THE ELEMENTS OF PIPE FLOW AND BASIC METERING CONCEPTS

by

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LECTURE No 1

PRINCIPLES AND PRACTICE OF FLOW MEASUREMENT

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CONTENTS

NOTATION

A	Cross-sectional area of pipe
C	Coefficient of discharge of a flowmeter, $\left(=\frac{Q_T}{Q_I}\right)$
D	Diameter of pipe
F	Meter factor, $\left(=\frac{V_T}{V_I}\right)$
K	\`K-factor', $\left(=\frac{n}{V_T}\right)$
K_n	Nominal K-factor
m	Mass
n	Meter pulse count
p	Pressure
Q	Flowrate
Q_I	Indicated flowrate
Q_m	Mass flowrate, $\left(=\frac{dm}{dt}\right)$
Q_T	'True' flowrate (as measured by a calibration standard)
Q_V	Volumetric flowrate, $\left(=\frac{dV}{dt}\right)$
q	One-pulse volume, $\left(=\frac{1}{K}\right)$
R	Gas law constant
R_D	Reynolds number (based on pipe diameter), $\left(=\frac{\rho\bar{v}D}{\mu}\right)$
R_d	Reynolds number (based on meter throat diameter)
T	Temperature (absolute)
t	Time
V	Volume
V_I	Indicated volume
V_s	Specific volume, $\left(=\frac{V}{m}\right)$
V_T	'True' volume (as measured by a calibration standard)
v	Velocity at a point
v_I	Indicated velocity

v_T	'True' velocity (as measured by a calibration standard)
$\bar{v}$	Mean velocity over a cross-section
Y	Flowmeter readout
Z	Gas law deviation coefficient
β	Thermal expansion coefficient, $\left(=\frac{1}{V_s}\frac{\partial V_s}{\partial T}\right)$
$\dot{\gamma}$	Rate of shear strain
Δ	Meter error
κ	Compressibility, $\left(=-\frac{1}{V_s}\frac{\partial V_s}{\partial p}\right)$
μ	Viscosity, $\left(=\frac{\tau}{\dot{\gamma}}\right)$
ν	Kinematic viscosity, $\left(=\frac{\mu}{\rho}\right)$
ρ	Density
τ	Shear stress

1 INTRODUCTION

This course aims to deal with the flow measurement of any fluid for any application and so has a very wide scope. It is important therefore at the start to establish the foundations on which the subsequent pattern of the course is built. For this reason no more than a general understanding of physics is assumed in presenting the elements and basic concepts which follow.

2 PROPERTIES OF FLUIDS

2.1 Continuous Fluids

A fluid is any substance that flows. Fluids are normally classified into liquids, which can only be compressed with difficulty but will move around quite easily, and gases, which have no boundaries of their own and whose volume depend on the volume of the container. A basic concept of conventional fluid dynamics therefore is that a fluid, whether liquid or gas, is a continuous medium and one for which any flow is continuous.

The movement of a fluid generates (and is generated by) shearing forces between layers of the fluid, and when fluid flows in a pipe the velocity of the fluid must be zero at the wall and must increase progressively with the distance from the wall.

2.2 The P-V-T Equation

Before turning to individual properties of the fluids whose flow is to be measured, it is useful to cover one important general relationship. This is the P-V-T equation, which relates the volume of a fluid to both its temperature and the pressure acting on it. This relationship is normally important only for gases.

For a 'perfect' gas the relation is simple, viz

$$\frac{pV}{T} = \text{constant} \qquad (1)$$

In practice the pressure-volume-temperature properties of fluids are rarely simple even for pure chemicals, and in the case of 'so-called' natural gases much remains to be discovered. Studies have been made to develop general equations which could be used to calculate the physical properties of these gases in practical applications.

