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A Study of the Measurement Issues Associated with the Monitoring of Gaseous Emissions from Industrial Plants.

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A Study of the Measurement Issues Associated with the Monitoring of Gaseous Emissions from Industrial Plants

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ABSTRACT
This final report described the work carried out under the NMSD Invitation to Tender: GBBK/003/00016C for "The study of measurement issues associated with the monitoring of gaseous emissions". The primary aim of this project has been to identify key issues related to the measurement of flow in emissions monitoring. The outputs of the study have been fed into the formulation of the DTI Flow Programme.

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Executive Summary

The work described in this report was carried out for the NMSD, contract GBBK/003/00016C for "The study of measurement issues associated with the monitoring of gaseous emissions" under the Department of trade and Industry's Flow Programme. The project has been delivered by a project team led by the National Physical Laboratory with the Source Testing Association and Littlebrook Calibration & Manufacturing Ltd as sub-contractors.

The primary aim of this project has been to identify key issues related to the measurement of flow in emissions monitoring. There is at present little understanding of the factors which affect the performance of flow measurement techniques in this field. The project has undertaken a detailed technical study of the current issues and requirements with regard to flow measurements including a survey of industrial operators, stack testers, instrument manufacturers and regulators. The outputs of the study identified the measurement areas with the greatest impact on UK industry; the top three areas have been developed into detailed proposals for future work items within the DTI's flow programme.

The measurement of flow has significant impact on stack emissions monitoring in a number of ways. The are four primary requirements for flow measurement;

- Measurement of the volume of sampled gas. This is a requirement for all extractive gas-sampling systems if the concentration results are reported in terms of mass per unit volume.
- Verification that the sampling plane meets stability requirements. It is also necessary to demonstrate that the gas flow profile in the stack at the sampling position meets the requirements of the method being followed.
- Allow isokinetic sampling conditions to be achieved and verified for particulate phase sampling. This has direct impact on monitoring of particulates and other substances for which the particulate phase is sampled, for example metals.
- Enable concentration measurements to be converted to stack emission fluxes.

There are a number of issues, which can potentially affect the competency of the measurements. The principle flow measurement technique used for manual sampling within the UK is based on measurements using the Pitot tube. This technique is based on a standardised design for a Pitot tube and has been extensively validated over a relatively limited range of conditions. There are questions regarding the affect of conditions on the measurements outside this range. These include the affect of high temperature, very high velocity, high moisture and particulate loading and off-axis velocity components of stack gas flow.

The proposed work programmes resulting from project are:

- Validation of air velocity measurements using Pitot systems for industrial emissions
- Improved calibration capability for air velocity measuring systems to meet emission regulations
- Improving the quality of industrial air flow and emission rates measurements

Contents

1 Introduction

This report details the measurement issues associated with the monitoring of gaseous emissions from industrial plants. The project has been carried out by the National Physical Laboratory, in collaboration with the Source Testing Association and Littlebrook Calibration and Measurement. The project has been carried out under the Department of Trade and Industry's Flow Programme.

The principle aim of this project has been to identify key issues related to the measurement of flow in emissions monitoring. The work programme included a detailed technical study of the current situation with regard to flow measurements. The outputs of this study have been reviewed and assessed to identify the key areas with the greatest impact on UK industry. The three most important areas will be developed into detailed proposals for future flow programme work items under subsequent phases of the project.

NPL led a strong project team brought together specifically to deliver the objectives of this study consisting of Littlebrook Calibration and Manufacturing (LCM) and the Source Testing Association (STA). Throughout the project the Environment Agency is also being consulted to provide advice on regulatory issues.

NPL, the UK's national standards laboratory, has a comprehensive knowledge of the requirements of the National Measurement System and its role in supporting the UK's measurement community. NPL have an in-depth practical knowledge of stack emissions monitoring and have been actively involved in improving and validating the quality of such measurements.

The STA represents the UK's stack emissions monitoring community and the membership also includes process operators, regulatory authorities and equipment manufacturers. The STA therefore have knowledge and understanding of the issues associated with stack emissions monitoring from a range of perspectives.

LCM is currently the only laboratory in the UK with UKAS accreditation for the calibration of air velocity measurements using Pitot tubes and anemometers. They have a comprehensive understanding of the metrological aspects of flow measurement in this field.

The first phase of the project provided a comprehensive review of measurement issues in industrial emissions monitoring. It provided a solid foundation for the second phase of the project which defined and proposed future work programmes within the Department of Trade and Industry's Flow Programme.

2 Project Work programme

The overall aim of the project has been to review measurement issues related to the monitoring of gaseous emissions from industrial plant and to identify potential work items that will address these in the formulation of future DTI Flow Programmes. The first phase of the project involved a review current knowledge and practice to identify potential measurement issues. A key part of this work was a comprehensive survey of practitioners in the flow-monitoring field. This consisted of a paper-based survey of all members of the source testing association, the trade body for stack emissions measurements in the UK, followed by targeted telephone interviews with key organisations. Following this a review of the metrological aspects of the measurement methods currently being used was carried out. This enabled the formulation of three potential work packages for submission to the flow programme formulation. Following submission of these the flow programme working part accepted that a project addressing the issues raised could go forward to further formulation stages and a revised single project formulation document was submitted to the programme formulators.

3 Background

3.1 Requirements for Emissions Monitoring

Emissions monitoring underpins the UK's strategy to meet its obligations to European and International law with respect to air quality and emissions regulations. Measurements of emissions from stacks are directly required to fulfil a number of regulatory requirements, including European Directives such as the Integrated Pollution Prevention and Control Directive (IPPC), the Large Combustion Plant Directive (LCP) and the Waste Incineration Directive (WID). In addition to the plants authorised under the IPPC Directive a large number of smaller plants are authorised by Local Authorities.

The requirements for monitoring emissions include:

- Monitoring against emissions limits
- Verification and commissioning of new abatement systems installed on plant
- Validation of carbon trading and other emissions trading schemes
- Provision of information for the UK's National Emissions Inventory, which is necessary to fulfil obligations under international treaties such as the Kyoto Protocol.
- Validation of reference methods being developed by national and international standardisation bodies

Measurement methods for stack emissions monitoring are defined in a number of international standards. European Directives place a number of data quality objects on reported emissions. In order to ensure these requirements can be met the European standardisation body, the Comité Européen de Normalisation (CEN), has a mandate to develop standard reference methods for emissions monitoring. A key European standard in this area is EN 14181, 'Stationary source emissions - Quality assurance of automated measuring systems'. This standard places requirements on the use of (generally manual) reference methods to calibrate and check continuous emissions monitors installed on stacks. Flow measurements are required within this measurement framework.

The majority of emissions monitoring in the UK is carried out within a legislative framework, to meet the requirements reviewed in the previous section. The Environment Agency of England and Wales is responsible to regulating emissions from major industrial plant, issuing authorisations for emissions under the Pollution Prevention and Control (PPC) framework. They provide authorisations for over 1600 sites, classed as Part A processes. A smaller number of installations regulated under PPC are authorised can controlled by local authorities, which also regulate emissions from small plant not covered by the PPC directives. The Environment Agency has issued a range of monitoring guidance notes which detail how measurements should be carried out in the UK. These include monitoring guidance note M1, which defines requirements for sampling. This includes requirements for the measurement of flow. Guidance note M2 defines a number of standards that may be used for emissions monitoring, including those which define methods for flow measurement. The Environment Agency also operate a certification scheme for stack monitoring, MCERTS, which places further requirements on emissions monitoring in order to improve the quality of reported data.

3.2 Requirements for Measurement of Flow

The measurement of flow is an integral part of stack emissions monitoring and impacts on stack emissions monitoring in a number of ways. The primary drivers for flow measurement in emissions monitoring are:

- To enable concentration measurements to be converted to stack emission fluxes. Where measurements are to be reported in terms of the total emitted flux it is necessary to measure the gas flow in the duct. A primary driver for these measurements will be to underpin emissions trading. While emissions trading will be mainly based on values calculated from process parameters it is also likely that such calculations will require validation, which will in turn require direct flow measurements. As the emission rate of stacks is directly dependent on the stack flow velocity, any error in this measurement will directly affect the emission allowance that that process has used. In the American market, one additional ton of SO_2 emissions costs ~$250. As an example consider a typical UK power station with an annual SO_2 release of 35000 tonnes. If flow measurements are used with an uncertainty of 10%, then the emissions may well be overestimated by 10%, with a consequent cost of $870000. There is therefore a strong economic driver from UK industry to reduce the uncertainty in flow measurement.
- For nearly all stack gas concentration measurements it is necessary to demonstrate that the gas flow profile in the stack at the sampling position meets the requirements of the method being followed. For example BS EN 13284-1:2002: ‘Stationary source emissions - Determination of low range mass concentration of dust’, which is the standard method for measurement of low dust (<50mg.m-3) in stacks, defines limits to the variation in gas velocity across the sampling plane. In many cases the flow conditions in the stack determine how many points must be sampled, and whether the results are representative of emission levels.
- To allow isokinetic sampling to be achieved and verified for particulate phase sampling. This has direct impact on monitoring of particulates and other measurands for which the particulate phase is sampled, for example metals. Isokinetic sampling is also required to measure other species that may be present in vapour or aerosol phase, for example HCl. It is important that sampling is isokinetic (ie that the gas entering the sampling nozzle has exactly the same velocity as the gas in the stack) to ensure that the material collected is a representative sample of the particulate matter in the stack. Isokinetic sampling is particularly important where there is a range of particle sizes in the stack. At lower than isokinetic sampling velocities there will be preferential sampling of larger particulates, at high velocities the reverse will be true. These effects can cause systematic errors in the reported emissions.
- Measurement of the volume of sampled gas. This is a requirement in manual sampling systems where the mass of material collected in the impinger solutions is related to the volume of sampled gas. It is also a requirement for

particulate sampling systems. For systems which are both calibrated and report the results in μmol/mol (ppm) then it is not necessary for the sampled volume to be measured, however it is usually required that the sample flow rate is the same as that under which the system was calibrated.

3.3 Flow Measurement Methods

In stack gas flow monitoring the principle method used is based on the Pitot differential pressure device. For isokinetic sampling, the method to be used is defined in BS EN 13284-1:2002. The method determines flow rate by measuring the differential pressure on a Pitot tube using a manometer, combined with temperature measurements from using a thermocouple. A similar method is defined in another particulate measurement standard BS 6069 (ISO 9096) which uses a digital manometer. The performance of these methods is limited in terms of the lowest detectable velocities by the ability of the manometer to measure small pressure differences. It is stated in the standard that the smallest pressure difference that can be measured is 5 kPa.

CEN TC 264 working group WG23 is responsible for producing the European standards for velocity and flow measurement in stacks. The documents presented for consideration by the initial meetings of this working group have been reviewed within this project. They include a number of research reports from EU member states. The CEN working group is currently waiting for funding issues to be resolved before continuing its work.

Sampled gas flow is generally measured using dry gas volume meters. The requirements on the performance characteristics for these meters are given in the appropriate measurement standards. For example EN 13284-1:2001 places a requirement on the gas meter of an uncertainty of less than or equal to 2% of measured value.

The measurement of continuous stack gas velocity is defined in BS ISO 14164:1999 'Stationary source emissions – Determination of the volume flow rate of gas streams in ducts- Automated method' and ISO 10780:1994 'Stationary source emissions - Measurement of velocity and volume flow-rate of gas streams in ducts'. The techniques defined in these standards include dynamic pressure measurement and ultrasonic sensors. The Environment Agency has also established the Monitoring Certification Scheme (MCERTS) to improve the quality of emissions monitoring data. MCERTS includes a number of individual certification schemes which cover different aspects of emissions monitoring. MCERTS for Continuous Emissions Monitors (CEMs) defines a number of performance characteristics to enable type approval of instrumentation. In principle this also covers continuous flow measuring devices, though in practice certification of these instruments has not been carried out. MCERTS also covers manual stack emissions monitoring. A key requirement of this scheme is that monitoring organisations are accredited to ISO 17025. This standard in turn requires the reporting of measurement uncertainty. It is therefore necessary to provide information on the uncertainty contribution of the flow measurement techniques used in stack emissions monitoring.

