TECHNOLOGICAL UNIVERSITY OF DELFT

DEPARTMENT OF AERONAUTICAL ENGINEERING

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**DETERMINATION OF THE POSITION OF
A SHOCK WAVE FROM
PITOT TUBE EXPERIMENTS**

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Summary.

The displacement of the effective centre of a circular pitot tube from its geometric centre when traversed through a conical shock wave has been measured at a free stream Mach number of 2.94. This displacement, defined with respect to the true shock wave position in the plane of the tube face, was found to be towards the region of higher pitot pressure. For inside to outside diameter ratios $\frac{d}{D}$ between about 0.4 and 0.6, the displacement was approximately proportional to the outside diameter and roughly independent of the inside diameter. The displacement, normalized by the outside diameter, could be expressed as a function of $\frac{d}{D}$; a minimum non-dimensional value of 0.06 was found within a range of $\frac{d}{D}$ between 0.5 and 0.6. For larger values of $\frac{d}{D}$, the bow wave in front of the tube was unsteady when interacting with the incident shock wave. This resulted in a marked increase of the displacement effect and of a more gradual rise of the measured pitot pressure through the shock wave.

Symbols.

D	outside diameter of the pitot tube.
M	Mach number.
d	inside diameter of the pitot tube.
h	distance from the intersection point of incident shock wave and pitot tube bow wave to the pitot tube axis.
m	magnification factor of the optical system.
p_p	pitot pressure.
p_{p_∞}	pitot pressure of the free stream.
s	stand-off distance of the bow shock wave measured at its intersection point with the incident shock wave.
Δ	position of the geometric centre of the tube with respect to the intersection point of the extended incident shock wave with the plane through the tube face.
δ	displacement: defined as the distance, in the plane of the pitot tube face, from the point half way the measured pressure jump to the actual position of the shock wave.
θ_w	angle of incident shock wave with the free stream direction.
σ	standard deviation of the displacement δ .

1. Introduction.

The experiments described in this report have been performed to investigate the position of a shock wave from pitot pressure measurements. The subject has been broached because of ref. 1, where certain difficulties appeared in the interpretation of the results from similar measurements. In ref. 1 the position and shape of a shock wave on the expansion side of a flat delta wing with supersonic leading edges were determined from pitot tube measurements. A conical shock wave was observed normal to the wing surface and curving towards the plane of symmetry of the wing with increasing height above the surface. The measurements of ref. 1 were made by spanwise traverses of a pitot tube of 1 mm outside diameter and 0.6 mm inside diameter. A steep local pressure rise was considered as indicative of a shock wave, and the position of this shock wave was assumed to coincide with the point half-way the measured pressure rise. In some cases, however, it was difficult to distinguish between the pressure rise due to the shock wave and the more gradual pressure rise caused by an adjoining region of flow with pressure gradients. In addition the question arises whether the point half-way the recorded pressure jump corresponds to the shock wave position.

Mainly in order to answer the latter question in a concrete situation, a series of pitot tube experiments have been performed on a known shock wave. As far as known to the authors no such investigations on the displacement of the effective centre of a pitot tube from its geometric centre when entering a shock wave have been reported elsewhere.

The influence of a gradual total head gradient has been investigated in subsonic flow (ref. 2,4) as well as in supersonic flow (ref. 3,4). In low subsonic flows it has been shown (ref. 2) that the effective centre of a pitot tube in a transverse gradient of total head is displaced from the geometric centre towards the region of increasing velocity. Over a range of conditions the displacement appeared to be about $0.18D$, where D is the outside dia-

meter of the pitot tube. Results of pitot tube measurements in supersonic flows have been reported in ref. 3. These experiments were conducted in the wake of a wedge aerofoil at a free stream Mach number of 1.96. In ref. 3 pitot tubes were used of large size compared with the dimensions of the wake ($D = 0.72"$, wake width $0.1"$). However, no displacement effect as found in ref. 2 could be detected.

