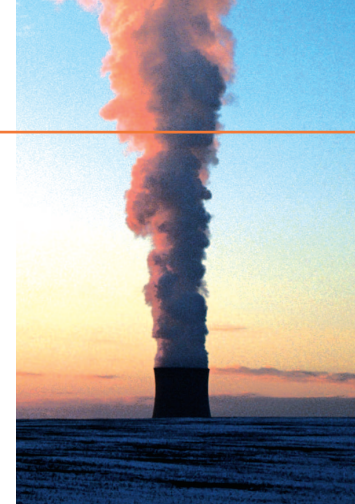


Problems with Pitots

ISSUES WITH FLOW MEASUREMENT IN STACKS



AIR Monitoring

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Question-AIR

This regular feature provides information relating to standards, requirements and technical snippets relating to emission monitoring. If there are any questions relating to air emission monitoring contact the Source Testing Association by email, air.answers@s-t-a.org.

Reliable and accurate measurements of gas flows in stacks underpin the monitoring of emissions. However, flow measurement has often been the poor relation in stack sampling. The measurement of flow has significant impact on stack emissions monitoring in a number of ways. In addition to enabling concentration measurements to be converted to emission fluxes, flow measurement is also necessary to demonstrate that the gas flow profile in the stack meets the requirements of the method. The most routinely used stack and duct gas flow monitoring techniques are based on the use of Pitot tubes. Pitot tube measurements are also used to enable isokinetic sampling to be achieved and verified. Issues with Pitot tube measurements can therefore result in significant errors in reported emissions.

It is often assumed that if a suitable Pitot tube is used, conforming to a recognised model, then the measurements will be fit for purpose. However, an increasing number of issues have been raised concerning potential measurement failures under a range of conditions. These include issues such as wall effects and the performance of Pitot tubes at high temperatures. In response to these concerns, the UK Department of Trade and Industry (DTI) has funded a project under its flow research programme to investigate potential flow measurement issues related to emissions monitoring [1]. This work is being carried out by the National Physical Laboratory, in collaboration with the Source Testing Association and Littlebrook Calibration and Manufacturing Ltd.

The aim of the project is to identify key issues related to the measurement of flow in emissions monitoring that have a practical impact on stack emissions monitoring. The principle aim is to review the potential measurement problems with the use of Pitot tubes. However, the project is also addressing issues with the measurement of the sampled gas volume. In most manual sampling methods it is necessary to measure the volume of sampled gas, using either a dry or wet gas meter.

The work programme has involved a detailed technical study of the current situation with regard to flow measurements. A key aspect was a survey of industrial operators, stack testers, instrument manufacturers and regulators to assess current issues and requirements. The outputs of this broad study have been reviewed and assessed to identify the key measurement areas with the greatest impact.

Flow measurement requirements

Pitot tube flow measurements are required by many sampling methods to characterise duct flows. For isokinetic sampling methods, Pitot measurements are required to achieve and demonstrate isokineticity [2]. Stack flow measurements are used to relate concentration measurements to mass emissions for regulatory purposes and will support future emissions trading schemes.

As legislative limits are lowered and European directives impose more rigorous data quality objectives, the requirements for the accuracy and traceability of flow measurements in stacks will increase [3].

Overview of Pitot tube measurements

The basic operation of a Pitot tube is described in Figure 1.

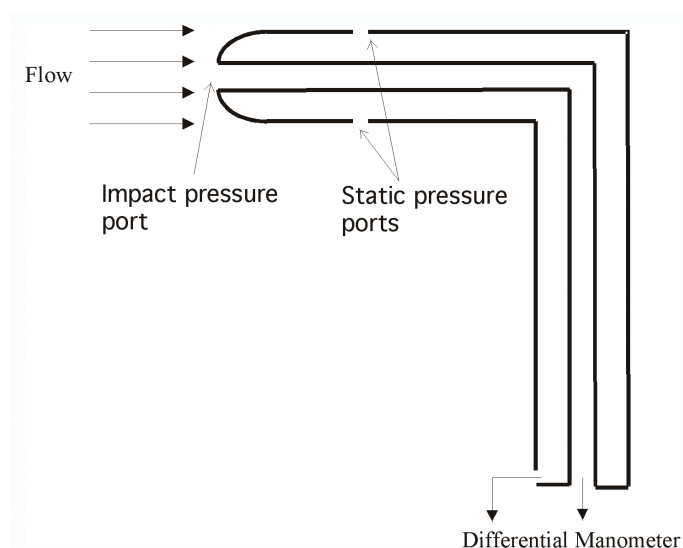


Figure 1: Basic operation of a Pitot-static tube.