3.4 Overview of Pitot Tube Flow Measurement Method.

This section provides an overview of the Pitot tube, the principle method used to measure the gas flow in stack emissions monitoring. Basic Pitot tubes come in two main types, the L-type, also known as the standard Pitot, and the S-type. A further refinement of the Standard Pitot is the Ellipsoidal (E-Type) sometimes known as the NPL type, which has an ellipsoidal profile to its tip. More advanced flow sensors based on the differential pressure technique have been developed, these include the 3d Pitot heads more routinely used in the US and averaging Pitots. These devices are used less commonly within the UK emissions testing community. These sensors are based on the principles of the basic Pitot tubes and will be discussed later in this document.

Figure 1, L Type Pitot, showing signs of wear.

Figure 1 shows a photograph of an L Type Pitot tube, and schematic diagrams of both types of Pitot tube are shown below in Figure 2.

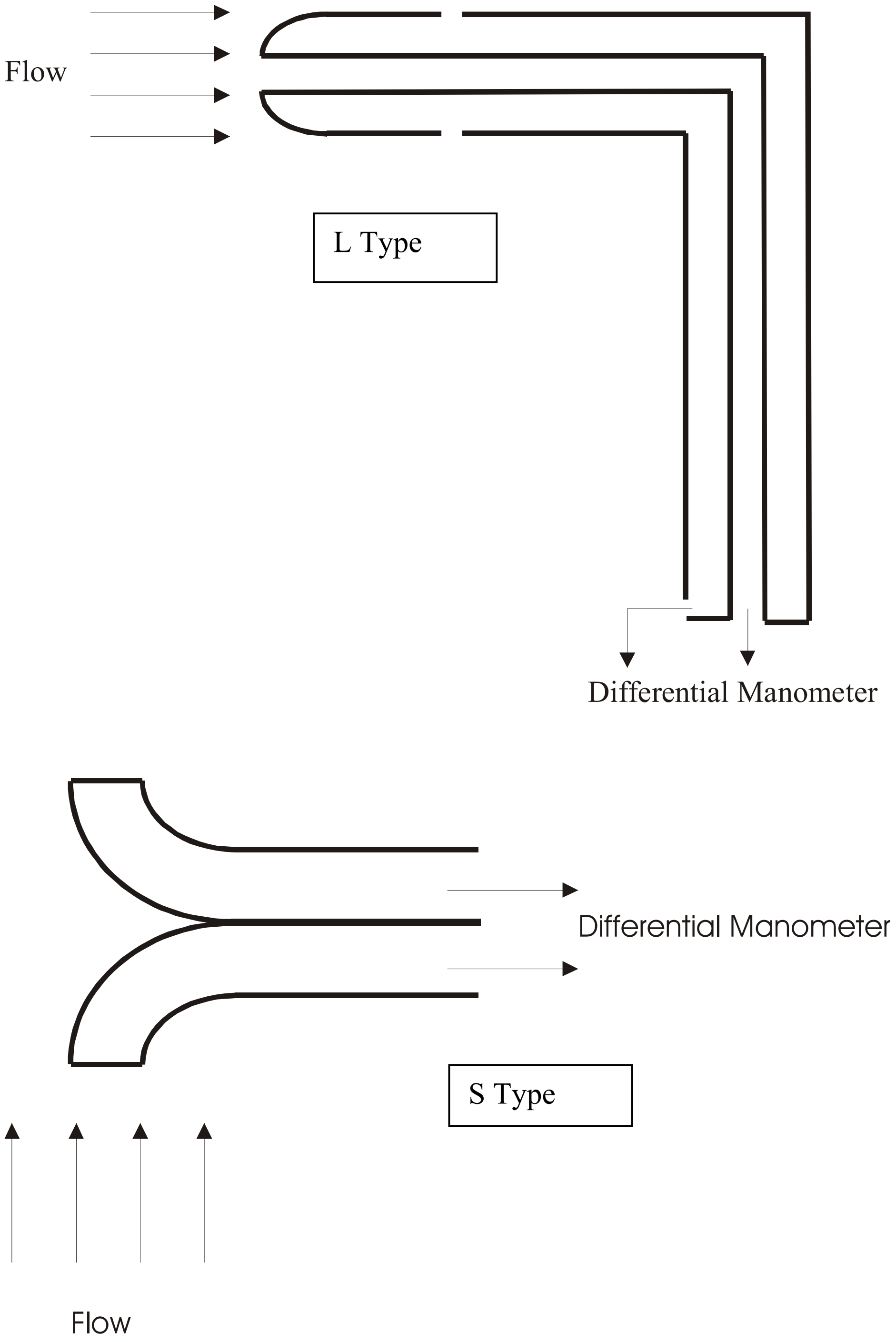


Figure 2 Schematic diagrams of L-Type and S-Type Pitots

Both devices measure the flow by the induced pressure difference between a pressure tap pointing directly into the direction of flow and a static pressure tap, which in the case of a standard type is perpendicular to the direction of flow. The flow velocity in m.sec^{-1} can be calculated from the measured pressure difference using the following equation:

$$velocity = \Gamma \sqrt{\frac{2\Delta p}{\rho}}$$

Eq.1

where:

Γ	=	Pitot tube calibration constant;
Δp	=	differential pressure in Pa;
ρ	=	density of the gas being measured in $kg.m^{-3}$;

The principle behind this equation is discussed later in this report.

Uncertainties in the measurement of calibration constant, differential pressure and the density of the stack gas will contribute to the uncertainty in the measurement of velocity. These uncertainties can be due to the integral uncertainty due to a device's calibration as well as any un-quantified uncertainty due to the way a device may be misused.
The S-Type Pitot was primarily developed for stack monitoring purposes, as its larger orifices are less prone to clogging, and its smaller profile means it can be inserted into a stack through standard sampling ports. L-Type Pitots with shorter 'arms' have also been employed for stack testing to attempt to overcome the access issues.

4 Technical Review of Pitot Tubes

The following sections present a more detailed description of the Pitot tube technique and a discussion of the assumptions underpinning their use.

Scientific background to Pitot Tubes

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 Pitot equation Eq. 1 given in the previous section used to calculate the fluid velocity from the differential pressure measured by the Pitot tube is derived from a specific form of Bernoulli's equation.

Bernoulli's Equation

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 most common forms Bernoulli's Equation used for Pitot tube measurements of is

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

where:

V is the velocity of the fluid;
p is the pressure of the fluid;
ρ 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 is only valid if the fluid is considered to be incompressible, inviscid, there is no change in height and the temperature is constant.

In the case of a Pitot tube, the streamline that impacts directly on the nose of the Pitot tube is brought to zero velocity. This point is called the stagnation point.

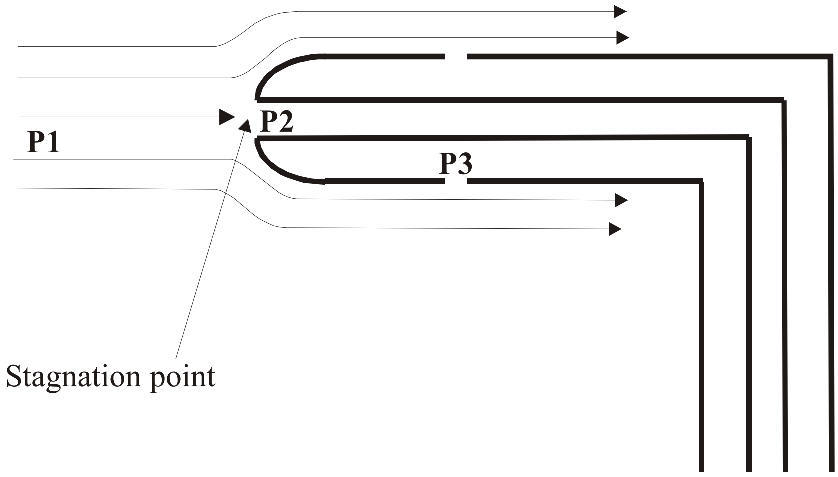


Figure 3 Basis of Pitot Measurements

Applying Equation 2 to two points, P1 and P2, along a single stream line gives:

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

If 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

$$V = \sqrt{\frac{2\Delta p}{\rho}}$$

Eq. 3

where:

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

Equation 3 forms the basis of the Pitot tube equation used in stack emissions flow monitoring and previously presented as Eq 1. It is applicable to ideal Pitot tubes which meet all of the assumptions implicit in its derivation. It is also assumed that the Pitot tube correctly produces the conditions assumed at P1 and P2, ie that the flow line at P2 is brought to a halt, with perfect transfer of energy and the pressure measured at P3 is representative of the flowing gas at P1. It is also assumed that the design of the Pitot allows the transfer of these pressures to the differential pressure measurment device used to record ΔP.

The Pitot equation Eq 1 contains an additional term, Γ, the calibration factor, which is used to relate a non-ideal Pitot tube to an ideal (Standard, L-Type) Pitot. This highlights a key assumption which underpins the use of Pitot tubes for stack measurements. It is assumed that a Pitot constructed to meet the mechanical tolerances given in standard methods will behave according to Eq 1. In addition, other

Pitot tubes which do not meet this design are assumed to require only a single linear calibration factor, Γ, to correct their performance to that of the standard Pitot. The consequences of this assumption are discussed in more detail in later sections of this report.

Limitations of Bernoulli's equation

In stack gas flow measurements most if not all of the fundamental assumptions made in deriving Bernoulli's equation in the form used by the standardised methods are not valid. In many cases this does not have significant impact on the results and does not necessarily invalidate the results. It should be noted that in many cases the impact of the breakdown of these assumptions has not been investigated experimentally in the scope of stack gas measurement. The various assumptions and their validity are discussed in the following sections:

Same flow line

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 is therefore an assumption 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 (Point 1 on Figure xx). 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 up stream 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 very unstable and non-lamina.

Non-viscous/ Inviscid

This is a requirement 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 could have am impact on the Pitot measurements. It is unclear whether significant levels of entrained particulate matter and water vapour in the stream line would significantly affect this.

Incompressible fluid

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 (Mach number). Such velocities will not generally be found in stack conditions. If the velocity is approaching 30% of the Mach number 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, and so this is not generally a significant source of uncertainties.

Perfect fluid/gas

In stack conditions the gas is rarely an perfect fluid. It will often have significant levels of water vapour and dust. In addition the water vapour and some other pollutants will be in a present in multiple phases.

Steady state conditions - Temperature

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.

Steady state conditions - Flow

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.

4.1 ISO Standard Methods for Pitot Flow Measurements

This section describes the key standards that have been developed for Pitot tube measurements in applied to stack emissions monitoring. Various national and international standards cover the designs and use of Pitot tubes including ISO 3966, the standard that defines the L type Pitot. The technical requirements of these are summarised below:

4.1.1 Non-turbulent flow- manual method

The standard Pitot is 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'. This standard is also 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.

These requirements include:

- Mechanical design tolerances
- Non viscous fluids
- Fluid velocity less than Mach 0.25
- Steady flow without turbulence or velocity gradient, although the standard recognises that both are present in all ducted flows, and provides procedures to determine 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 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.

The standard Pitot defined ion ISO 3966 is accepted as the reference flow measurement technique, however limitations, particularly with respect to dust laden flows in stacks led to a further standard specifically aimed at the measurement of non-turbulent flow from stationary source emissions. This standard, ISO 10780 “Stationary Source emissions – Measurement of velocity and volume flow-rate of gas streams in ducts”, 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.

ISO 10780 states that the L-type Pitot tube described in ISO 3966 is ‘preferred when the velocity measurement is made before and after the pollutant sample is collected. This Pitot tube is less sensitive to flow misalignment errors than the S-type. However, its pressure sensing ports can be come plugged in certain sampling conditions. Its use can be difficult in high concentrations of particulate matter or aerosols. In addition its insertion into thick walled ducts or smoke stacks requires large openings. If the L-type tube and sampling nozzle are too close to each other they will adversely influence each other’s performance’.

With reference to the alternative, S-type Pitot, the standard states it ‘can be used when the pollutant sample is collected at the same time the velocity is measured. It is also preferred if the porthole is small, the stack wall is thick, the stack gas is dusty and the stack gas contains aerosols such as water droplets and sulphuric acid. The S-type Pitot is considerably more sensitive to alignment error than the L-type, but is less sensitive to interference by a sampling probe nozzle when the distance between the sides of the Pitot tube and the nozzle is at least 1.9cm. The Pitot tube can be designed to reduce its sensitivity to alignment error.’