To investigate the displacement effect over a wide range of Mach numbers and tube diameters, a number of tests have been carried out in ref. 4. These experiments also included subsonic speeds. At low speeds, the results of ref. 2 were confirmed for tubes with diameters less than one third of the wake width, whereas at supersonic speeds no convincing relation could be shown to exist. If the tube diameter was larger than three times the maximum wake width, the displacement was towards the region of decreasing velocity and roughly proportional to D^2 , to the ratio of total head measured in the wake to that outside the wake, and to the transverse gradient of this ratio across the tube face. The influence of inside diameter on the results of ref. 4 was found to be negligible.

Pitot pressure measurements across a shock wave can to some extent be compared to measurements in a wake having a maximum width which is small with respect to the tube diameter. In both cases the change in pitot pressure occurs over a small distance compared to the tube diameter.

The experiments described in this report have been made at a free stream Mach number of 2.94 on a shock wave generated by a cone with an apex angle of 30° .

Thirteen different pitot tubes were tested with outside diameters ranging from 1 mm to 4 mm.

2. Description of equipment and experiments.

2.1. Wind tunnel.

The experiments have been performed in the 15 cm x 15 cm

supersonic blow down tunnel of the Department of Aeronautical Engineering. The tunnel has interchangeable nozzle blocks and a free jet chamber immediately downstream of the closed test section. The free jet chamber precedes a fixed diffuser. Dry air is obtained from a 7 m³ cylindrical storage vessel at an initial pressure of 150 kg/cm². During the experiments the stagnation pressure of the tunnel was maintained at approximately 6.75 kg/cm², the exact value being measured with a Statham pressure transducer.

The free stream Mach number was determined from pitot pressure measurements reported in ref. 5.

2.2 Experiments.

The dimensions of the pitot tubes are given in table 2. A cone having an apex angle of 30° and a length of 76 mm was aligned to the flow until the pressure differences between symmetrically disposed pairs of pressure orifices, both in the horizontal and in the vertical plane, were zero (± 0.5 mm Hg).

The Mach number derived from the static pressure measured on the cone surface was in close agreement with that obtained from the calibrations in ref. 5.

The reasons for taking a cone as shock wave generator are twofold. In the first place, the character of this type of shock wave corresponds to that of the inboard shock wave on the expansion side of the delta wing in ref. 1 (a curved shock wave behind which a gradient in pitot pressure exists). Secondly, the determination of this shock wave from a schlieren picture was found to be more accurate than in the case of a flat oblique shock wave such as generated by a wedge. In the latter case, three-dimensional effects made it difficult to obtain the true distance of the pitot tube to the shock wave from schlieren pictures.

The tubes were fitted in the vertical plane through the cone axis. From an initial position parallel to the free stream direction, the pitot tube was moved in discrete steps through the shock wave

as shown in fig. 1. In this way the angle between the pitot tube and the local velocity vector was kept below 5° in any position of the tube. As the initial position was carefully reproduced for each tube, the orifices of all tubes described identical paths. The length of the pitot tubes to the support was always larger than 15 D.

A shadowgraph of a configuration with the tube moved slightly into the shock wave is shown in fig. 2.

To eliminate the influence of a possible time lag, every measuring point has been recorded with the tube stationary. A schlieren system has been used for the determination of the tube position with respect to the incident shock wave. Simultaneously with each pressure measurement a 14 times magnified schlieren picture was recorded by direct projection on photographic paper (0.3 sec. exposure time). The actual position of the tube was measured from the photographs to eliminate errors due to backlash or deflection of the positioning mechanism.

The pressures were measured with strain gauge transducers (Statham, range 0-50 p.s.i.). The analog output was digitised and recorded by a Teletype tape puncher (punching speed 110 digits per sec.).

During the exposure time the pressure was recorded about 10 times, and the average value was then taken as representative for the measuring point. The corresponding pitot pressure of the free stream was measured with a fixed reference tube. The pitot pressure readings were corrected for slight variations of the reference conditions between runs.