Normally the perfect gas law is extended to real gases by introducing a single parameter, Z, called the compressibility factor (or the 'gas law deviation coefficient' or 'super-compressibility factor')

$$pV = ZmRT \qquad (2)$$

2.3 Density and Specific Volume

The density of a fluid, ρ, is the ratio of its mass m to its volume V, while the specific volume is its reciprocal. That is to say

$$\rho = \frac{1}{V_s} = \frac{m}{V}. \qquad (3)$$

Densities vary widely according to the fluid and its temperature and pressure. As a rough indication, the density of water is about a thousand times that of air at atmospheric pressure and room temperature.

2.4 Thermal Expansion Coefficient

The thermal expansion coefficient of a fluid, β, otherwise known as its coefficient of volumetric expansion, is the fractional increase in specific volume (or the fractional decrease in density) caused by a temperature increase of 1°. That is

$$\beta = \frac{1}{V_S}\frac{\partial V_S}{\partial T} = -\frac{1}{\rho}\frac{\partial \rho}{\partial T} \qquad (4)$$

The thermal expansion coefficient of cold water is very small, 20×10^{-5}/°C at 20°C, and is usually disregarded except when very high accuracy is required, but it increases rapidly with increasing temperature. The thermal expansion of oils and liquid fuels, however, is very much higher than that of water, and is much less dependent on temperature. It cannot be neglected if high accuracy is required. Thermal expansion in gases is very much greater still, and must always be taken into account.

2.5 Compressibility

The compressibility of a fluid, κ, is the fractional decrease in specific volume (or the fractional increase in density) caused by unit increase of pressure. That is

$$\kappa = -\frac{1}{V_s}\frac{\partial V_s}{\partial p} = \frac{1}{\rho}\frac{\partial \rho}{\partial p}. \tag{5}$$

The compressibility of water is about one twenty-thousandth of that of air at atmospheric pressure, and for most purposes can be ignored. The compressibility of liquid petroleum products varies with their composition, viscous oils being only a little more compressible than water and light fuels being more than twice as compressible as water. In the large-scale commercial metering of oils and fuels compressibility is generally taken into account when pressures above about 2 bar are encountered.

Gases are very highly compressible at low pressures, but much less so at high pressures.

2.6 Viscosity

The viscosity, μ, of a fluid is a measure of its resistance to shearing at a constant rate. In terms of Figure 1 below

$$\mu = \frac{\tau}{\dot{\gamma}} \tag{6}$$

where τ is the shear stress, and

$\dot{\gamma}$ is the rate of shear strain.

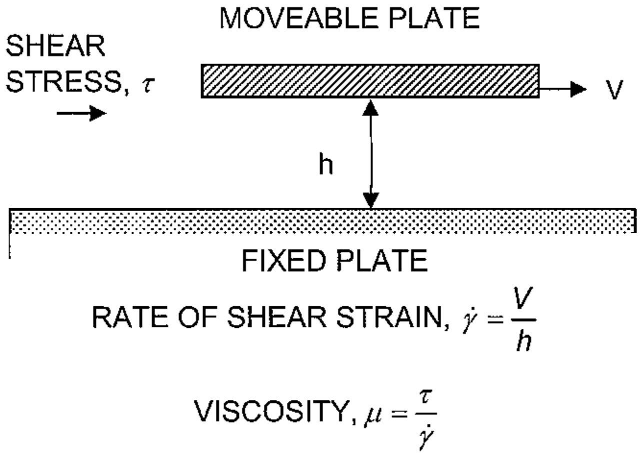


Figure 1 - Basis of Definition of Viscosity

The SI unit of viscosity is the Pascal second (Pa s), but it is more usual to express viscosities in centipoise (cP), one cP being 10^{-3} Pa s. Viscosity is often referred to as 'absolute viscosity' or 'dynamic viscosity', to distinguish it from kinematic viscosity, ν, the latter brings in another factor, being the ratio of viscosity to density, μ/ρ. The SI unit of kinematic viscosity is m^2/s, and the common unit is the centistoke (cSt), one cSt being 10^{-6} m^2/s.

To give the reader a feel for viscosity values, some values for common substances are given in Table 1. The values quoted are at normal ambient temperatures; it should be noted that the viscosity of a *liquid* falls rapidly with increasing temperature, while that of a *gas* increases with temperature.