The standard places the following requirements and conditions for the use of L-Type Pitots:

- If precise alignment of the Pitot tube with the stack axis is not possible but there is no swirl, the differential pressure should be independent as possible of the yaw of the head in uniform flow.
- For an L-Type Pitot that does not meet all of the construction requirements of ISO 3966 the standard requires that the calibration factor, Γ, shall be 0.99 ± 0.01.
- The calibration factors for different specimens of tubes to a particular specification shall be identical to within ±1.0% and shall remain so for the working life of any such tube.
- The static pressure holes shall be:
    1. not larger than 1.6 mm in diameter;
    2. at least six, and sufficient in number such that the damping in the static pressure circuit is equal to that in the total pressure circuit. On small diameter Pitot tubes the orifices may be placed on two planes;
    3. free of burs and uniform in diameter;
    4. placed not less than six head diameters from the tip of the nose;
    5. placed not less than eight diameters from the axis of the stem.

Requirements on S-Type:

- The distance between the base of each leg of the Pitot tube and its face-opening (orifice) plane shall be equal for each leg. The distance shall not be less than 1.05 and not more than 10.0 times the external diameter of the tubing.
- Pitot should be calibrated against a L-Type to establish its calibration factor. The S-Type Pitot is not defined as a standard method, its use had been adopted following extensive practical field operation in the US. This has led to an assumed calibration factor of 0.84 with reference to the standard Pitot.
- If used with a sampling probe attached then the spacing between the probe and the Pitot must be a minimum of 1.9cm

The standard contains a calibration procedure for both types of Pitot tube.
L-Type Pitots that do not meet the construction requirements in ISO 3966 and S-Type Pitots should be calibrated against a standard Pitot that conforms to 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 tub is calibrated at the velocity it will be used at. No tolerance is given as to 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 test duct should b e 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 4, and the average K is determined as the calibration factor for the Pitot under test.

$$K_{test} = K_{ref}\sqrt{\frac{\Delta\rho_{ref}}{\Delta\rho_{test}}}$$

In addition all indvidual 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.

The standard has specifications for ancillary equipment as well as the environmental conditions under which the measurement should be made:

- Reynolds number >1200 in the stack gas around the Pitot
- Flow velocity 5 $m.sec^{-1}$ to $50m.sec^{-1}$ the Pitot must be calibrated over this range if measurements are expected to be of this range.
- Swirl angle $\leq 15^{o}$.
- 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.

As can be seen there are a large number of key requirements which are required to be met to perform reliable Pitot tube measurements. These in general relate to atypical stack conditions and were developed, in the case of ISO 3966, to take account of conditions in clean air ducts, not emission stacks.

A key issue currently affecting the stack emissions monitoring community is that the ISO standard ISO 3966 which defines the reference Pitot against which all ducted flow measurements are calibrated (and which is a normative reference for emissions monitoring standards) has been withdrawn by ISO. This is, according to the convenor of the relevant BSI committee, which is concerned with ducted air flow not emissions monitoring, because no one uses this standard anymore. It should be noted that the UK BS standard which is identical to ISO 3966 has not been withdrawn. It is also the case that in practice, national calibration labs that carry out primary Pitot calibration within wind tunnels have now almost exclusively transferred the primary calibration of the wind tunnels to Laser Doppler Anemometer (LDA) velocity measurements. This has reduced the impact of a potential issue which arose when Pitot tubes which had calibrations traceable to the LDA were compared with those traceable to standard Pitots. Biases were observed of several percent, however such issues are now less common as traceabilities are routinely made to the LDA.

4.1.2 Turbulent flow – manual method

The current standard for the measurement of turbulent flow from stationary source emissions is BS 1042 Part 2.3 "Measurement of flow in closed conduits, methods of flow measurement in swirling or asymmetric flow conditions in circular ducts by means of current meters or Pitot static tubes".

BS 1042 Part 2.3 specifies velocity area methods for measuring flow is swirling or asymmetric flow conditions in circular ducts by means of current meters or Pitot static tubes. It specifies the measurements required, the precautions to be taken, the corrections to apply and describes additional uncertainties, which are introduced when a measurement is an asymmetric or swirling flow has to be made.

When measuring flows where swirl is known to be present, a preliminary traverse using a yaw probe is necessary to determine the angle of swirl at each measuring position. A yaw probe works like an S-type Pitot, except that its dynamic pressure taps are on two sides of an equilateral triangle or set at 90^o on a circular probe, and is aligned with the direction of flow when the pressure difference between the two pressure traps is zero.

Two measurement methods are described:

1) If the swirl angle is less than 20^o, measure the swirl angle at each point using the yaw probe and align the Pitot with the duct axis for each measurement. Correct each Δp for the each individual swirl angle.
2) If the swirl angle is between 20^o and 40^o,measure the swirl angle with the yaw probe and align the Pitot with the local flow direction for each measurement. Calculate axial velocity for each position measured.

The standard states that little is known on the effect of swirl on Pitot tubes. The assumed uncertainty due to swirl for swirl angles up to 20^o is 5%. For swirl angles $>20^o$ the assessment of uncertainty is less reliable.

For turbulent flows the value for the uncertainty arising from the turbulence shall be taken as equal to the applied correction (±1% to ±2%).

As a guide the overall uncertainty in flow-rate measurement in asymmetric or swirling flow will normally be between ±2% and ±4%.

4.1.3 Automatic methods

The current standard for the measurement of non-turbulent flow from stationary source emissions is ISO 14164 "Stationary source emissions – Determination of the volume flow-rate of gas streams in ducts – Automated method".

ISO 14164 describes the operating principals and most important performance characteristics of automated flow measuring systems for determining the volume flow rate in ducts of stationary sources. It gives procedures for determining the performance characteristics and is not limited to specific measurement principals or instrument systems.

The standard specifies that volume flow measuring automated measuring systems (AMS) should not be used in ducts where non-uniform, asymmetrical, developing, swirling and/or stratified flow is present.

The following measurement methods are described:

1) Differential pressure sensing systems - Single Pitot tube with data logging of dynamic pressure

2) Multiple-point Pitot tube – The average impact and wake pressures are compared using an electrical pressure transducer or other differential pressure-sensing device. These systems suffer from the same limitations as single Pitot devices. They can also yield erroneous measurements where the velocity varies substantially across the duct. The latter error results because secondary flows in the device effect the average pressure differentials measured.

3) Temperature sensing systems - The most widely used systems employ two thermal convection mass flow sensors; one of which is heated and the other maintained at ambient temperature. Both sensors are inserted into the gas stream. The temperature differential (measured in terms of voltage or current) between the two sensors is used to determine the flow rate of the gas stream.

   Two types generally used, constant power and constant temperature. The constant power system is not widely used as it is slow to respond to changes in temperature and velocity, does not have a stable zero and has a limited range of temperature compensation.

   The advantages of temperature measuring devices is that they are more accurate at low velocities and have a good repeatability from 0^{o} C to 450^{o} C. Thermal devices should be calibrated against a static Pitot tube before they are used. Thermal sensing devices cannot be used in ducts where condensing liquid droplets are present, nor can they be used in cases where the velocity vector of the gas stream differs by more than 10 degrees from the ducts primary axis.

4) Sound based systems - These systems determine the flow rate by comparing the time taken for a sound pulse to travel in the general direction of the gas

flow to the time taken for an identical pulse to travel along the same path in the opposite direction.

The following performance characteristics are given:

Standard deviation	≤5%	Expressed as a percentage of full scale range of the AMS
Systematic Error	≤3%	Expressed as a percentage of full scale range of the AMS

Procedures for the determination of the main performance characteristics are given in Annex A.

Additional performance characteristics are given in Annex B and procedures for their determination. These are as follows:

Performance characteristic	Numerical method
Linearity	≤ 3%[a]
Zero drift	≤ 3%[a, b]
Span drift	≤ 3%[a, b]
Response time	≤10 seconds

[a] As a percentage of full scale
[b] Should be done during a period of unattended operation

There are key issues related to the calibration and traceability of these new techniques. This is highlighted by differences that have been observed between the calibrations of wind tunnels using Laser Doppler techniques, which are traceable to SI units of time and length, and calibrations using standard Pitots (which are by definition an artefact standard). These issues are currently being addressed by a number of national metrology laboratories.

4.2 US EPA Methods

The US EPA methods have been superseded in the UK by ISO methods and these in turn will be superseded by the CEN standard currently being drafted. EPA Method 2 formed the basis of the ISO 10780 standard and the equipment described in the original parts of the US methods has historically been used with in the UK. Of interest, however, are a number of recent revisions and additions to the methods, published as three additional parts of Method 2. These revisions were prompted following reports of measurement issues and failures in the US, particularly related to the requirements of emissions trading. The revised methods are concerned with non-axial flow and wall effects, and are mainly appropriate for power plant measurements, due to drivers from the emissions trading scheme within the US.

4.2.1 Method 2

In May 1999 the US EPA published three new parts to Method 2 "Determination of Stack Gas Velocity and Volumetric Flow Rate". The three new methods are:

1. **Method 2G** allows Type-S probes and 3-D probes (DAT and spherical) to be rotated in the flow to measure the total pressure and yaw angle. The yaw angle is used to calculate "near-axial" velocity from total velocity.
2. **Method 2F** allows 3-D probes to be used to measure total velocity, yaw angles and pitch angle pressure. Pitch angle pressure is used with a calibration curve to determine pitch angle. Yaw and pitch angles are used to calculate axial velocity from total velocity.
3. **Method 2H** provides a procedure for accounting for wall effects by using either a default wall effects adjustment factor or one derived from near wall measurements. The wall effect factor is used with methods 2-, 2G or 2F-calculated velocity to derive a wall effect adjusted velocity.

The three new methods have been developed following a series of wind tunnel and field tests. Seven types of probes were tested: Type S, United Sciences Testing Incorporated Autoprobe Type S, Prandtl (Standard Pitot), French, modified Kiel, DAT and Spherical. A Codel flow monitor was also tested.

The conclusions from wind tunnel and field tests were:

- Probes that could determine the yaw and pitch angles of flow produced results closer to those predicted by scientific theory;
- The Type S, Autoprobe, DAT and spherical probes produced the best results. They tended to be less variable, did not consistently under read velocity and were closer to the theoretically derived results;
- Automated probes were less variable than manually operated probes.
- The modified Kiel and French probes and the Codel flow monitor produced highly variable test results and should not be included in new test methods;
- Measuring wall effects produced a ½% to 3% improvement in volumetric flow measurements;
- The amount of wall effect is lower for stacks with smooth interiors than stacks with rougher interiors;
- Calibration curves for three-dimensional (3-D) probes; i.e., DAT and spherical probes, are less reliable for velocities below 20 feet per second (6 $m.sec^{-1}$);
- Scratches on the surface of spherical probes did not significantly effect their calibrations.

The major steps for performing Method 2F or 2G are summarised below:

(1) Qualify Wind Tunnel

The wind tunnel tests revealed that some wind tunnels used by vendors or source testers to calibrate probes were inadequate, because they were either too small or did not have uniform flow. To avoid such problems, any wind tunnel used to calibrate probes for Methods 2F or 2G must satisfy certain design and performance specifications to ensure that the flow is axial (straight) and uniform in the wind tunnel calibration location. The wind tunnel must meet two design criteria: (1) The diameter must be at least 12 inches; and (2) the projected area of the tested probe and reference calibration Pitot tube must not exceed 4% of the cross-sectional area of the wind tunnel. The wind tunnel must also meet two performance specifications: (1) A velocity pressure cross-check to ensure that the velocity is the same at all locations where the tested and reference probes will be positioned during calibration; and (2) an axial flow verification to ensure that there are no significant yaw or pitch components of flow at these locations. These two tests are performed before the initial use of the wind tunnel and are repeated after any alterations are made to the tunnel.