3. Results.

The pitot tubes were first tested in the empty test section. All tubes gave identical results within the normal scatter.

Deviations due to viscous effects are expected to be negligible, considering the high value of the Reynolds number based either on free stream conditions or on conditions behind the bow wave

in front of the tube (57,000 per mm and 23,000 per mm respectively).

The pitot pressures have been reduced to the non-dimensional form $\frac{p_p}{p_{p_\infty}}$, where p_p represents the pitot pressure and the symbol ∞ denotes the free stream condition just outside the incident shock wave. In the plane through the tube face the geometric centre of the tube is given by the distance Δ with respect to the intersection of the extended shock wave with this plane. The distance Δ is considered positive when the geometric centre is downstream of the shock wave (see fig. 5). The displacement δ is now defined as the distance, measured in the plane of the tube face, from the position of the observed shock wave on the schlieren picture to the position deduced from the measured pitot pressure distribution, assuming that the latter position coincides with the point half-way the measured pressure jump. From a practical point of view this definition of the displacement is the most useful one.

In figure 3 the measured pitot pressures are given as a function of the distance Δ . Also given is the theoretical pitot pressure distribution downstream of the cone shock wave at the location of the tube face if no distortion due to the tube would be present. The calculations were carried out using ref. 6.

Fig. 4 shows the displacement, relative to the outside diameter, as a function of the ratio $\frac{d}{D}$. Also given in this figure are two curves showing the deviation obtained if, instead of the point half-way the pressure jump, different pressure levels are considered.

Typical schlieren pictures have been selected in fig. 6, 7 and 8. Fig. 6 shows the pitot tube having the smallest outside diameter (1 mm) and fig. 7 a pitot tube with an outside diameter of 4 mm. Fig. 8 shows a tube having an unstable bow wave at certain conditions, in the present investigation $D = 3.4$ mm, $d/D = 0.885$.

4. Discussion.

4.1 The pitot pressure distribution measured across the shock wave.

The determination of the shock wave position from a measured

pitot pressure distribution provides some difficulty in the case of a conical shock wave if the theoretical pitot pressure distribution is not known. In that case no distinction between a shock wave and a gradual compression can be made.

With increasing values of the ratio $\frac{d}{D}$ the calculated and measured pitot pressure distributions downstream of the cone shock wave coincide at the smaller positive values of Δ . Also the distinction between shock wave and gradual compression is easier. Tubes having $\frac{d}{D}$ values larger than about 0.5 show, in the region downstream of the shock wave, measured pitot pressures exceeding the theoretical values.

As the measured pitot pressures are determined by conditions immediately behind the intersection of the incident shock wave and the tube bow wave, it might be argued that these pressures should be correlated to the position of the intersection point. However, as has been emphasised earlier, the purpose of the underlying experiments is to investigate the discrepancies that arise between the actual and the measured shock wave position in the plane of the tube face.

The pitot pressure plottings in fig. 3 show local deviations from a smooth curve, where local changes of slope occur. These changes occur at approximately the same relative position of the tubes, so it seems unlikely that they emanate from disturbances in the free stream or are due to irregularities in the adjusting mechanism. Moreover, one of these more or less discontinuous pressure rises may be noted for practically all tubes in the final stage of the pressure change across the shock wave. This phenomenon emerges very clearly for the tube having the highest $\frac{d}{D}$ ratio (0.885), as shown in fig. 3e. In this case the bow wave in front of the tube appears to start oscillating as soon as the pitot pressure rises above the free stream value. This is clearly indicated by the schlieren pictures of fig. 8. The unstable situation becomes first noticeable for tubes of $\frac{d}{D}$ ratios of 0.673 ($D = 3$ mm, $d = 2$ mm nominal).