Table 1 - Approximate Viscosities of Common Substances

Substance	Approximate viscosity, cP, at 20°C
Air	0.02
Water	1
Engine oil	100
Gear oil	1 000
Honey	10 000

Viscosity can be measured conveniently in a concentric-cylinder viscometer, as shown in Figure 2, or, more accurately, in a U-tube viscometer, Figure 3.

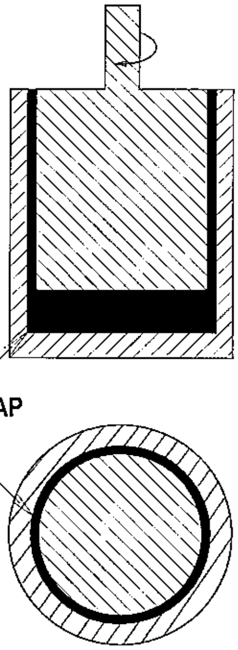
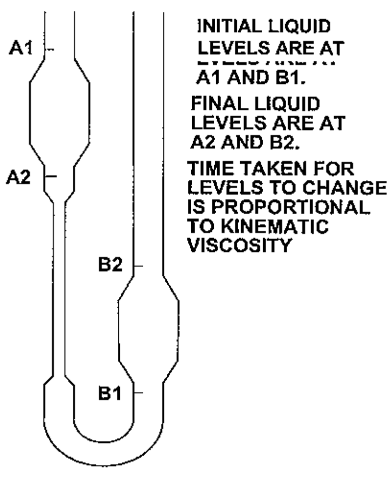


Figure 2 - Principle of the Concentric



PRINCIPLE OF THE U - TUBE VISCOMETER

Figure 3

Some liquids, including molten polymers and suspensions of solids in liquids, have a viscosity which varies with the rate of shear strain, $\dot{\gamma}$. They are termed 'non-Newtonian' and their behaviour is very complex; **they will not be dealt with in the formal part of this course.**

2.7 Solubility of Air in Liquids

Air is soluble in liquids, and its solubility is directly proportional to the absolute pressure. The solubility of air in water is about 2 per cent by volume at an absolute pressure of 1 bar, 4 per cent at 2 bar, 1 per cent at 0.5 bar, and so on. Air is very much more soluble in hydrocarbons: typical values at 1 bar are 8 per cent in lubricating oil, 12 per cent in kerosine and 16 per cent in gasoline.

Dissolved air is likely to be released from solution in oils and fuels if the pressure is allowed to fall momentarily much below atmospheric. The resulting air bubbles in the liquid can cause metering errors. (See Section 3.8.)

2.8 Humidity in Gases

Gases may be either dry or humid (damp). This is because a gas at a given temperature is capable of holding up to a certain maximum amount of water vapour; this maximum amount increases as the temperature increases. When a gas is holding the maximum amount of water vapour it is said to be saturated with water vapour. If it is unsaturated, its degree of saturation may be expressed as a relative humidity.

The humidity of a gas affects its density. For example, in the case of air at 1 bar and 23°C, the density when dry is about 1 per cent greater than the density when saturated with water vapour.

Sudden changes in humidity may cause errors in gas flow measurement. In particular, errors can easily occur if unsaturated gas is passed through a wet gas meter, or if a sudden expansion cools a gas sufficiently to cause precipitation of some of its water vapour.

3 SOME IMPORTANT PRINCIPLES OF PIPE FLOW

Flow measurement in industry is mainly concerned with measuring the flow of fluids in pipes. It is therefore most important to understand the basic principles of pipe flow.

3.1 Reynolds Number

The behaviour of fluids flowing through pipes can be said to be broadly governed by a quantity known as Reynolds Number (R_D). This is defined as follows:

$$R_D = \frac{\rho \bar{v} D}{\mu} \qquad (7)$$

where $\bar{v}$ is the mean velocity and D is the pipe diameter.