(2) Prepare To Calibrate Probe

The wind tunnel and field tests also showed that pre-calibration probe inspection and procedures for placing a scribe line on a probe were important prerequisites for accurate yaw angle measurements. Therefore, the methods include the following five general activities to be performed prior to calibrating a probe (1) put a straight permanent line (scribe line) on the probe. This activity only needs to be performed once, not every time a probe is calibrated. The scribe line must meet certain straightness and width criteria so that a yaw angle-measuring device can be accurately placed on the probe. (2) Check that the probe is not bent and does not have significant sag. (3) Pressure devices must be zeroed and calibrated. (4) The yaw angle measurement device must be calibrated and aligned relative to the reference scribe line. (5) The probe system must be leak checked.

(3) Perform Yaw Angle Calibration

Yaw angle errors were observed in the wind tunnel tests when the offset of the scribe line from the probe’s zero yaw position was not accurately determined in the wind tunnel. The methods, therefore, include a yaw angle calibration procedure, which must be performed on the complete probe assembly in a wind tunnel to determine the ‘‘reference scribe line rotational offset’’ angle (R_{slo}). The R_{slo} indicates the rotational position of a probe’s reference scribe line relative to the probe’s yaw null position and is used in determining the yaw angle of flow in a stack or duct.

(4) Perform Velocity and Pitch Calibrations

The field and wind tunnel tests showed that robust velocity and pitch calibration procedures were required if errors in velocity and volumetric flow determinations are to be avoided. For Method 2G, this consists of a wind tunnel procedure to determine a velocity calibration coefficient for the tested probe. This calibration coefficient is used to calculate stack gas velocity from pressure measurements taken in the field. The velocity calibration procedure involves taking three pairs of pressure measurements with the tested probe and a reference calibration Pitot tube at two wind tunnel velocity settings. Calibration coefficients obtained at wind tunnel velocity settings of 60 and 90 feet per second (fps) are usable in all field applications where the velocities are 30 fps or greater. Calibration coefficients derived at other velocity settings are usable in field applications where the measured velocity does not fall outside the limits defined by those velocity settings. Method 2F includes wind tunnel procedures to determine both velocity and pitch angle calibration curves. These curves are used to determine both the pitch angle and velocity of flue gas flow when using a 3-dimensional probe. The pitch and velocity calibration procedure involves positioning the tested probe at a series of pitch angles settings relative to the flow in the wind tunnel and then taking pressure measurements with the tested probe and a reference probe. The measurements are repeated at two wind tunnel velocity settings. Calibration curves obtained at wind tunnel velocity settings of 60 and 90 fps are usable in all field applications over the entire velocity range allowed by the method. Calibration curves derived at other velocity settings are usable in all field applications allowed by the method as long as the measured velocity does not exceed both of the wind tunnel velocity settings used to derive the curves.

(5) Prepare for Field Test

The field tests showed that the inspection of probes and the set-up procedures described above under step 2 were not only a critical prerequisite for wind tunnel testing, but were equally important in field testing. For example, during one of the field tests, an inspection detected damage to the probe head, which resulted in spurious readings from a probe. Thus, prior to beginning a field test, each method requires performance of all the checks described in item 2 (‘‘Prepare to Calibrate Probe’’) above, except for putting a scribe line on the probe. Additionally, the tester must inspect the probe for damage, mark traverse point distances on the probe, and determine a system response time.

(6) Perform Field Test

The field tests also showed that the quality of measurements was affected by procedures followed by testers when performing the field tests. For example, allowing sufficient response time and checking for probe plugging were shown to be important considerations during the field test. Thus, the methods give specific instructions on how to perform a field test. In particular, the methods instruct testers to perform the following steps. Insert the probe into a test port in the stack or duct, and move the probe to the first traverse point. After the system response time has elapsed, measure the yaw angle, impact pressure, and pitch angle pressure (Method 2F only). Take these measurements at each traverse point of the run. In addition, measure barometric pressure, flue gas molecular weight, moisture and static pressure. Check the probe periodically for plugging to prevent erratic results or sluggish responses.

(7) Perform Calculations

To account for pitch and yaw components of flow, the methods had to include new calculation procedures that were not needed in Method 2. These procedures were employed in the field tests and shown to be workable. They include calculating the pitch angle (Method 2F only) and impact velocity at each traverse point using the pressure measurements taken in the field and the calibration coefficient (Method 2G) or curves (Method 2F) derived in the wind tunnel. Using these values and the yaw angles measured in the field, the axial velocity (Method 2F) or yaw-adjusted velocity (Method 2G) is calculated at each traverse point. Stack or duct average velocity is then calculated by averaging over all the traverse point velocities. Checks are performed to see that the calibration coefficients or curves are appropriate for the velocity encountered in the field. Finally, multiplying the stack or duct cross-sectional area and the average velocity derives the volumetric flow rate.

Method 2H, ‘‘Determination of Stack Gas Velocity Taking into Account Velocity Decay Near the Stack Wall’’, can be used in conjunction with existing Method 2 or new Methods 2F or 2G to account for velocity drop-off near stack (or duct) walls in circular stacks (or ducts) no less than 3.3 feet in diameter. Method 2H is not suitable for use in rectangular stacks or ducts because the procedures in this method are not applicable to the complex and varying flow dynamics characteristic of such configurations.

There are two main approaches for determining wall effects adjusted velocity in Method 2H. Either a default wall effects adjustment factor (WAF) (i.e., 0.9900 (for brick and mortar stacks), or 0.9950 (for all other stacks or ducts)) may be used with Method 2, 2F, or 2G without taking any wall effects measurements or a WAF may be calculated from velocity measurements taken at 16 or more Method 1 traverse points and at 8 or more wall effects points. EPA’s Method 1, ‘‘Sample and Velocity Traverses for Stationary Sources’’, is the test method for determining the number and location of traverse points in a stack or duct. Method 1 alone is generally not suitable for determining wall effects. During the course of wall effects field testing, several potential problems were uncovered. Procedures were incorporated into Method 2H to prevent these problems. These are described below.

(1) Locate Traverse Points

The field test revealed that care needs to be exercised when locating wall effects traverse points; otherwise, the full wall effect may not be measured. Thus, Method 2H instructs testers to take measurements at 1-inch intervals starting at 1 inch from the wall or at the next closest 1-inch interval from the wall possible. Testers may perform either a partial or complete wall effects traverse. For a partial traverse, measurements are taken at two wall effects traverse points per test port, at a minimum. For a complete traverse, a series of 1-inch incremented measurements are taken beginning no further than 4 inches from the wall and extending in 1-inch intervals as far as 12 inches from the wall. The method presents procedures for determining the location of the wall effects points.

(2) Determine Sampling Order

Field tests also showed that an incorrect WAF might be calculated if the wall effects sampling is decoupled from the Method 1 sampling. Therefore, the method includes instructions on how sampling is to be performed. The sampling order may be from the wall to the center or from the center to the wall. Although the Method 1 and wall effects points need not be interspersed at each port, there should be no interruption between sampling at the wall effects and Method 1 points. The intent of this sampling sequence is to keep the Method 1 and the wall effects measurements as close together in time as possible to reduce the possibility of different velocity conditions occurring during the Method 1 and wall effects measurements.

(3) Take and Record Measurements

As in Methods 2F and 2G, field tests showed that the procedures followed by testers were critical to the quality of the measurements obtained. Wall effects testing not only required the procedures found in Method 2F and 2G, but also additional procedures for taking measurements close to a stack or duct wall. For example, the method had to include instructions for testing in situations where it may not be possible to obtain measurements within a certain proximity (e.g., 1 inch) of the stack or duct wall. Method 2H instructs testers to perform the following steps. After inserting the probe into the gas stream, wait for the pressure and temperature readings to stabilize to stack or duct conditions before taking measurements at the first traverse point. (This time period is called the ‘‘system response time’’ and is defined in Methods 2F and 2G.) At all other traverse points, testers must allow enough time to obtain representative pressure measurements. If no velocity is detected at the wall effects point closest to the wall, move to the next 1-inch incremented wall effects point. Complete the integrated traverse as quickly as possible, consistent with adequate sampling time, so that the measurements are all taken under the same stack or duct conditions. In addition, take other measurements required by Method 2, 2F, or 2G (e.g., moisture, barometric pressure). Record all measurements.

(4) Perform Wall Effects Calculations

The field tests confirmed that a series of measurements near a stack wall could capture the impact of wall effects on flue gas flow in a stack or duct. To capture this effect, a new calculation procedure was developed which was tested in the field. This procedure was incorporated in Method 2H. It involves calculating the velocity at each wall effects traverse point and entering the resulting values in a table. The entered values are then used to find the wall effects-adjusted replacement velocities for the four Method 1 traverse points closest to the wall. These four values and the unadjusted velocity at the Method 1 traverse points are used to calculate a WAF. The WAF is a multiplier, which can then be applied to the velocity derived using Methods 2, 2F, and 2G to account for velocity decay near the stack or duct wall. The WAF may be no less than 0.9800 for a partial traverse and no less than 0.9700 for a complete traverse. We derived these limits from analysis of wall effects tests performed on a variety of utility stacks (different stack lining material, velocities, and stack dimensions). If actual field testing indicates that the WAF for a particular stack or duct may be less than 0.970, the tester should increase the number of traverse points in the Method 1 traverse (e.g., to 20 or 24 points if a 16-point traverse was initially performed) and re-calculate the WAF to capture the full extent of the wall effect.

(5) Obtain Wall Effects Adjusted Velocity and Volumetric Flow Rate

While the field test showed the calculation procedures to be effective, the new test method also needed to clarify how WAFs were to be applied to calculate the wall effects adjusted volumetric flow rate for the stack or duct. Thus, the final steps in Method 2H include instructions on how to calculate the wall effects adjusted velocity for the stack or duct by multiplying the unadjusted velocity from Method 2, 2F, or 2G by the WAF (either calculated or default). The calculated WAF from one run may be applied to all runs of the same relative accuracy test audit (RATA). If calculated WAFs are obtained for several runs, the tester must average the WAFs and apply the resulting value to all runs of the same RATA. The stack or duct volumetric flow rate is then obtained by multiplying the wall effects adjusted velocity by the stack or duct cross-sectional area.

The following limitations are placed on the three methods:

Method 2F	The spherical probe must not be used to take static pressure measurements, as it is unable to provide this measurement. An alternative device must be used.
Method 2G	Dimensional specifications on a S-Type Pitot with regards to the alignment of the two pressure taps are given.
Method 2H	This method is not applicable for testing stacks and ducts less than 1.0 m in diameter. The calculated procedure based on velocity measurements is not applicable for horizontal circular ducts where build up of particulate matter or other material in the bottom of the duct is present.

Method 2H has defined default wall effect adjustment factors of:

0.99	Circular brick and motor stacks
0.9950	All other circulars tacks and ducts

Work performed by RMB Consulting gave calculated estimates of wall effect adjustment factors, which were supported by field measurement data, ranging from about 4-5% in contrast to factors for circular stacks that are usually in the 2-3% range.

4.2.2 Method 5

USEPA Method 5 "Determination Of Particulate Matter Emissions From Stationary Sources" references Method 2 and its sub-sections for the measurement of the stack gas velocity. It makes no modifications to Method 2 for the measurement of flow. Dry gas meters are required to be calibrated to within ±2%.

5 A Review of Relevant Research and Papers

In addition to standards reviewed above a number of key research papers have been reviewed. The most relevant of these are summarised below:

5.1 RMB Consulting, Heat rate discrepancy project, May 1998

This work, carried out by RMB Consulting, on the error introduced by using standard S-type Pitot tubes and associated problems in measuring the emission flux from a stack prompted the US EPA to instigate its research program that resulted in parts F, G and H beign added to Method 2.

They found that the effect of swirl on the standard S-type Pitot probe was considerably less than previously published. Earlier work suggested that the axial velocity bias of around 25% for yaw angles approached 30^o while their wind tunnel tests only indicated a bias of around 15%.

Two field tests where then carried out comparing the standard S-type Pitot probe with the proposed new three dimensional probes.