To what extent the instability is connected with the noticed local pitot pressure rise is by no means clear, because this same local pressure rise occurs also for tubes having a ratio $\frac{d}{D}$ smaller than 0.673 for which the tube bow wave was steady. It seems probable that the instability is connected with the geometry of the tubes, but the restricted scope of the present investigation does not allow to discard a possible influence of the properties of the incident shock wave and of the wind tunnel flow.

4.2 Direction and magnitude of the displacement.

The experiments have been restricted to one Mach number and one type of incident shock wave. Thus, no general rules concerning the displacement can be given. Nevertheless the obtained results provide some insight in the magnitude and direction of the displacement effect. In the present case the point at $\frac{p_p}{p_{p\infty}} = 1.175$ (roughly corresponding to the point half-way the pitot pressure jump) is taken as representing the position of the shock wave as derived from pressure measurements. The direction of the displacements δ of the effective centre of the tube is then towards the region of higher pitot pressure as shown in fig. 3. The effect of the outside diameter (with constant inside diameter) emerges clearly from this figure. It appears to have an almost linear influence on δ , although this relationship is disturbed for those tubes having an unsteady bow wave.

It is possible to express the relative distance $\frac{\Delta}{D}$ as a function of $\frac{d}{D}$ only. This is shown in fig. 4 for three pitot pressure levels, including the pressure level half-way the pressure jump which was used to define the relative displacement δ/D . This figure shows that the trajectory relative to D , in which the pressure rise through the shock wave is measured, increases with the ratio $\frac{d}{D}$. The curve representing the relative displacement $\frac{\delta}{D}$ shows only a slight variation of $\frac{\delta}{D}$ for $\frac{d}{D}$ ratios between 0.4 and 0.6, which indicates that the dependence of the inside diameter (with constant outside diameter) is rather small.

This is not the case for $\frac{d}{D}$ ratios outside the interval mentioned, where the influence of the inside diameter cannot be neglected. The latter result is not in agreement with the results of the measurements in a supersonic wake reported in ref. 4, where no influence of the inside diameter could be detected at all.

The minimum relative displacement is found to be about $0.06 D$ at $\frac{d}{D}$ ratios between approximately 0.4 and 0.6 . The most suitable pitot tube at the underlying measuring conditions has to be selected within this interval of $\frac{d}{D}$ values. In general, when using a certain pitot tube for this kind of measurements, it is recommendable to verify whether unsteady phenomena occur, and if so, at which values of $\frac{d}{D}$. The possibility may not be precluded that under different conditions these phenomena do not occur and that a further decrease of the displacement may be obtained.

4.3 Qualitative considerations about the nature of the flow field in front of the tube.

As yet only a qualitative consideration about the flow pattern in the region between the bow wave and the tube face can be given. This consideration will be based on observations from the schlieren pictures. In the following discussion we exclude the situations where unsteady phenomena appear.

The pictures of fig. 7 show typical examples of the shock wave pattern. For clarity, the flow field near the face of the tube has been sketched in fig. 5. In the vicinity of the intersection point I the bow wave in the region downstream of the incident shock wave shows a strong curvature towards the tube, adapting the conditions in the immediate vicinity of I. This curvature appears for not too large values of h , the vertical distance between the tube axis and the intersection point. As h increases, the curvature diminishes and finally disappears when h is larger than about $0.3 D$. From the schlieren pictures it may be seen that for h exceeding this value, the bow wave in the region downstream of the incident shock wave

has lost its normal shock wave nature. For the smaller values of h it may still be considered as a normal shock wave of the very part in the vicinity of the intersection point is excluded. These two forms of the bow wave behind the incident shock wave are accompanied by different shapes of the slipstream emanating from the intersection point towards the tube face (see fig. 7). For the higher values of h the slipstream tends towards the edge of tube (fig. 7a). In this case a pitot pressure is measured corresponding to the free stream value. In fig. 7b the slipstream hits the rim of the tube (inwards of the edge), yet the measured pitot pressure is still equal to the free stream value. In fig. 3c it may be seen that the rise of pitot pressure starts at a Δ value of about 0.3 mm, nearly corresponding to the value of 0.27 mm in fig. 7c.