The Reynolds Number is a valuable concept. Consider the numerator in Equation (7); ρ is mass per unit volume. $\rho \bar{v}$ is therefore momentum per unit volume, and $\rho \bar{v} D$ is moment of momentum per unit volume. The numerator is therefore a measure of the flowing fluid's ability to generate dynamic forces, whilst the denominator, μ, its dynamic viscosity, is a measure of its ability to generate viscous forces.

This means that the Reynolds Number indicates which kind of forces will predominate in the flowing fluid. When $\rho \bar{v} D$ is relatively large R_D will be large and dynamic forces will prevail, but when μ is relatively large R_D will be smaller and viscous forces will prevail.

Incidentally, R_D is called Reynolds Number because the dimensions of $\rho \bar{v} D$ are the same as those of μ, and R_D is therefore a dimensionless ratio.

3.2 Laminar and Turbulent Flow

A fluid can flow along a pipe in either of two very different ways.

Laminar flow - or, as it is sometimes called, 'streamline flow', or 'viscous flow' - occurs at Reynolds Numbers below about 2000. This can be likened to the flow of traffic on a busy motorway, with the traffic in the various lanes travelling on parallel paths at different speeds; the slow lane is next to the pipe wall and the fast lane in the centre of the pipe. When studying laminar flow in pipes engineers usually assume that the 'traffic' never changes lanes. In fact, gradual lane-changing does occur. It is called 'secondary flow' and is a complex subject, which is generally ignored in practical situations though it can have important consequences at times.

Turbulent flow occurs at Reynolds Numbers above about 2000 (and sometimes can persist or be initiated at much lower Reynolds Numbers, too). It can be likened to the flight of a flock of starlings. The flock as a whole may be travelling in a straight line at a constant speed, but if you could watch the flight of any individual bird it will appear to be zig-zagging and gyrating wildly within the flock.

In industry, pipe Reynolds Numbers are usually well above 2000 and laminar flow is rarely encountered, unless very viscous liquids are being piped. **Throughout this course it can be assumed that turbulent flow is always being considered, unless laminar flow is specifically mentioned.**

3.3 Velocity Profile

A graph showing how the velocity varies across a diameter of a pipe is called a velocity profile. Examples of three important types of velocity profile are given in Figure 4.

In laminar flow the velocity profile is a parabola, and the velocity in the centre of the pipe is twice the mean velocity, Figure 4(a).

With turbulent flow, the velocity profile at the downstream end of a very long length of straight pipe is much flatter, and the velocity at the centre is about 1.2 times the mean velocity. Under these conditions the profile is said to be 'fully developed', or 'normal', Figure 4(b)

3.4 Asymmetry

In practical pipe circuits the layout will contain changes of section and direction. The profile can be greatly distorted by the presence of a bend in the pipe, or by a flowmeter or a valve etc, Figure 4(c) shows two typical asymmetrical profiles, derived from measurements with a laser velocimeter 5 and 20 diameters down-stream of the same bend in a 75 mm pipe.