The results from the Columbia Unit field test showed that the S-type Pitot measurements averaged 4.1% higher than the 3-D probe. This difference demonstrated the effect of the slight yaw swirl present in the Colombia stack on the S-type Pitot. The effect of this bias on the unit heat rate was calculated for full load tests. For this calculation the standard FC-factor of 1800 for sub-bituminous coal was used and no corrections were made for wall effects. The unit heat rate based on S-type Pitot flow measurements and reference method CO2 values was an average of 10.8% higher and the heat rate based on CEMS data was an average of 9.8% higher than the heat rate calculated using the input/output method. The uncorrected heat rate based on 3-D probe flow measurements and reference method CO2 values was an average of 7.1% higher than the input/output method. The discrepancies between the 3-D probe result and the input/output method is discussed later.

The results from the Coal Creak Unit-2 field test showed good agreement on all seven tests between two companies measuring flows using a S-type Pitot probe and the 3-D probe. The S-type measurements agreed to 1.2% and the 3-D measurements agreed to 0.8%. Due to the good agreement, the average of the two companies results were used for all comparisons at the Coal Creak Unit. The S-type Pitot measurements were an average of 15.0% higher (12.3%-19.9%) than the 3-D probe. This large difference demonstrated the effect of the significant amount of swirl (the average yaw angle was $\sim 21^o$) on the S-type. The CEMS flow meter reported values an average of 6.6% higher (2.4%-9.9%) than the 3-D probe. The CEMs flow meter was an ultrasonic type. The heat rate for the unit was then calculated from these flows assuming the standard FC-factor of 1910 for lignite and no corrections were made for wall effects. The heat rates based on S-type Pitot flow measurements and reference method CO2 values were an average of 23.7% higher than heat rate values calculated using the input/output method and values based on CEMS data were an average of 18.6% higher. The heat rates based on uncorrected 3-D probe flow measurements and reference method CO2 values were an average of 8.1% higher. The discrepancies between the 3-D probe result and the input/output method is discussed later.

Assessments of pitch and yaw angle were also performed at the Coal Creak Unit. There was some variability in the angles measured from test to test and fairly significant differences from port to port, however the pitch and yaw patterns remained relatively consistent during the tests.

The discrepancies between the calculated heat rate and the input/output calculated heat rate for both of the field tests were investigated. When biases were corrected there were very good agreement between the two methods. The corrected 3-D-based heat rate agreed within 1.9% of the input/output-based heat rate at Columbia and within 3.4% at Coal Creek. Corrected biases to the 3-D-based heat rate values included:

1) Wall effects

The S-type and the 3-D flow values were based on equal area traverses, which do not take into account the fact that, the stack velocity goes to zero at the stack wall. To account for this effect, near wall measurements were taken at Coal Creek. Based on numerical integration, not taking into account the wall effects introduces a bias of 1.9%. Similar effects were also seen in the "swirl" tunnel tests. (Although near wall flow measurements were not taken at Columbia, it is assumed that the wall effect at Columbia is approximately equal to that seen at Coal Creek based on the similarity of the stacks).

2) Manual pressure reading bias

During the field tests, Pitot Delta P readings were made both manually using calibrated magnehelics and automatically using a data logger equipped with precision pressure transducers. Subsequent analysis revealed a consistent bias in the manual readings when compared to the readings collected automatically using the data logger. This bias appears to be related to a tendency of individuals to overestimate when doing "eyeball averaging" of fluctuating readings. At Columbia, the manual readings resulted in flow values 1.1% higher than those based on the automatic readings. At Coal Creek, the manual readings resulted in flow values 0.9% higher than those based on the automatic readings.

3) FC-factor

At Columbia, the FC-factor calculated based on the average coal percent as-fired carbon and average gross calorific value as determined from as-fired samples collected during the tests was 1839 scf CO_2/mmBtu. Using the standard FC-factor of 1800 would result in an overestimation of the heat rate by approximately 2.2%. At Coal Creek, the FC-factor determined from the as-fired coal analysis was 1942 scf CO_2/mmBtu. Using the standard FC-factor of 1910 for lignite would result in an overestimation of the heat rate by approximately 1.6%.

With S-type Pitot measurements, in addition to the bias introduced by the FC-factor, wall effects and manual pressure readings, bias is also introduced by non-axial flow:

4) Non-axial flow

The difference between the S-type and the 3-D flow values is related to the non-axial components of the flow that are erroneously included in the velocity head of the S-type measurement. At Columbia where only small non-axial flow components were found, the S-type Pitot yielded full-load flow values that were 4.1% higher than the 3-

D measurements. Thus, the S-type measurements, and subsequently the CEMS flow meter data, were biased 4.1% high due to non-axial flow conditions. At Coal Creek, where significant non-axial flow components were found, a 15.0% high bias due to non-axial flow conditions was seen.

5) CEM calibration

Since CEMS flow meters are calibrated and certified using S-type Pitot reference method flow measurements, any bias in the reference method would be passed on to the certified flow meter. These "calibration bias" effects include wall effects, non-axial flow effects and manual pressure reading bias. In addition to "calibration bias" and FC-factor bias, any bias in the CEMS CO2 measurement would also be transferred to the CEMS-based heat rate value.

5.2 Bauer BF, Errors in Air Flow Calibration Measurements

A partial differential analysis was performed on the airflow equation (1) and found that if all the uncertainties associated with the parameters that make up the equation are set at 1%, then the overall airflow uncertainty is 3.4%. The author discusses all of his uncertainty as %error and has failed to add the different components of uncertainty as the sum of squares, they have just been added in a straight sum. If the sum of squares method is employed then the overall uncertainty in air flow, assuming the above uncertainties, is 1.04%

$$AF = V\rho A \qquad \text{(Eq 1)}$$

From analysing the impacts of the different measured parameters on the overall uncertainty it was found that the uncertainty contributions due to barometric pressure and static temperature were negligible. However, it was found that the uncertainties in the measurement of duct temperature, differential pressure and duct dimensions had a significant impact in the overall measurement uncertainty.

It was found that a 1% uncertainty in the measurement of duct temperature yielded a 0.54% uncertainty in total airflow. It is possible to keep the measurement uncertainty of temperature within 1% if it is measured at every sampling point. However, this can extend the total measurement time and leads to problems maintaining steady flow conditions within the duct throughout the period of all the measurements, therefore some testers fail to measure the temperature at every point. It is not unusual for temperature within a duct to vary by ~60^{o}C, which can lead to an uncertainty of 9.2% in the total flow. It may be advisable to run a temperature profile of the duct before the airflow test is run to determine how frequently temperature should be measured.

It was found that a 1% uncertainty in the measurement of pressure differential yielded a 0.5% uncertainty in total airflow. It is difficult to ensure a 1% uncertainty in the measurement of partial pressure under field conditions. A more likely measurement uncertainty of 5% in partial pressure would result in impact of 2.5% in the uncertainty in total airflow.

The measurement uncertainty in the duct dimensions is the only uncertainty that feeds directly on a 1:1 basis into the overall uncertainty in total airflow. If duct dimensions are not measured directly, it is difficult to ensure a 1% contribution to the overall uncertainty in total airflow.

Taking into account the impacts of the uncertainties discussed above and setting the uncertainty in differential pressure to 5% and the uncertainty in temperature to 1%, then the overall uncertainty in air flow is 4.06%. The author discusses all of his uncertainty as % error and did not add the different components of uncertainty as the sum of squares; they have been added in a straight sum, which implies the uncertainty sources are fully correlated. Assuming the above uncertainties and summing them as the sum of squares method then an overall uncertainty in airflow of 2.65% is obtained.

5.3 Leland BJ et al, Correction of S-Type Pitot Static Tube Coefficients when used for Isokinetic Sampling from Stationary Sources

In many instances where an un-calibrated S-type Pitot is used a calibration factor of 0.85 is assumed. The study by Leleand et al concludes that this approach normally results in emission values being quoted higher than their true value. A calibration factor obtained for a S-type Pitot tube was found to be 0.76 when corrections for stem blockage, aerodynamic interference, misalignment, Reynolds number and turbulence were applied.

A series of studies has shown that the proximity of the sampling probe, thermocouple and probe sheath cause a significant lowering of the calibration factor of around 4%. It is therefore important to calibrate the S-type Pitot with the probe, thermocouple and probe sheath attached. This calibration should also be performed over the flow velocities and Reynolds numbers that are likely to be encountered in field operation.

Pitch angles up to $\pm 10^{o}$ and yaw angles up to $\pm 5^{o}$ gave little effect on the calibration factor. The asymmetry in response to pitch and yaw angles between sides A and B of the S-type Pitot is probably due to the different configuration presented to the flow by the probe nozzle.

The Pitot tube calibration factor is not only dependent on the pressure distribution around the Pitot assembly, but also on the velocity and fluid properties of the flow stream. The property that characterises these properties is the Reynolds number. The Reynolds number characterises the type of boundary layer and correspondingly the frictional losses in the flow around any obstruction in the flow stream, in this case the Pitot tube assembly. It is there fore important to determine the calibration factor over the Reynolds numbers and flow velocities that are likely to be encountered in field operation.

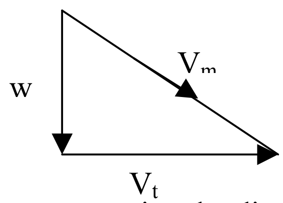
When determining the calibration factor for a Pitot tube in a relatively small diameter pipe and then making measurements in a relatively large diameter pipe a correction for stem blockage must be made to the calibration. A blockage of 2-3% has been demonstrated to decrease the calibration factor by 1%.

If there is turbulence in the flow stream a Pitot tube will sense an additional pressure difference due to the turbulence present at the impact and static pressure taps. Because of the configuration and relative size of a S-type Pitot tube's impact and static pressure taps, the turbulence effect sensed at each tap is identical and is cancelled out in the measuring process. However a standard type (L-type) Pitot tube will sense different turbulence effects at its impact and static pressure taps due to its configuration. Therefore when determining the calibration factor of a S-type Pitot tube when using a L-Type Pitot tube as the standard, a correction for turbulence in the flow duct must be performed. The correction is significant when the turbulence is greater than 1%. The correction increases significantly and nonlinearly for turbulence intensities above 1%.

The author gives a recommended calibration procedure and a modified formula for deriving the calibration factor taking the corrections for stem blockage, aerodynamic interference, misalignment, Reynolds number and turbulence into account.

5.4 Various papers on Displacement effect

When taking measurements of flow when there is a large velocity gradient across the stack, the 'displacement' effect has to be taken into account. This occurs because the flow on one edge of the Pitot is higher than at the opposite side; this sets up a small flow, w, perpendicular to the main flow. Thus the Pitot tube measures a velocity V_m, which is greater than the true velocity, V_t, at the geometric centre of the Pitot tube. This means that it measures the velocity at a point displaced from the geometric centre towards the region of higher velocity. There is



Various papers examine the displacement effect and propose different formulas describing its effect. Displacement effect is only relevant if measurements are taken where high velocity gradients occur. This normally happens near the duct wall, however there are other cases where a high velocity gradient can occur.

5.5 Robertson JM et al, On improving the Pitot tube determination of flows in large pipes

Turbulent flow is inherently unsteady so that the manometer attached to the Pitot will show pulsations. Additional pulsation can result from unsteady flow about the Pitot head due to vortex street occurrences. These vortex street occurrences cause the Pitot tube and its assembly vibrate. When the frequency of these oscillations matches the natural frequency of the Pitot assembly, resonance occurs. The result of the resonance of the Pitot tube assembly can increase the indicated velocity by a few percent and hence invalidate the measurement. Resonance should be avoided at all time when measuring flow with a Pitot tube. This may mean that two Pitot tubes of different resonant frequency may have to be used when measuring at different locations in a stack.

5.6 Measurement of Solids in Flue gases P Hawksley et al.

Difference in measurement between a long stemmed and short-stemmed L-type Pitot is in the order of 0.5%.

Suggests that the normal range for Δp is 2Pa to 400 Pa, which is outside the allowable pressure range of ISO 10780. ISO 10780 specifies a minimum Δp of 5Pa. However, it recommends that pressure differences of less than 10Pa are not practically measured in the field by the use of an inclined manometer. This equates to a velocity of 4 $m.sec^{-1}$ at $20^{o}C$.

5.7 CEN/TC 264/WG 23 N26, Assessment of the performance of Pitot tubes when used under the ISO 10780 method

KEMA Nederland BV has determined the performance characteristics of trueness (accuracy), detection limit, repeatability and reproducibility of the ISO standard ISO10780.