The gas flow is calculated from the measurement of the differential pressure between the direct flow pressure and the static pressure ports. The type of Pitot tube used in emissions monitoring is more correctly known as a Pitot-static tube because the static pressure is also measured within the same measurement head [4].

Two key international standards underpin the use of Pitot tubes in stack emissions monitoring. The standard Pitot was defined in the international standard ISO 3966-1977, 'Measurement of fluid flow in closed conduits, Part 2 Velocity area methods, Section 2.1 Method using Pitot static tubes' [5]. This standard has been withdrawn but it is still published as British Standard BS1042 Part 1. The standard defines a measurement method using standard L-Type Pitot tubes, and defines the standard Pitot tube by detailing its construction. It places design tolerances and operational limitations on standard Pitot tubes. This standard was not developed specifically for stack emissions monitoring applications and limitations in the use of standard Pitots in stack conditions, particularly with respect to dust laden flows, led to the development of a further standard specifically aimed at the measurement of non-turbulent flow from stationary source emissions. This standard, ISO 10780 'Stationary Source emis-

sions – Measurement of velocity and volume flow-rate of gas streams in ducts" [6], references ISO 3966-1977 to provide the standard or reference Pitot tube, but also describes the construction and use of S-Type Pitot tubes (Figure 2) and specifies how these should be calibrated against the Standard Pitot. It gives requirements and guidance on the design and use of both the L-type and S-Type Pitot tubes.

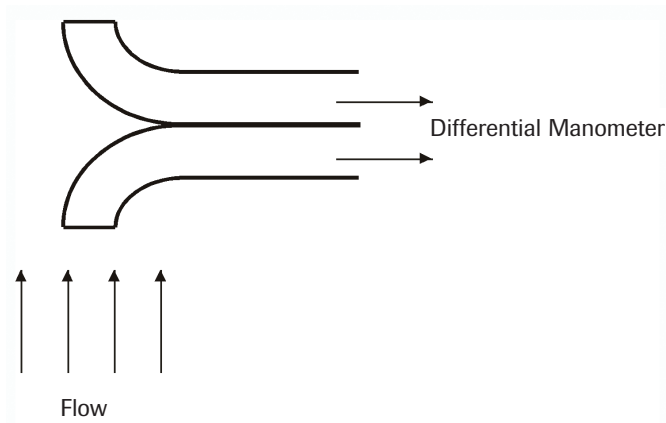


Figure 2: The S Type Pitot tube.

Pitot tube theory

The operation of the Pitot tube is dependent on a fundamental theory of fluid flow, which states that in a steady state, closed system, there is conservation of energy along a flow line. This was first described by Daniel Bernoulli in the 18th Century. The Bernoulli equation describes a non-turbulent, perfect, incompressible, and barotropic fluid undergoing steady motion. A number of forms of the equation can be derived, depending on assumptions and simplifications made about the fluid flow. One of the common forms of Bernoulli's Equation used for Pitot tube measurements is:

$$\frac{V^2}{2g} + \frac{p}{\rho g} = C \quad \text{Eq.1}$$

where:

- V is the velocity of the fluid;
- p is the pressure of the fluid;
- r is the density of the fluid;
- g is the acceleration due to gravity;
- C is constant over a streamline.

This form of the Bernoulli equation assumes that the fluid is incompressible, non-viscous, there is no change in height between points P1 and P2 (see Figure 2), and the temperature is constant. In the case of a Pitot-static tube, the streamline that impacts directly on the nose of the Pitot tube is brought to zero velocity. This point, P2, is called the stagnation point.