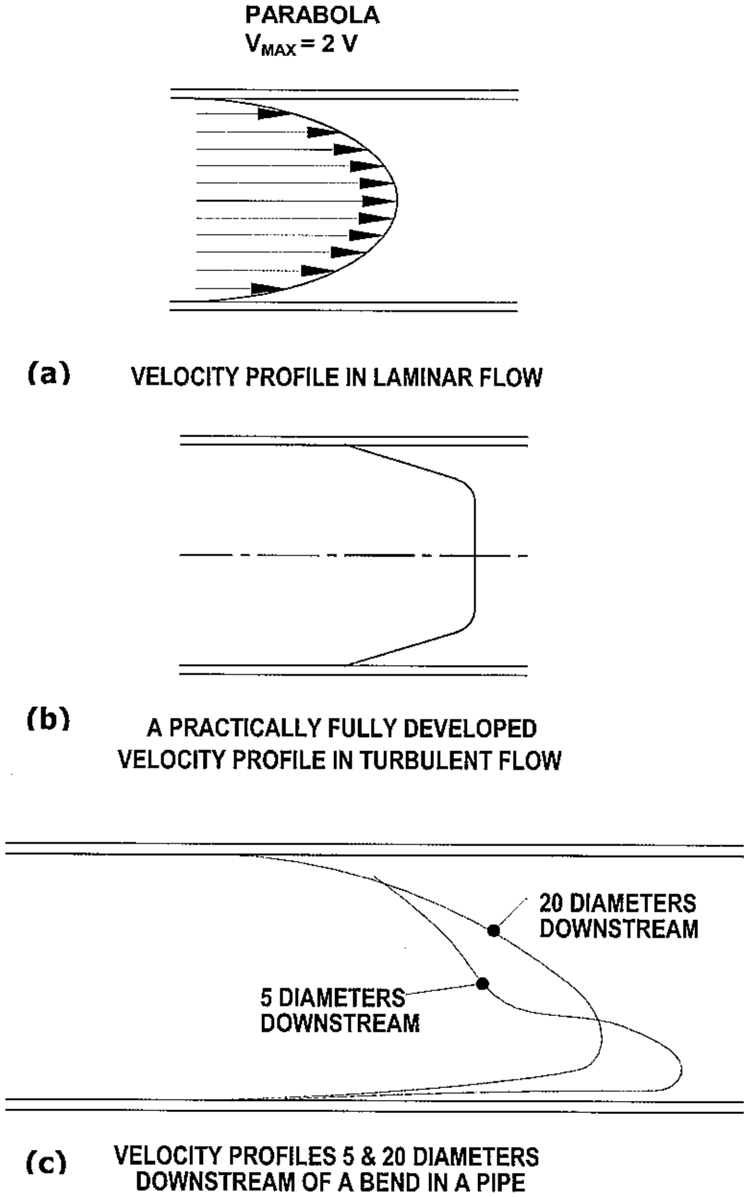


Figure 4 - Velocity Profiles in Various Flow Situations

3.5 Secondary Flow and Swirl

Bends, flowmeters, valves, etc. also produce what is known as secondary flow. In addition to distorting the velocity profile in the axial direction there is flow in the plane perpendicular to the axial direction. Downstream of a single bend there are two counter-rotating vortices in the downstream straight pipe, which are superimposed on the forward velocity.

The most severe kind of secondary flow is the three-dimensional rotational flow, or 'swirl', created by two adjacent bends in different planes, as shown in Figure 5. This causes the flow to rotate in a corkscrew fashion, and the effect persists for very long distances. At very high Reynolds Numbers in a very smooth pipe the swirl decays at the rate of about 1 per cent per diameter, and at lower Reynolds Numbers at only about 2 or 3 per cent per diameter - that is to say, in a pipe of say, 100 mm diameter, the severity of the swirl present diminishes by only 1 (or 2 or 3) per cent for each 100 mm it travels along the pipe.

Severe swirl can, if necessary, be suppressed by the installation of a flow straightener, as will be discussed in a later lecture.

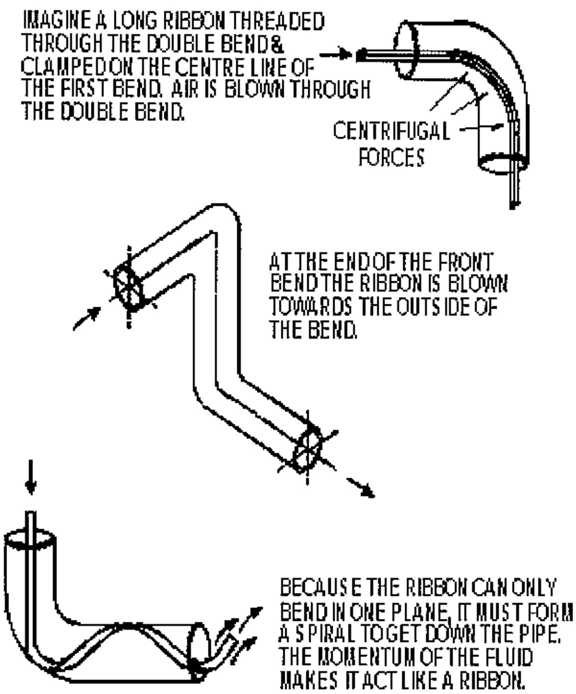


Figure 5 – Helical Swirling Flow Created by Two Adjacent Bends in Planes at Right

3.6 Continuity and Bernoulli's Equation

The principle of continuity states that mass flowrate is the same at all cross-sections of one continuous pipe. What goes in at one end of a pipe must come out of the other. If the fluid is incompressible, the volumetric flowrate remains constant also.