From analysing the uncertainty calculation the maximum theoretical measuring uncertainty expressed with a level of confidence of 95%, at a velocity of approximately $9m.sec^{-1}$ is 7.8%.

Results

Average accuracy over the velocity range 2.2 $m.sec^{-1}$ to 50.0 $m.sec^{-1}$:

S-type -1.4% L-type -3.5%

The detection limit, determined from the standard deviation of ten successive measurements at a velocity close to the expected detection limit, was 0.9 $m.sec^{-1}$.

The repeatability of a S-type Pitot under controlled laboratory conditions was determined at three different velocities over ten measurements at each velocity. The absolute repeatability was found to be constant over the three velocities with a value of 0.2 $m.sec^{-1}$.

The repeatability of a S-type Pitot under field conditions was also determined. The absolute repeatability was found to be constant within the measurement range with a value of 0.3 $m.sec^{-1}$.

Six different measuring teams at one stack determined the repeatability of both L-type and S-type Pitots. The sampling strategy was identical to the strategy performed under laboratory conditions. The results show that the repeatability between the teams can differ up to a factor of 4.

15 combinations of parallel measurements of each 2 teams determined the reproducibility of both S-type and L-type Pitots. Due to failure of some of the apparatus 14 of the results of these measurements have been used for the calculation of the reproducibility. The reproducibility for the S-type Pitot within a velocity range of 9.7 $m.sec^{-1}$ to 15 $m.sec^{-1}$ was determined to be 1.2 $m.sec^{-1}$ (10%). The reproducibility for the L-type Pitot with a velocity range of 10 $m.sec^{-1}$ to 15 $m.sec^{-1}$ was determined to be 2.5 $m.sec^{-1}$ (20%).

5.8 CEN/TC 264/WG23 N32, Swedish report on repeatability of Pitot measurements

Measurements in Sweden had given an indication of errors up to 20%. Seventeen laboratories made measurements of the same 300mm diameter wind tunnel at pressures below 1013 mbar with L-type Pitot tubes. The results showed:

- All measured too high airflow velocity
- The test was done at 5m/s, 10m/s and 20m/s, and all had higher errors with increased wind tunnel velocity.
- Institutes using liquid type manometers were likely to have lesser measurement errors than institutes using electronic pressure cell manometers.
- Up to 10% overestimation was frequent seen in the test. Possible source of errors were identified as:

    1. Possible faulty calibration of the orifice.
    2. Possible cyclonic flow in the wind tunnel due to the way the duct is welded.
    3. Possible errors from pulsating wind pressure from the driving ventilator.

Experiments in Sweden indicate errors up to 50% as a result of pulsating pressure in the duct. An exhaustive explanation has not been found (damping with a $10dm^3$ bucket of dry sand (time average) solved the problem).

One of the conclusions of the report was, that liquid manometers are more reliable than the electrical manometers.

The experts presented at the meeting agreed that in practical use, the liquid manometer is the most reliable.

5.9 A Review of Stack Gas Flow Measurement Technology, Joint Environmental Programme, D P Graham, Nov 2004.

This comprehensive review has recently been produced by the Joint Environmental Programme (JEP) of the electricity generation industry. The review covered a range

of flow measurement techniques including Pitot tubes, but also covering continuous measurement systems such as ultrasonic and correlation flow sensors. The review raises concerns regarding the accuracy of Pitot tubes as a measurement technique, and highlights the developments in the US with respect to EPA Method 2 and the use of 3d-Pitot tubes. The review favours the use of the US Methods due to the recent research and development carried out to underpin Methods 2F, 2G and 2H.
The review also considers Mean velocity probes such as averaging Pitots, raising the point that the average pressure differential is not equal to the average velocity as the relationship between the two is non-linear. Other issues can arise with non-uniform pressure profiles across the different pressure ports, and for devices installed permanently in a stack there can be problems due to blockages of the probes over time.
With regard to continuous flow monitors, such as ultrasonic devices, the review highlights the requirement that these techniques have for in-situ calibration against a reference method. This calibration may only be relevant to the conditions present in the stack during the calibration process, and stack gas flow conditions can vary with time as plant conditions alter.
The review also covers a range of experiences from the US mainly gained from the SO_2 trading arrangements which require facilities to continuously monitor flow, and from JEP experience in the UK. One finding from the UK experience when using S-type Pitots was that these read, at one location, 7% higher than measurements carried out using a 3d-Pitot which corrected for swirl.
The review highlights the use of calculated emissions, based on fuel burn and composition, as the preferred option under the EU emissions trading scheme for CO_2.
In a separate communication with the authors of this report, D Graham, the author of the JEP report raised a number of points for consideration in this review (reproduced here);

- Early experience in the US demonstrated that substantial errors can occur when using conventional Pitot designs for stack flow measurement (typically 7% but as high as 28%);
- The use of ‘advanced’ Pitot head designs and associated methods produced very close agreement (better than 3%) with calculated flow rates based on fuel consumption and stack oxygen measurements in well controlled trials – these do not of course rely on any other means of gas flow measurement;
- Even so, Pitot tubes are not viewed as an ideal reference method within the power industry for the following reasons:
    - Particulate fouling
    - Difficulty in complying with standards with regard to measurement locations, even in circular stacks
    - The length of time required to perform traverses (from both a testing and operational viewpoint);
- An alternative reference method based on tracer gas injection should be considered.

However it is recognised that the same may not be true of higher temperature applications.

6 A Summary of Standards and Papers related to Issues with Pitot Tube Measurements

6.1 Standards

Table 1 gives a summary of the requirements for Pitot tube measurements from the different international standards and published papers.

Table 1 Requirements on Pitot Tube Measurement

	Standard					
Performance characteristic	**BS 1042 Part 2.1**	**ISO 10780**	**USEPA 40 CFR Part 60**	**BS 1042 Part 2.3**	**KEMA Study**	**ISO 14164**
Off axial flow	15^o Swirl 3^o alignment	15^o	Corrected for yaw and pitch in Method 2F, yaw only in Method 2G	20^o and 20^0 to 40^o	N/A	Not specified
Requirements on Δp	~0.6Pa	5 Pa	No	~0.6Pa	N/A	Not specified
Compressibility compensation	Density and Δp	No	No	Density and Δp	N/A	Not specified
Method for determining discharge velocity	3 Methods	Mean of all measurements	Mean of all measurements corrected by wall adjustment factor	3 Methods	N/A	Mean of all measurements
Max stem blockage	2%	3%	4%	2%	N/A	Not specified
Uncertainty	≤±2%	≤±3%	Not stated	5% + 2% for turbulence	≤±7.8%. Reproducibility of 10% for S-Type and 20% for L-Type.	Standard deviation ≤5% Systematic error ≤3%.
Design requirements	L-Type	L and S-Type	Prism and spherical 3-D probe and S-Type	L-Type	N/A	Performance characteristics defined
Ancillary equipment specified	No	Yes	Yes	No	N/A	Not specified
Required sampling strategy	Yes	Yes	Yes	Yes	N/A	Not specified
Calibration procedure	No	Yes	Yes	No	No	No Yes

Table 2 gives the requirements for flow measurements using a Pitot according to ISO 10780, which is the standard that all flow measurements made in the UK using a Pitot tube should adhere to.

Table 2 Requirements For Flow measurement using a Pitot according to ISO 10780-1994

Characteristic	Requirement
Dynamic pressure	>= 5Pa to <=4800 Pa
Velocity	>2.9 m.sec^{-1} to <~90 m.sec^{-1} at 20C
	>=6.0 m.sec^{-1} to <~180 m.sec^{-1} at 1273K
Reynolds number	>1200
Cross sectional area of duct	>=0.07m^2
Stem blockage	<=3%

Pitot tube measurements are believed to incur large errors when the temperature of the gas being measured exceeds 1000^{o}C. The main reason put forward has been that the Reynolds number is now out of specification. If the following assumptions are made: velocity is 3 m.sec^{-1}, diameter is 0.3m, kinematic viscosity = 1.76.10^{-4} then the Reynolds number = 5122, which is still within specification. To get a Reynolds number of greater than 1200 under the above conditions then the velocity required has to drop to ~0.7 m.sec^{-1}, which is then below the minimum flow measurement that is allowed by the standard. The variation in Reynolds number may not be the reason why the error occurs. However, a literature search on the subject, found no published work which investigates the behaviour of Pitot tube measurements at high temperature, assuming that the Pitot tube is still structurally intact. The calculation above also assumes that the conditions laid down by the standard are correct. There appears to be no published work describing the validation of the Pitot tube measurement method over the conditions prescribed by the standard, or indeed providing any justification for the ranges given in the standard, and so it is not possible to quantify any error in flow measurement caused by high temperatures, or other variation from the conditions prescribed in the standard. Further work on the validation of the Pitot tube is required to quantify the effect of stack conditions.

6.2 Summary of Issues from Reviewed Papers.

Paper 1 demonstrated that that there could be a significant flow measurement error due to misalignment of the Pitot tube with the direction of flow. Yaw and pitch angles of greater than 10^o can induce errors in the region of 15%. Field trials performed showed that there could be good agreement between emission rates calculated using flow measurements performed by Pitot tubes and unit heat rates calculated by the input/output method. Good agreement was only found after corrections for wall effects, manual pressure reading bias, fuel FC-factor, non-axial flow and CEM calibration. This paper also showed that the effect due to swirl could be removed by making measurements with a 3-D probe instead of the S-type probe.

Paper 2 performed a partial differential analysis on the airflow equation and found that if all the uncertainties associated with the parameters that make up the equation are set to 1% then the overall airflow uncertainty is 3.4%. From analysing the impacts of the different measured parameters on the overall uncertainty it was found that uncertainty contribution due to barometric pressure and static temperature is negligible. However, it was found that the uncertainties in the measurement of temperature, differential pressure and duct dimensions had a significant impact in the overall measurement uncertainty. Uncertainties in the duct dimensions feed directly on a 1:1 basis into the overall uncertainty, it is therefore of paramount importance to measure the duct dimensions correctly. It was found from talking to a consultant that in one case that he had come across the measurement of duct diameter was in error by ~50% and hence a 50% error in the emission rate was reported.

Paper 3 highlighted the need for the proper calibration of Pitot tubes. If an uncalibrated S-type Pitot tube is used a calibration factor of 0.85 is assumed and this can result in emission values being calculated incorrectly. A calibration factor obtained for a S-type Pitot tube was found to be 0.76. This would lead to a difference in calculated emission value of 10%. The effect of stem blockage, aerodynamic interference, misalignment, Reynolds number and turbulence also need to be taken into account when calibrating a Pitot tube.

Paper 4 highlight the problems associated with measuring flows when there is a high velocity gradient across the duct. As the standards state that a velocity profile should be performed before any absolute flow measurements are made and these areas avoided, then this problem will not generally affect the measured flow. However there are some situations where a high velocity gradient cannot be avoided and a correction for displacement should be performed.

Paper 5 states that resonance of the Pitot tube should be avoided at all times. This may mean that two Pitot tubes of different resonant frequency may have to be used when measuring at different locations within the duct. This should therefore not lead to problems in flow measurement.

6.3 Summary of Issues with Pitot Measurements

The following sources of errors in Pitot tube measurement have been found:

1) Velocity gradient correction due to stem blockage[1] neglected if stem blockage <=2% Theoretical

   [1] Can be corrected for when measuring near the wall Published

2) Turbulence 10% turbulence creates 0.5% to 2% error Theoretical

3) Wall effects

Wall effects	Circular ducts	1% – 2%	WAF = 0.99 to 0.98
	Rectangular ducts	3% - 5%	WAF = 0.97 to 0.95

   Published

4) Eye balling of fluctuating pressure in a manometer appears to be biased positive by 1% - 2% when compared to digitally averaged data. Published

5) Pulsating flow causes large errors when measuring with a Pitot, max pressure variation over measurement allowed by standard = 24Pa. This is very large

when compared with an allowable Δp of 5Pa! A Δp of 24 Pa is equivalent to 7.3 m.sec^{-1} at 100°C or 6.3 m.sec^{-1} at 20°C. If you were measuring a mean Δp of 13Pa you would be measuring a flow of 4.6 m.sec^{-1} ± 4.5 m.sec^{-1}. Errors of up to +40% have been seen in field tests measuring exhaust duct velocities with both the standard and S-Type Pitots. Published

6) Operator induced errors Training required

7) Metrology of pressure, temperature and gas volume measurement.

