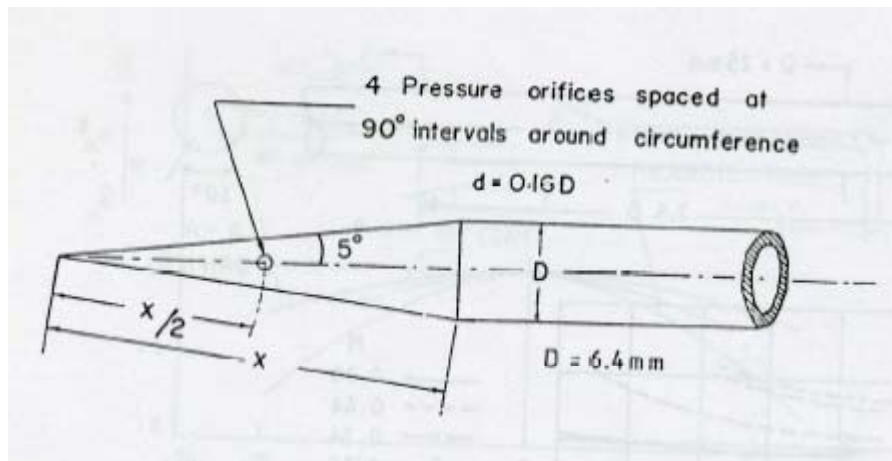
Static Pressure Probes

Measurement errors:

Another source of errors is the boundary layer developing along the probe. This results in a slight change of the nose shape and the cylindrical probe becomes slightly conical.

The measured static pressure is therefore Reynolds number dependent.

Placing the static pressure orifices on the cone will eliminate most of the non-linear effects such as boundary layer separation or upstream influence of the shock boundary layer interaction.



Reading Assignments:

1. Chue S.H. (1975) Pressure probes for fluid measurements. Prog. Aerospace Sciences, Vol. 16, pp. 147-223
2. Shaw R (1960) Influence of hole dimensions on static pressure measurements, J. Fluid Mechanics, Vol. 7, pp 550-564
3. Benedict R.P. and Wyler J.S Analytical and Experimental Studies of ASME Flow Nozzles. Trans. ASME J. Fluids Eng. Sept. 1978 p.265

Read the papers and prepare a summary presentation of 10 slides for each paper. Each slide should explain a subsection of the paper. The presentations should have a title page, an introduction, results and a conclusion part.

You should perform the homework **alone and make the slides by your own with your **own words**.**

Homework is due to 6 November 2009 Friday until 14:30.

No later submission will be accepted.

Please bring your homework earlier rather than waiting last minutes.

There will be additional class on 5.11.2009 at 18:00.

Each group will present an introduction to the class for the project work and lab work that they will perform.

See the website for the groups and their corresponding labs and projects.