This principle is of great importance when studying flowmeter behaviour. It means that when the cross-section decreases the mean velocity must increase and vice versa.

The total momentum possessed by a flowing fluid is approximately the same at every cross-section along the pipe. Bernoulli's equation expresses this fact in mathematical terms.

$$\frac{\overline{v}^2}{2g} + \frac{p}{\rho g} = \text{constant at all cross-sections} \qquad (8)$$

This simple equation is used to derive theoretical expressions for the behaviour of many types of flowmeter.

3.7 Velocity Head

The expression $\bar{v}^2/2g$, where g is the acceleration of gravity, provides a convenient way of indicating the amount of kinetic energy possessed by the fluid flowing in a pipe. It has the dimensions of length, and is equal to the height (head) to which the fluid would rise if it were projected vertically upwards at a velocity $\bar{v}$ in an ideal world where there was no such thing as friction.

An important use of this concept is to express the tendency of pipe fittings to dissipate energy. For example, if a certain flowmeter is said to cause a 'loss of three velocity heads', this means that the head loss across that meter will always be approximately 3 $\bar{v}^2/2g$, regardless of the nature of the fluid or its velocity.

3.8 Cavitation

It follows from Equation (8) that when the mean velocity increases (as it must do when the cross-sectional area of flow is reduced) the pressure will decrease. In a flowing liquid, if the pressure drop is large enough, a phenomenon known as cavitation can occur. This can take two different forms.

In water and in liquefied gases cavitation generally occurs only when the pressure at some point approaches the vapour pressure of the liquid. Then bubbles of pockets of vapour appear, only to collapse as soon as they enter a region of higher pressure. If this occurs inside a flowmeter it will give wrong readings. When this sort of cavitation occurs in a severe form it often betrays its presence by a crackling noise.

In oils and liquid fuels cavitation generally takes a different form. It begins at pressures somewhat below atmospheric, but well above the vapour pressure, and consists of the release from solution of bubbles of air. These bubbles take quite a long time to dissolve again, and can therefore affect the readings of flowmeters installed well downstream of the point of cavitation.

Both types of cavitation must be avoided if accurate flow metering is required.

4 WHAT MEASUREMENT OF THE FLOW IS REQUIRED

The term 'flow measurement' can refer to any of six different types of measurement. These are briefly described below.

4.1 Point Velocity Measurement

Instruments are available with which the velocity, v, of a fluid at a point can be measured. These are often (though not invariably), called 'anemometers' if intended for use in free-flowing air, 'current meters' if intended for use in water and 'insertion meters' if intended for use specifically inside a pipe or duct.

4.2 Mean Pipe Velocity Measurement

Mean pipe velocity, $\bar{v}$, is related to volumetric flowrate, Q_V (see Section 4.3), and pipe cross-sectional area, A, by the relationship

$$\bar{v} = \frac{Q_V}{A} \qquad (9)$$

$\bar{v}$ can be determined in three ways: by measuring Q_V and A and then employing Equation (9), by measuring v at numerous points on one cross-section and then taking an appropriately weighted mean; or, less accurately, by measuring the velocity at a point three-quarters of the way between the pipe centre and the wall, since it is known that in fully developed profiles the velocity there is approximately equal to the mean velocity.

4.3 Volumetric Flowrate Measurement

Volumetric flowrate, Q_V, is defined as the passage of a given volume of fluid, V, in a given time, t. Thus:

$$Q_V = \frac{V}{t}. \qquad (10)$$

Many flowmeters are designed to indicate directly the value of Q_V; such meters are sometimes referred to as 'flowrate meters'.