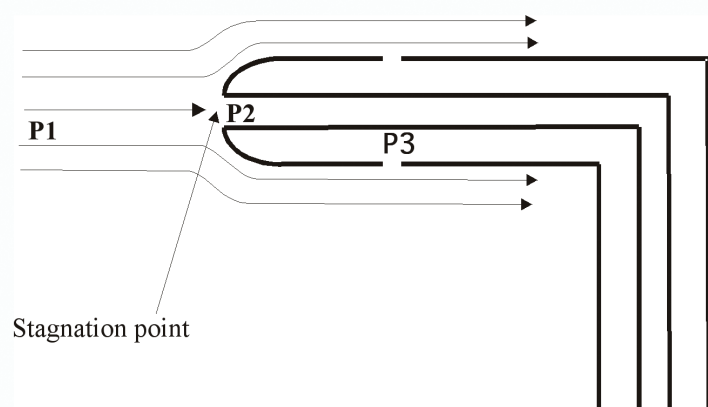


Figure 2

Applying Equation 1 to two points, P1 and P2, along a single stream line gives:

$$\frac{V_1^2}{2g} + \frac{p_1}{\rho g} = \frac{V_2^2}{2g} + \frac{p_2}{\rho g}$$

Point 2 is at the stagnation point, $V_2 = 0$, the above equation reduces to:

$$\frac{V_1^2}{2g} + \frac{p_1}{\rho g} = \frac{p_2}{\rho g}$$

Therefore the velocity of the fluid can be obtained from:

$$V = \sqrt{\frac{2\Delta p}{\rho}} \quad \text{Eq. 2}$$

where:

- Δp is the dynamic pressure, which is the pressure difference between the stagnation pressure tap and the static pressure tap.

Equation 2 is applicable to 'standard' Pitot tubes. It is assumed that the Pitot tube correctly produces the conditions assumed at P1 and P2, ie that the flow line at P1 is stagnant and the pressure measured at P3 is representative of the static pressure in the flowing gas at P2. It is also assumed that the design of the Pitot allows the transfer of these pressures to the differential pressure measurement device used to record Δp .

In practice Pitot tubes used in the field are not standard Pitot tubes, and it is necessary to calibrate them against a reference standard Pitot tube. Equation 2 is modified to add an additional term, G, the calibration factor, which is used to relate a non-ideal Pitot tube to an ideal (Standard, L-Type) Pitot. This calibration factor, defined in ISO 10780, is assumed to correct all the deviations caused by the non ideal Pitot design. There is significant evidence (including personal experience of the authors and A Leonard, private communication) to indicate this is not always the case.

Limitations to the use of Pitot tubes.

Most if not all of the fundamental assumptions when applying Bernoulli's equation to stack gas flow measurements are not strictly valid. In many cases this does not have significant impact on the results. However, it should be noted that the impact of the breakdown of these assumptions has not been fully investigated experimentally in the scope of stack gas measurement and it is therefore difficult to assess their impact. The various assumptions and their validity are discussed in the following sections:

Deviations from the same flow line assumption

Bernoulli's equation applies to different regions along the same flow line. The two pressures measured in a Pitot tube are not directly on the same stream line. It must therefore be assumed that the static pressure measured at the side ports of the L-type Pitot, or at the downstream orifice of the S-type Pitot, is representative of the static pressure of the stagnated flow line. However, the two pressure sampling points are close enough to allow an assumption that, under reasonably non-turbulent flow, the measured static pressure is appropriate for the upstream stagnated flow line. This does also assume constant stack gas velocity with height through the vertical region in which the Pitot is positioned.

It is also a consequence of the requirement for flow lines that the flow be non turbulent, a requirement which is often not the case in typical industrial stacks. The required conditions on the stack flow, in terms of the Reynolds number, may well be met theoretically, based on stack diameter and average flow. However, actual conditions in the stack, such as obstructions, complex flow conditions, pulsed flow from fans, and the sample probe itself, may well cause the flow to become highly unstable and non-laminar.

Air viscosity

The equation assumes that there is no dissipation of energy within the stream line due to viscous forces. The viscosity of air is small, but is not zero, and under certain circumstances this could have an impact on the Pitot measurements. It is unclear whether the presence of significant levels of dust and water vapour will significantly affect the operation of Pitot tubes in industrial stack environments.