The photograph of fig. 7d shows the situation at the moment when the measured pressure rise has just been completed, see also fig. 3c.

The shape of the slipstream and the position where it hits the tube face seem to determine the measured pitot pressure. Due to the strong curvature of the slipstream towards the region of lower pitot pressure, a higher pitot pressure is measured than would be expected from the position of the intersection point of two shock waves. With respect to the intersection point this means a deviation of the effective centre of the tube towards the region of lower pitot pressure. In fig. 3a the position of Q (Q being the projection of the intersection point I on the tube face, see fig. 5) is indicated by a dotted line, for the tube having an outside diameter of 4 mm. The absolute value of the displacement δ is therefore less than the distance QS (see fig. 5), where S is the intersection of the extended incident shock wave and the tube face. QS is equal to $s \tan \theta_w$, where s is the stand-off distance of the bow wave and θ_w the angle of the incident shock wave with respect to the free stream direction. As the stand-off distance s varies with the position of the intersection point I , an average value has

been taken of 0.38 D. With $\theta_w = 25.3^\circ$, QS turns out to be about 0.18 D.

Summarising, it appears from a simple consideration of the phenomena observed in front of the tube, that the problem is entirely different from that arising in the case of strong velocity gradients not generated by shock waves (ref.3,4).

To give general rules concerning the behaviour of a pitot tube traversing through shock waves would require a more extensive investigation involving more variables such as different strengths and angles of the incident shock wave and different free stream Mach numbers. Such an investigation might also throw more light on the occurrence of an unsteady bow wave as found in this experiments for tubes of fairly large d/D ratios.

5. Measuring errors.

5.1 Accuracy of the measurements.

It is important to know what errors may arise in the different steps obtaining p_p/p_{p_∞} and δ .

The inaccuracies in the measurements have been determined by measuring the same quantity a number of times and defining the inaccuracy as the bandwidth containing 90 % of all deviations from the mean value. The results of this procedure are listed in table 1. The inaccuracy in pitot pressure is made up of an error of 0.7 % due to the pressure transducer and an error of 0.3 % due to the digital instrumentation. The position of the incident shock wave with respect to the centre of the tube face was determined by measuring the black-white gradation on the schlieren pictures. Inside the shock wave image, which appears as a band of about 1 mm width on the picture (about 14 times real size), a dividing-line between a bright and a less bright region could be observed and its position measured to an accuracy of within 0.3 mm. In the same way the edges of the tube image were determined, giving the centre

within 0.3 mm. As to how far the dividing-line corresponds to the real shock wave position cannot be checked. A misinterpretation due to this uncertainty is a typical systematic error which does not belong to the random measuring errors.

The position of the extended incident shock wave on the tube face involves an additional error within 0.3 mm. It was found that the reading apparatus, which was used to measure the distances on the pictures, was accurate within 0.1 mm.

Finally the magnification factor of the optical system, as checked by calibrations, could only be determined within 0.7 %.

5.2. Standard-deviation of δ

In the following an estimate will be made of the standard-deviation σ of the displacement δ (δ is defined in section 3). It has been assumed that the measuring errors occur according to a normal distribution. Given the fact that 90 % of all errors fall within certain limits (e.g. the 90 % confidence limit), it is possible to calculate standard deviations due to each error separately and due to the combined error distribution, this has been done following ref. 7. According to the theory of the normal distribution the combined standard-deviation is found by taking the r.m.s. value of the separate standard deviations (ref. 7).

The calculation of the errors in δ proceeds as follows, using table 1 for the evaluation of the errors.