Pressure transducers are often used at the bottom of their range, but are calibrated only at the top of the range and the reported uncertainty is quoted as a percent of full scale. If a 200 Pa device is calibrated at 2% of full scale and then makes a measurement of 6Pa, the associated uncertainty of the measurement is ±4Pa!

Pressure differences of less than 10Pa are not practically measured in the field by the use of an inclined manometer. This equates to a velocity of 4 m.sec^{-1} at 20°C.

Difference in measurement between a long stemmed and short-stemmed L-type Pitot is in the order of 0.5%.

8) Temperature

There is no physical reason why Pitot tubes should not work correctly above ambient temperature as long as the Pitot tube is structurally sound. There is a possible problem with the Reynolds number specification laid out in BS1042 Part 1. BS 1042 Part 1 stipulates that the Reynolds number for the total pressure port of a Standard or L-Type Pitot must be greater than 200 (this is the Reynolds number for the gas inside the Pitot tube port, not the duct flow). The table below gives the calculated Reynolds number for different flow conditions. It also gives the minimum measurable flow at different temperatures for Standard Pitots with different total pressure port diameters

Port diameter, mm	**Temperature, C**	**Velocity, m.sec^{-1}**	**Reynolds number**
1 A commonly sold size	0	3	230
1	20	3	203
1	**100**	**3**	**132**
1	100	5	220
1	**200**	**5**	**147**
1	200	7	206
1	300	10	214
1	**500**	**15**	**199**
1	800	25	201
1.5 (Min specified by std)	**100**	**3**	**199**
1.5	200	5	221
1.5	**500**	**10**	**199**

1.5	800	17	205
3.18 or 1/8”	300	3	204
3.18	500	5	211
3.18	800	8	204
5.25 (Max specified by std)	500	3	209
5.25	800	5	211

Conditions highlighted in **bold font** are out of specification with regards to the standard. As can be seen many typical Pitot measurement situations fall outside conditions defined within the standard. Once again there is no metrological information available to enable the effects of such conditions to be quantified.

7 Laser Doppler Anemometer

The UK, USA, Germany, France, Australia and Japan are transferring the calibration of National Standard Wind tunnel facilities which are used to calibrate Pitot tubes, to be traceable to the Doppler Anemometry method instead of the Standard Pitot tube method.

Bean[10] outlines the reasons that have prompted NIST to move from the standard Pitot tube to a fiber optic laser Doppler anemometer (LDA) as the United States primary standard for air speed measurement. The main reason being that the LDA can be directly calibrated through measurements of length and time, while measurements with the Pitot tube can only be verified by comparing the measurements with those of other Pitot tubes. The cut off point for low air speed measurements with a Pitot tube is ~3 $m.sec^{-1}$, and the uncertainty is dominated by the uncertainty in differential pressure measurement. This uncertainty is in the order of a couple of percent, while the uncertainty of the LDA measurements at low velocities is in the order of 0.5% at 1 $m.sec^{-1}$ and 0.3% at 3 $m.sec^{-1}$. The uncertainty of the LDA measurement is 0.006 $m.sec^{-1}$ expressed with a level of confidence of 95%.

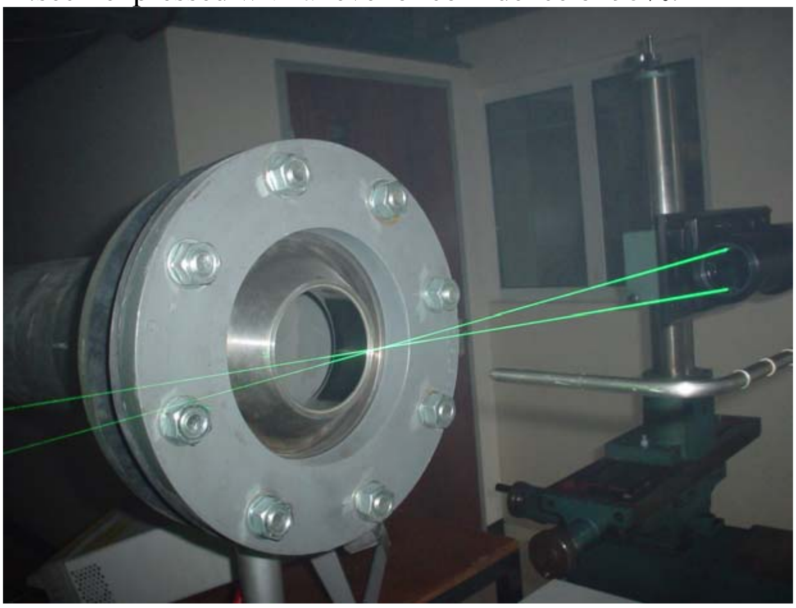


Figure 4, Laser Doppler Anemometer providing air velocity calibration of one of LCM's flow facilities.

In the UK the ISO17025 certified Pitot calibration facility at Littlebrook Calibration and Manufacturing now has flow calibrated and traceable to the LDA system.

Due to the measurement method used by the LDA there should be no effect on the result induced by high measurement temperatures. The only limitation is in the use of the seeding material. If titanium dioxide particles are used for the seeding then measurements should be able to be made up to 1500^{o}C.

There has been a +~5% systematic difference reported between measurements made using Pitot tubes and those made using laser Doppler instrumentation. However this has not been reproduced and may have been caused by the use of transfer standards. In general discrepancies of less than 2% have subsequently been observed. As all Pitot tube calibrations transfer to facilities which derive their traceability from LDA such discrepancies have minimal impact. There does however remain the issue that the reference method defined in the ISO standards is still the standard L-Type Pitot tube, an artifact standard based on the design specification in ISO 3966.

8 Pitot Users Questionnaire

A questionnaire was developed and sent out to the STA membership, which represents a comprehensive and representative sample of the emission monitoring community. The questionnaire was approved by the DTI Survey Control Unit and a copy is appended to this report as Annex A.

29 organisations returned the questionnaire. There are 360 Pitots in use by those surveyed, 41% L type, 56% S type (3% other types).

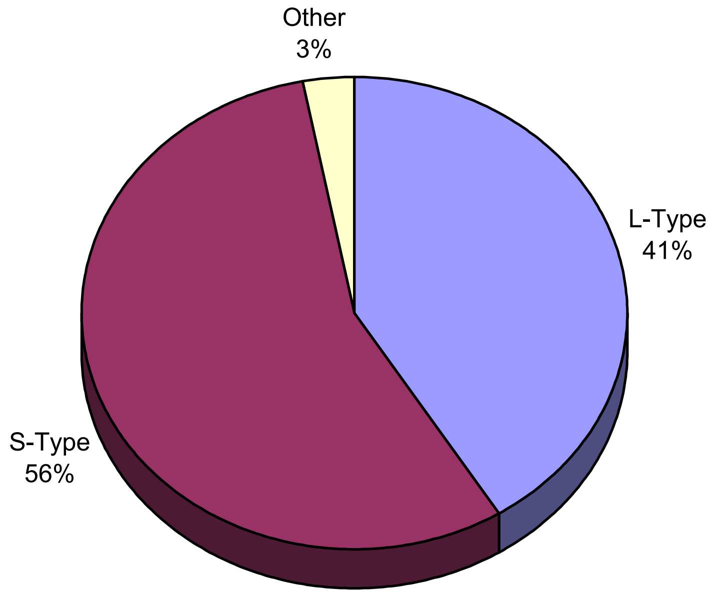


Figure 5. Pitot usage in the UK by type.

Following a review of the results of the questionnaire the following observations can be made:

1) With regard to the 3.0 m.sec^{-}1 minimum flow requirement from ISO 10780 derived from quoted minimum dynamic pressure of 5Pa

   17 organisations reported measuring flow below 3.0 m.sec^{-1} using a total of 264 Pitots.

2) With regard to the 0.07m^2 stack cross sectional area requirement from ISO 10780

11 organisations reported making measurements on stacks with a cross sectional area less than 0.07m^2 using a total of 198 Pitots.

3) With reagard to the requirements for the uncertainty in dynamic pressure measurement

Table 3 shows the minimum allowed measurement of the dynamic pressure of 5 Pa, expressed as a percentage of the pressure transducers range.

Company	5 Pa expressed as percentage of range
1	0.26
2	0.20
3	0.20
4	0.01
5	0.03
6	0.14
7	0.26
8	0.20
9	0.21
10	4.0, 0.2, 1.0
11	0.26
12	0.20
13	2.00
14	0.20
15	0.02
16	0.51
17	0.56
18	0.14
19	2.5, 1.25, 0.25
20	4.09
21	0.71
22	0.20
23	0.26
24	0.20
25	0.04
26	0.10

It can bee seen that all the participants are using their pressure transducers in the bottom part of their range where calibration errors are likely to be the greatest, and some are using pressure devices at 0.01% of their full scale range.

9 Recommendations for future work

The work programme has identified a number of areas where issues related to the use of Pitot tubes for measurements of gas flow in stack

9.1 Validation of Pitot tubes over different environmental conditions

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 influences on Pitot tube measurements be carried out, to enable a better understanding of the metrological issues surrounding the use of Pitot tubes under typical and extreme stack conditions.

A key area would be research 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. Titanium dioxide seeding of the stack should allow LDA measurements up to 1500^{o}C. What are the structural limitations of Pitots?

9.2 Training and metrology of measurement

After reviewing the results of the questionnaire and the follow up telephone conversations it was apparent that there were a number of issues that needed addressing. The following highlight the significant sources of uncertainty in flow measurement by Pitot devices and metrological problems:

- Duct dimensions
- Temperature
- Differential Pressure
- Resonance
- Velocity profile
- Materials

Rationale

The following paragraphs describe the significant sources of uncertainty in the measurement of air speed by Pitot Systems and the conversion of stack flow to emission rate.

Duct Dimensions

The measurement uncertainty in the duct dimensions is the only uncertainty that feeds directly on a 1:1 basis into the overall uncertainty in total airflow. If duct dimensions are not measured directly, it is difficult to ensure that an accurate measurement of emissions is made.

Temperature

BS 1042 Part 1 stipulates that the Reynolds number for the total pressure port of a Standard or L-Type Pitot must be greater than 200.

A 1% uncertainty in the measurement of duct temperature yields a 0.54% uncertainty in total airflow. It is possible to keep the measurement uncertainty of temperature within 1% if it is measured at every sampling point. However, this can extend the total measurement time and leads to problems maintaining steady flow conditions within the duct throughout the period of all the measurements, therefore some testers fail to measure the temperature at every point. It is not unusual for temperature within a duct to vary by ~60^{o}C, which can lead to an uncertainty of 9.2% in the total flow.

Differential Pressure

Pressure transducers are often used at the bottom of their range, but are calibrated only at the top of the range and the reported uncertainty is quoted as a percent of full scale. If a 200 Pa device is calibrated at 2% of full scale and then makes a measurement of 6Pa, the associated uncertainty of the measurement is ±4Pa! Pressure differences of less than 10Pa are not practically measured in the field by the use of an inclined manometer. This equates to a velocity of 4 m.sec^{-1} at 20^{o}C.

Resonance

The result of any resonance of the Pitot tube assembly can increase the indicated velocity by a few percent and hence invalidate the measurement. Resonance should be avoided at all time when measuring flow with a Pitot System.

Velocity profile

A full velocity profile of the stack under measurement must be performed before any pollutant species are measured. This ensures that there is no stratification of the stack flow and that the sample taken is a representative one. Pollutant samples should not be taken from areas in that stack that exhibit negative flow velocities.

Materials

All materials used for the construction of the Pitot System and its associated transducers should be fit for purpose. S-type Pitot tubes of less that 3/8" should not be used as the specifications on tubes below this diameter do not specify the internal diameter and this is the most important specification for a Pitot tube.