Air compressibility

The compressibility of the fluid starts to have a significant effect when the velocity is greater than 30% of the speed of sound in the fluid (a Mach number of 0.3). Such velocities will not generally be found in stack conditions. If the velocity is approaching 30% of the speed of sound then the compressibility of the fluid can be corrected for. The ISO flow standard describing Pitot measurements in a closed duct requires the Mach number to be less than 0.25. The standard also provides a correction factor to take account of compressibility when calculating the velocity. The largest correction factor given in the standard is >0.98 , which implies this is not generally a significant source of uncertainties.

Deviations from the assumption of a perfect gas

In stack conditions the gas can rarely be considered a perfect fluid. It will often have significant levels of water vapour and dust. In addition the water vapour and some other pollutants will be present in multiple phases. There is little evidence of experimental investigations of the effects of dust and water vapour on the Pitot tube calibration.

Deviations from steady temperature conditions

Bernoulli's equation only applies under steady state conditions. Therefore the Pitot tube should be left in the stack long enough for thermal equilibrium to occur between the 'hot' stack end of the Pitot and the 'cold' pressure measurement end. If a non stable temperature gradient is set up then the measurement of dynamic pressure will potentially be in error. If temperature differences occur between the two pressure tubes in the Pitot, then the gas in these will have different densities, which may lead to further errors. This is another area where further experimental investigation is required.

Deviations from steady flow conditions

The derivation of the Pitot equation, Eq.1 assumes that the flow is steady over time. In many stacks this is not the case due to process conditions and abatement technologies, for example dust extraction equipment and wind breaks.

Measures to overcome the limitations

The ISO standards 3966 and 10780 recognise the difficulties in obtaining valid measurements with Pitot tubes in industrial stack conditions and place a large number of restrictions on the use of Pitot tubes in an attempt to control these:

- Mechanical design tolerances on the construction of the Pitot
- Non viscous fluids
- Fluid velocity less than Mach 0.25
- Steady flow without turbulence or velocity gradient, although ISO 3966 recognises that both are present in all ducted flows, and provides procedures to estimate the magnitude of the consequent errors. The standard states that turbulence leads to an overestimation of velocity.
- Limit on size of Pitot relative to duct size to reduce stem blockage
- Differential pressure measurement device to have an uncertainty of less than 1%
- Reynolds number based on the diameter of the total pressure hole at the tip of the Pitot to be greater than 200 for L-type Pitot.
- Reynolds number > 1200 in the stack gas around the Pitot
- Flow velocity 5 m/s to 50 m/s. If the Pitot is to be used outside this range it must be calibrated at the measured flow rate.
- Swirl angle $\leq 150^\circ$.
- No regular or cyclic pressure fluctuations in the gas stream.
- Irregular pressure fluctuations ≤ 25 Pa.
- For circular stacks, measurements shall be made over at least two diameters that are at right angles to each other and the differences between the average velocities across each diameter should not exceed 5% of the mean of all the diameters. If the difference exceeds 5%, additional sampling points shall be taken or a new sampling location selected.
- The internal dimensions of the duct shall be known to within 1% of the duct linear dimensions.
- The duct shall not exhibit any sudden variations in internal diameter for a distance of at least 5 hydraulic diameters upstream and downstream from the plane of measurements.
- A negative flow shall not be present at any point on the cross sectional area where the Pitot is used.
- The absolute temperature at each velocity measurement shall not differ by more than 5% from the average absolute temperature of the duct cross section.
- Density of the stack gas to be 'approximately' the same as that of air.

Pitot tube calibration

The ISO standards contain a calibration procedure for both types of Pitot tube. S-Type Pitots and those L-Type Pitots that do not meet the construction requirements given in ISO 3966 should be calibrated against a standard (L-Type) Pitot that conforms to the requirements of ISO 3966. ISO 10780 states that tubes calibrated according to the procedure given will have an accuracy of 3% for velocities in the region 5 m/s to 50 m/s. If the Pitot is to be used outside these velocities then the standard allows this if the tube is calibrated at the velocity it will be used at. No tolerance is given in the standard for how close the calibration point must be to the measured flow.