1. An error in p_p contributes to the error in δ as given by

$$\Delta \delta = \frac{d\delta}{d(p_p/p_{p\infty})} \cdot \frac{\Delta p_p}{p_p} \cdot \frac{p_p}{p_{p\infty}}, \quad (1)$$

where Δ denotes the deviation of the quantity from its mean value.

2. An error in p_{p_∞} results in

$$\Delta \delta = - \frac{d\delta}{d(p_p/p_{p_\infty})} \frac{\Delta p_{p_\infty}}{p_{p_\infty}} \frac{1}{p_p/p_{p_\infty}} \quad (2)$$

As the displacement δ is obtained from the measured position on the schlieren picture, given by

$$\delta = \frac{S-M}{m}$$

where S is the position of the incident shock wave at the tube face with respect to the geometrical centre M of the tube and m represents the optical magnification factor ($m = 13.95$), the following three errors may be involved.

3. An error in S , giving

$$\Delta \delta = \frac{\Delta S}{m} \quad (3)$$

4. An error in M , resulting in

$$\Delta \delta = \frac{\Delta M}{m} \quad (4)$$

5. Finally the error in δ due to an inaccuracy of m becomes

$$\Delta \delta = \delta \frac{\Delta m}{m} \quad (5)$$

In the expressions (1) to (5) $\frac{d\delta}{d(p_p/p_{p_\infty})}$ and δ may be obtained from fig. 3, taking the mean value for $\frac{d\delta}{d(p_p/p_{p_\infty})}$

In table 2 the calculated standard-deviations of the displacement

δ are given with respect to the outside diameters of the pitot tubes. It may be seen that, except for the last tube, the standard-deviation itself is quite constant due to the dominating effect of the errors which may occur in the measurements from the schlieren pictures.

6. Conclusions.

The conclusions of the present investigation may be stated as follows:

1. All tubes show a displacement towards the higher pitot pressure, the magnitude of the displacement being closely related to the outside diameter D and the inside-outside diameter ratio $\frac{d}{D}$.
2. For $\frac{d}{D}$ ratios between 0.4 and 0.6 the displacement is roughly independant of the inside diameter and proportional to the outside diameter of the tube.
3. The minimum relative displacement $\frac{\delta}{D} = 0.06$ occurs at $\frac{d}{D}$ between 0.5 and 0.6.
4. Tubes of large $\frac{d}{D}$ ratios (larger than 0.6) show oscillations of the bow wave when passing through the incident shock wave. This phenomenon is coupled to an increase of the relative displacement $\frac{\delta}{D}$. Also, the pressure rise through the shock wave is spread out over a greater lenght of travel of the pitot tube.

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7. References

1. Bannink, W.J.,
Reyn, J.W. and
Nebbeling, C.
Investigation of the flow field
on the expansion side of a delta
wing with supersonic leading
edges,
Report VTH-128, Technological
University Delft, Department of
Aeronautical Engineering,
August 1965.
2. Young, A.D. and
Maas, J.N.
The behaviour of a pitot tube in
a transverse total-pressure
gradient, R. & M. No. 1770.
Aeronautical Research Committee,
London, September 1936.
3. Johannesen, N.H. and
Mair, W.A.
Experiments with large pitot tubes
in a narrow supersonic wake,
Journal of the Aeronautical
Sciences, vol. 19, no. 11,
p. 785, November 1952.
4. Marson, G.B. and
Lilley, G.M.
The displacement effect of pitot
tubes in narrow wakes,
CoA Report No. 107, the College of
Aeronautics, Cranfield, Oktober 1956.
5. Bannink, W.J.
The Mach number distribution in a
part of the test section of the
supersonic wind tunnel no. 2 at a
design Mach number of 3,
Memorandum M 75; Technological
University Delft, Department of
Aeronautical Engineering, 1963
(in Dutch).

6. Sims, J.L.

Tables for supersonic flow around
right circular cones at zero angle
of attack,

NASA SP - 3004, 1964.