9.3 Issues with the Calibration of Pitot Tubes

The following sections highlight significant sources of uncertainty when calibrating a Pitot tube and common problems which can arise:

- Stem blockage
- Aerodynamic interference
- Misalignment
- Reynolds number
- Turbulence
- Displacement effect
- Inter-calibration of Pitot devices

9.3.1 Stem blockage

If the cross sectional area of the Pitot tube is >2% of the cross sectional area of the wind tunnel used for calibration, then stem blockage can become an influencing factor on the calibration. Stem blockage occurs because the Pitot is now effecting the flow in the wind tunnel to such an extent that the local flow around the Pitot is being accelerated and thus leading to an over estimation of the true flow by the Pitot. A stem blockage of 2-3% has been demonstrated to decrease the calibration factor by 1%.

9.3.2 Aerodynamic interference

The geometry of the Pitot, probe, thermocouple and probe sheath can have a significant effect on the calibration of the Pitot. ISO13284 conflicts with ISO 10780 of the location of the thermocouple and sampling probe with reference to the Pitot. It is therefore important to calibrate the S-type Pitot with the probe, thermocouple and probe sheath attached. This calibration should also be performed over the flow velocities and Reynolds numbers that are likely to be encountered in field operation.

9.3.3 Misalignment

Pitch angles of greater than $\pm 10^0$ and yaw angles greater than $\pm 5^o$ have a significant effect on the calibration of a Pitot. It is therefore important to ensure that the Pitot tube is correctly aligned with the flow direction in the wind tunnel. The asymmetry in response to pitch and yaw angles between sides A and B of the S-type Pitot is probably due to the different configuration presented to the flow by the probe nozzle.

9.3.4 Reynolds number

The Pitot tube calibration factor is not only dependent on the pressure distribution around the Pitot assembly, but also on the velocity and fluid properties of the flow stream. The property that characterises these properties is the Reynolds number. The Reynolds number characterises the type of boundary layer and correspondingly the frictional losses in the flow around any obstruction in the flow stream, in this case the Pitot tube assembly. It is therefore important to determine the calibration factor over the Reynolds numbers and flow velocities that are likely to be encountered in field operation.

9.3.5 Turbulence

If there is turbulence in the flow stream a Pitot tube will sense an additional pressure difference due to the turbulence present at the impact and static pressure taps. Due to the configuration and relative size of a S-type Pitot tube's impact and static pressure taps, the turbulence effect sensed at each tap is identical and is cancelled out in the measuring process. However a standard type (L-type) Pitot tube will sense different turbulence effects at its impact and static pressure taps due to its configuration. Therefore, when determining the calibration factor of a S-type Pitot tube when using a L-Type Pitot tube as the standard, a correction for turbulence in the flow duct must be performed. The correction is significant when the turbulence is greater than 1%. The correction increases significantly and nonlinearly for turbulence intensities above 1%.

9.3.6 Displacement effect

When taking measurements of flow when there is a large velocity gradient present, the 'displacement' effect has to be taken into account. This occurs because the flow on one edge of the Pitot is higher than at the opposite side, this sets up a small flow, perpendicular to the main flow. Thus the Pitot tube measures a velocity, which is greater than the true velocity, at the geometric centre of the Pitot tube. This means that it measures the velocity at a point displaced from the geometric centre towards the region of higher velocity. Displacement effect is only relevant if measurements are taken where high velocity gradients occur, for example close to the wind tunnel wall.

9.3.7 Inter-calibration of Pitot devices

It has been noted that some organisations send one or two of their Pitot tubes for traceable (UKAS) calibrations, while they currently use many more Pitots and claim traceability. Organisations which use S-type Pitots for field measurements often hold one standard Pitot which is used in house to verify the calibration funtion of the S-type Pitots.

It must be noted that if inter-calibrations are performed on these additional Pitots then the uncertainty in the calibration factor will increase. If an incorrectly designed and / or operated calibration facility is used to determine the calibration of these extra Pitot then their calibration can be significantly in error.

9.4 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. 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. These are of specific concern where newer technologies are traceable to SI units of time and length, and not to the artifact standard of the Pitot. Related to this are

It is also of note that the ISO standard ISO 3966, which underpins current emissions monitoring standards, such as the CEN low dust standard EN 13284, has been withdrawn by ISO. There is currently no funding for the CEN working group TC264 WG 23) to develop CEN standard methods for stack flow monitoring, though this is being strongly lobbied by the industry and related group.

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Standards

Organisation	Std Number	Title	Date
BSI	BS 1042-2.1	Measurement of fluid flow in closed conduits. Method using Pitot static tubes	1983
BSI	BS 1042-2.3	Measurement of fluid flow in closed conduits. Methods of flow measurement in swirling or asymmetric flow conditions in circular ducts by means of current meters or Pitot static tubes	1983
ISO	ISO 10780	Stationary source emissions. Measurement of velocity and volume flow rate of gas streams in ducts	1994
ISO	ISO 14164	Stationary source emissions. Determination of volume flow rate of gas streams in ducts – automated method	1999
AFNOR	XP X 43-360	Measurement of velocity and volume flow rate of gas streams in ducts	
US EPA	40 CFR Part 60	Three new test methods for velocity and volumetric flow rate determination in stacks or ducts; final and proposed rules	1999
BS	BS EN 13284	Stationary source emissions. Determination of low range mass concentration of dust.	2002
US EPA	40 CFR Parts 72 and 75	Emissions monitoring policy manual	2003

Papers

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Annex A, Questionnaire

Flow Measurement Issues Associated with Gaseous Flow from Industrial Plant

Questionnaire on usage of Pitot Tubes for Emission Monitoring

NPL, STA and Littlebrook Calibration Services are conducting a survey on behalf of the DTI to support a project on the measurement of Gaseous Flow in Stacks. Could you please complete this questionnaire and either faxback to +44(0) 1462 457535 or email to flowproject@s-t-a.org.

Company Name	
Contact	
Tel No	
Email Address	

Q1 Please state the number of each type of Pitot tube you have within your organisation/site

Standard (E type) Pitot		Other (state type)	
S Type Pitot			

Q2 What stack / duct velocity and temperature range do you encounter

Velocity	Min		Max	
Temperature	Min		Max	

Q3 Please indicate the types of process you use Pitots e.g combustion, incineration etc

1	5
2	6
3	7
4	8

Q4 From Question 3 please indicate the range of duct sizes encountered

1	5
2	6
3	7
4	8

Part 2; This section relates to ancillary equipment used in flow measurement;

Q5 Please list the differential pressure devices used in conjunction with your Pitot tubes;

Type	Manufacturer	Range
Example *Liquid manometer*	*AnyInst Ltd*	*0-300 mm WG*

Q6 Please can you indicate if you use dry gas meters for monitoring the flow in sample trains

Manufacturer	Range

Q7 Please provide and additional comments or concerns you have in the use of Pitots or other flow devices

Annex B. Project definition submitted to the flow programme formulation, December 2004.

Theme : **Research** **Category :** **Environmental & Regulatory Issues**

Title : **The measurement stack emissions**

Aims

The aim of this work is to improve the determination of industrial emissions by improving the capability within the UK to measure gaseous flow rates in industrial stacks. Such measurements are required to meet EU regulatory requirements and to underpin and validate emissions trading. The Pitot Static tube is the reference method (defined in European standards) for flow measurement in stacks and Pitot Systems are used for almost all test work carried out in the UK. A Pitot System is an air velocity measurement system, comprising of a Pitot static tube and a low-pressure differential manometer The key aims of the proposed project will be to provide quantification of the errors associated with the use of Pitot Tubes in industrial environment and assess the performance of Pitot tubes under stack conditions, improve calibration and traceability for emissions flow measurement including the use of new technologies and reduce errors caused by the poor understanding of the use of Pitot systems within the stack measurement community by defining procedures for the correct use of Pitot Tubes and developing training and workshops on the issues related to the measurement of flow in stacks.

Justification

A study carried out within the DTI flow programme identified requirements in three areas: the underlying metrology of the Pitot tube when used in a stack environment, the calibration and traceability of emissions flow measurement and training needs in the monitoring community (a questionnaire exposed issues such as the incorrect use of pressure measurement devices).

The review identified that Pitots are routinely used in conditions that lead to the breakdown of a number of the fundamental assumptions underpinning their use, but the impact of these failures on the results are not understood or quantified. Some studies have been carried out on the overall performance of Pitot tubes, and for example a Swedish study in a wind tunnel found errors of between 5% to 50% in the Pitot flow readings. However no studies have been identified which determined the effects on Pitot flow measurements caused by typical conditions in the stack (ie high temperatures, high humidity, multiple phases, rapid velocity changes etc) and there is little understanding of the uncertainties in flow measurement. The monitoring industry and regulators have raised concerns that effects of high temperatures on Pitot readings are unknown and never accounted for by those carrying out emissions measurements.

There are also issues with calibration including the traceability of S type Pitot calibrations and the widespread use of ad-hoc calibration procedures by test houses. Laser Doppler anemometry provides the reference for flow measurements in the UK through ISO 17025 accreditation, and there are requirements for an international comparison and for the integration of this technique into emissions flow measurement standards.

Benefits

Improved measurement of flow in emissions monitoring will have significant economic benefit to UK industry. There are currently a number of EU directives including the Integrated Pollution Prevention and Control (IPPC), Large Combustion Plant and Waste Incineration directives, which require emissions monitoring. All emissions monitoring requires flow within the stack to be measured, either directly for the calculation of mass emission, for ensuring correct isokinetic sampling for particulate monitoring or for stack characterisation for concentration measurements. Better understanding of the uncertainties in flow measurements will improve industry's reporting of emissions, reduce their risks due to legislative enforcement actions and reduce costs of monitoring. Improved monitoring data which will result from better flow measurement uncertainty will support the UK in meeting obligations under international agreements such as the national emissions ceilings directive and support the introduction of emissions trading schemes which have a key role in meeting obligations under the Kyoto protocol. The further development of laser Doppler anemometry, improvements in the calibration of flow measurement devices and better training of users will reduce the measurement uncertainty of Pitot tubes used in the field. Errors in mass emission figures due to typical Pitot tube uncertainties of 10% would have a potential cost implication for a typical UK power station of several hundred thousand pounds pa (based on typical US emissions trading costs).

Scope

The project will cover core requirements driven by the needs of industry and the measurement community.

1) Investigation and quantification of measurement errors in stack gas flow measurements, this will include an experimental study of the impact of temperature, flow variation, dust and humidity and other influence factors on Pitot tube measurements. The uncertainty of Pitot tube measurements under real stack conditions will be investigated.
2) Improve the calibration methodology and traceability infrastructure for air velocity measuring systems. The measurement method of the laser Doppler anemometer should be validated, against first principals of measurement of length and time, at ambient temperatures over the range of flow velocity expected in a stack (0 – 40 $m.sec^{-1}$). The LDA should then be tested in the hot wind tunnel to be developed under this project, to validate the effect of raised gas temperature on flow velocity measurement. Work at high temperatures will input into the work on validating Pitot Systems over different environmental conditions.
3) Reduction in the uncertainty of flow measurements in stacks by defining guidance and improved protocols for the use of Pitot tubes, and developing training programmes to address issues in their use in the field, including problems identified with the measurement of the differential pressure.

Deliverables

1) Report on Pitot System performance in stack conditions, including quantification of the effects of stack conditions and guidance on the determination of the uncertainty of Pitot tube measurements
2) Development and validation of improved calibration and traceability for stack flow measurements in the UK, including high temperature test duct.
3) Protocol for the use of Pitot tubes in stack conditions

Risks

The risks within this project are relatively low, the requirement from industry is clear, potential uptake is likely to be high and the target audience is well defined. Dissemination routes are well understood.
Technical challenges in investigating the performance of Pitot tubes under stack conditions including high temperatures are significant but manageable.

Dissemination and Exploitation

Dissemination routes include those already utilised for the preliminary investigation, for example the CEM conference on emissions monitoring, the SES conference in the US and the EmCerts conference organised by the Source Testing Association. In addition technical guidance notes published through the STA provide a focussed method of informing the target communities and direct training can be provided through the STA. Issues related to the metrology of Pitot tubes and LDA may also lead to the publication of peer reviewed papers and input into European and international standardisation activities.

Collaboration and Co-funding Opportunities

Collaboration with the STA will be advantageous, providing access to testing companies, industries, manufacturers and regulators. Additional collaboration with international flow calibration laboratories will be possible. Limited opportunities for co-funding exist, particularly from manufacturers of the measurement systems.