The calibration should be carried out in a wind tunnel, under steady flow conditions with a velocity between 11 m/s and 18 m/s steady flow. The flow should be stable to 1% over the calibration period. The blockage of the Pitot tube within the test duct should be less than 3% of the cross sectional area. The calibration is carried out by measuring the differential pressure on the reference L-Type Pitot and the test Pitot three times. The calibration factor K is determined for each pair of differential pressure readings from Eq 3, and the average K is determined as the calibration factor for the Pitot under test.

$$K_{test} = K_{ref} \sqrt{\frac{\Delta p_{ref}}{\Delta p_{test}}} \quad \text{Eq.3}$$

In addition all individual K's determined for the test Pitot must be within 0.02 of the average value for K. A further restriction placed on S-Type tubes is that the K should be determined for both orientations of the tube, with first one leg pointing into the flow, and then the other. The two K's determined shall not differ by more than 0.01. There are significant issues regarding the use of a single calibration factor, determined at roughly 15 m/s, being applied to measurements over a range from 5 m/s to 50 m/s. In addition concerns have been raised on the transfer of calibrations from a relatively small test duct with clean, cool air to the range of conditions typically observed in industrial stacks.

Current practice

A questionnaire was developed and sent out to the STA membership, which represents a comprehensive and representative sample of the emission monitoring community in the UK. The aim of the questionnaire was to obtain a snap shot of the current situation and illustrate the likely impact of the issues discussed above on real measurements carried out in the field. 29 organisations returned the questionnaire, with a total of 360 Pitots being used. Of these 41% were L-Type(Ellipsoidal), and 56% S- Type, the remaining 3% were a small number of other types. From the results of the questionnaire the following observation can be drawn:

- 1) 3.0 m/s minimum flow requirement from ISO 10780 derived from quoted minimum differential pressure of 5Pa
17 organisations (59%) reported measuring flow below 3.0 m/s.
- 2) Minimum 0.07 m² stack cross sectional area requirement from ISO 10780
11 organisations (38%) reported making measurements on stacks with a cross sectional area less than 0.07 m².
- 3) Uncertainty in dynamic pressure measurement

All the participants are using pressure transducers for measuring the differential pressure across the Pitot at the bottom of their range. In many cases the measurement is being made at less than 0.1% of the full-scale range of the pressure transducer.

In addition to the questionnaire and review of the basis of the Pitot measurements this project has also involved a comprehensive review of papers and reports that have investigated Pitot tube performance in Stack emissions monitoring. These include work which was undertaken in the USA forming part of the revision of US EPA Method 2, mainly addressing non axial flow and wall effects. Other papers reviewed include those examining the performance of ISO 10780, investigations into displacement effects, and assessments of Pitot calibrations. The overall conclusion that can be drawn from these reviews is that there are still significant uncertainties in the understanding of Pitot tube performance under extreme stack conditions.

Conclusions

Pitot tubes have the potential to provide measurements of the flow of industrial stack emissions at a suitable level of uncertainty, in a cost effective manner. However, despite their widespread use in the industrial emissions monitoring industry, knowledge of their potential failings and the assumptions implicit in their use is incomplete. A large body of work was carried out during the development of Pitot tubes as measurement devices, but very little in relation to their use in the harsh environment of an industrial stack. Significant quality assurance and quality control has to be applied to the use of Pitot tubes to enable measurements to be made with the required level of uncertainty [7,8,9]. There are a number of aspects where training of the user community is essential if measurement failures are to be avoided.

A key issue that has been identified is that not only are Pitot being routinely used outside of their accepted range, leading to the breakdown of a number of the fundamental assumptions underpinning their use, but that the impact of these failures on the results is not understood. It is therefore proposed that further research into the impact of a number of influences on Pitot tube measurements be carried out, to enable the effects to be quantified under typical and extreme stack conditions.

One area requiring research is the effect of sample temperature on Pitot measurements. The use of a hot wind tunnel and laser Doppler anemometer (LDA) should facilitate this. After a Pitot has been characterised in the hot wind tunnel the LDA could be transferred to a 'hot' stack and an intercomparison made between the Pitot and the LDA.

A further area identified for future investigation is the use of alternative technologies, such as the laser Doppler anemometer, in industrial emissions monitoring.

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