7. Parratt, L.G.

Probability and experimental
errors in Science,

John Wiley and Sons, inc. New York
1961.

a. Pitot pressure p_p , $p_{p\infty}$

Errors due to inaccuracies in

1. pressure transducer : ± 0.7 % of full scale.
2. digital instrumentation : ± 0.3 % " " " .

b. Position of the incident shock wave at the tube face

Errors due to inaccuracies in

1. the measured position of the shock wave on the schlieren picture : ± 0.3 mm on the picture.
2. the position of the extended shock wave at the tube face : ± 0.3 mm " " " .
3. the calibration of the reading apparatus : ± 0.1 mm " " " .

c. Position of the geometrical centre of the tube face

Errors due to inaccuracies in

1. the measured position of the centre on the schlieren picture : ± 0.3 mm on the picture.
2. the calibration of the reading apparatus : ± 0.1 mm " " " .

d. Inaccuracy of the optical magnification factor: ± 0.7 %

Table 1. Inaccuracies in the various quantities.

$\frac{d}{D}$	d	D	$\frac{\sigma}{D}$
	mm	mm	%
0.153	3.99	0.61	0.6
0.201	2.99	0.60	0.8
0.253	3.99	1.01	0.6
0.294	2.04	0.60	1.2
0.338	2.99	1.01	0.8
0.405	3.98	1.61	0.7
0.506	3.99	2.02	0.7
0.517	2.03	1.05	1.2
0.537	3.00	1.61	0.8
0.597	1.01	0.60	2.4
0.673	3.00	2.02	0.9
0.805	2.00	1.61	1.3
0.885	3.39	3.00	1.5

Table 2 Standard-deviation of the displacement δ .

Fig.1: Position of the pitot tube

Fig. 2: Shadowgraph of test set-up

Fig. 3a: Normalised pitot pressure distributions through a shock wave generated by a cone of 30° apex angle at $M = 2.94$.

Fig. 3b: Continued

Fig. 3c: Continued

Fig. 3d: Continued

Fig. 3 e: Concluded

Fig. 4: Variation of the relative distance $\frac{\Delta}{D}$ with the inside-outside diameter ratio.

Fig. 5: Sketch of phenomena visible on a schlieren picture for a typical position of the tube.

a. $P_p/P_{p_\infty} = 1,000$
 $\Delta = - 0.214 \text{ mm}$

b. $P_p/P_{p_\infty} = 1,176$
 $\Delta = 0,071 \text{ mm}$

c. $P_p/P_{p_\infty} = 1,341$
 $\Delta = 0.208 \text{ mm}$

d. $P_p/P_{p_\infty} = 1,351$
 $\Delta = 0.419 \text{ mm}$

Fig. 6: Pitot tube : $D = 1 \text{ mm}$, $d = 0.6 \text{ mm}$ (nominal)

a. $p_p/p_{p_\infty} = 1.001$
 $\Delta = -0.603 \text{ mm}$

b. $p_p/p_{p_\infty} = 0.999$
 $\Delta = -0.426 \text{ mm}$

c. $p_p/p_{p_\infty} = 1.158$
 $\Delta = 0.271 \text{ mm}$

d. $p_p/p_{p_\infty} = 1.344$
 $\Delta = 0.656 \text{ mm}$

Fig. 7 : Pitot tube : $D = 4 \text{ mm}$, $d = 1.6 \text{ mm}$ (nominal)

a. $P_p/P_{p_\infty} = 1.000$
 $\Delta = -0.525 \text{ mm}$

b. $P_p/P_{p_\infty} = 1.030$
 $\Delta = -0.275 \text{ mm}$

c. $P_p/P_{p_\infty} = 1.299$
 $\Delta = 1.115 \text{ mm}$

d. $P_p/P_{p_\infty} = 1.385$
 $\Delta = 1.156 \text{ mm}$

Fig. 8 : Pitot tube : $D = 3.4 \text{ mm}$, $d = 3 \text{ mm}$ (nominal)