4.4 Total Volume Measurement

Some meters are designed to indicate directly the total volume V passing through the meter; they are sometimes called 'volume meters', or 'bulk meters', to distinguish them from flowrate meters.

It follows from Equations (9) and (10) that you can derive V from a flowrate meter by integrating its output over a period, and that you can derive Q_V from a volume meter by differentiating its output with respect to time. These operations usually result in some loss of accuracy, however.

4.5 Mass Flowrate Measurement

Mass flowrate, Q_m, is the passage of a given mass of fluid in a given time, or

$$Q_m = \frac{M}{t}. \qquad (11)$$

Some flowmeters are designed to indicate mass flowrate directly. They are called 'mass flowmeters', or 'true mass flowmeters'.

Q_m is frequently determined by making simultaneous measurements of Q_V and ρ, and then employing the relationship

$$Q_m = \rho Q_V \qquad (12)$$

4.6 Total Mass Measurement

As yet there is no flowmeter capable of measuring directly the total mass of fluid passing during a period. To determine M it is necessary either to measure Q_m and integrate the measurements over a period using Equation (11), or to measure V and ρ and then employ Equation (2).

5 CHARACTERISTIC CURVES

A calibration curve (or characteristic curve) is a graph showing how the performance of a flowmeter varies with flowrate, or with velocity or Reynolds Number, in cases where one of these is more appropriate.

Such a curve is generally derived from a calibration, that is to say from a series of tests over a range of flowrates or velocities in which the reading of the flowmeter is compared with a measured value of flowrate (or of volume, or of mass, or of velocity, if this is what the flowmeter concerned is designed to indicate) derived from a measuring device of higher accuracy.

5.1 Linear and Non-linear Flowmeters

In principle, the results of a calibration may be plotted as a graph of flowmeter readout, Y, against flowrate, Q. If the graph forms a more-or-less straight line through the origin as in Figure 6 the flowmeter is described as 'linear'. Many non-linear flowmeters have a characteristic of the form shown in Figure 7 overleaf, where Q is proportional to $Y^{1/2}$. Venturi meters, orifice plates and pitot tubes, where Y is a measured value of pressure difference, come into this category.

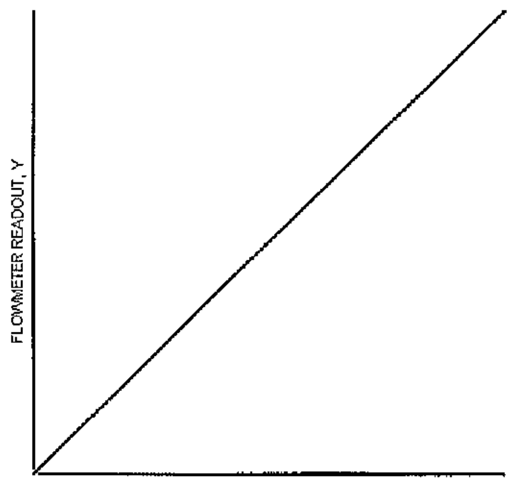


Figure 6 - Linear Flowmeter Characteristic Curve

5.2 Use of a Flowmeter Performance Index

In practice, graphs of the form shown in Figures 6 and 7 are rarely used, because they are not capable of showing sufficient detail. What is needed is a graph that clearly displays any small deviations from ideal behaviour by the flowmeter.

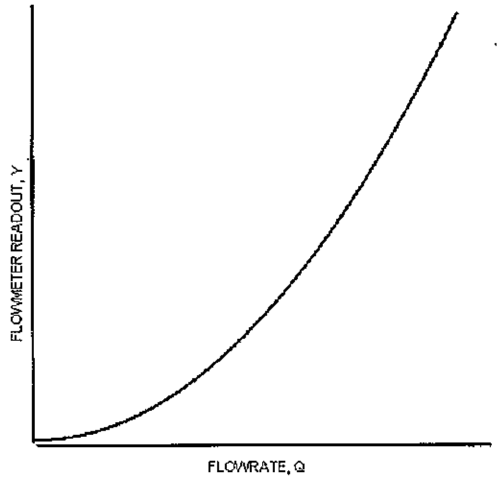


Figure 7 - Non-Linear Flowmeter Characteristic Curve

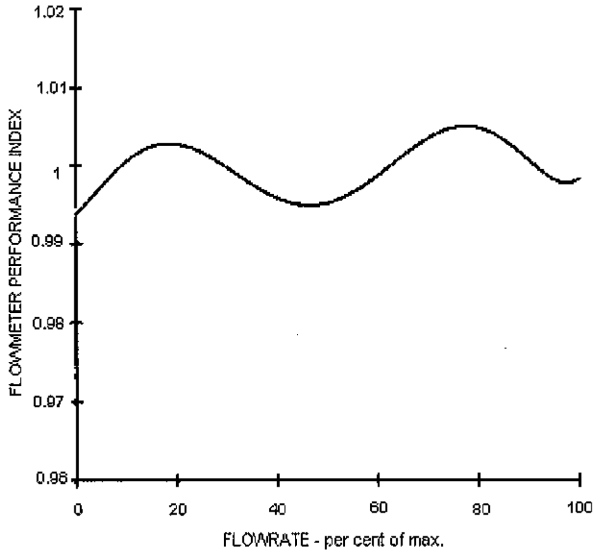


Figure 8 - Use of a Performance Index Enables Flowmeter Calibration Characteristics to be Exhibited More Clearly

It is therefore usual to plot some kind of flowmeter performance index against flowrate or against some comparable quantity such as Reynolds Number, as illustrated in Figure 9 below. The closer the resulting graph is to a horizontal straight line, the closer is the performance of the flowmeter to the ideal.

Numerous types of index are possible, but only four are in common use. They are briefly described below.

5.3 Coefficient of Discharge

Coefficient of discharge (or discharge coefficient), C, is defined for flowrate meters by the equation

$$C = \frac{Q_T}{Q_I} \qquad (13)$$

and for velocity meters by the equation

$$C = \frac{v_T}{v_I} \qquad (14)$$

where Q_T and v_T denote what is commonly called 'true' flowrate and 'true' velocity, by which is meant the quantities as measured by the higher accuracy device used in the calibration. Q_I and v_I denote the flowrate or velocity indicated by the meter, or calculated from its readings.

The coefficient of discharge, Figure 9, is used extensively in connection with differential pressure meters. In this case Q_I may be based on a simplified model of meter performance, and thus the discharge coefficient may differ significantly from 1. The discharge coefficient is often plotted against R_d, the Reynolds Number at the throat of the meter, as in Figure 9, though R_D, the Reynolds Number based on pipe diameter is often preferred.

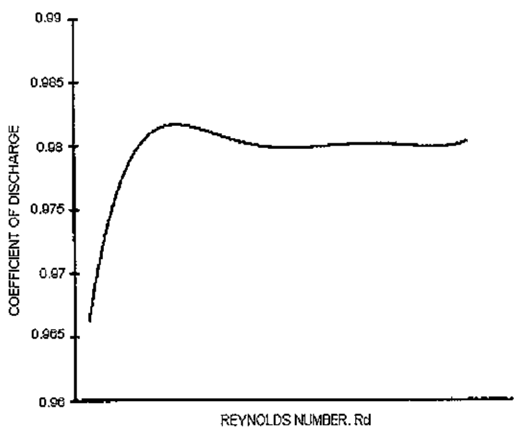


Figure 9 - Example of Characteristic Curve Based on Coefficient of Discharge

5.4 Meter Error

Meter error, Δ, is a term used in connection with volume meters of the type that read directly in volume units, especially displacement meters. It is defined as

$$\Delta = \frac{V_I - V_T}{V_T} \qquad (15)$$

where V_T and V_I denote 'true' and indicated volume respectively. It is normally expressed as a percentage of the 'true' volume.

5.5 Meter Factor

Meter factor, F, is a term mainly used in connection with meters used for measuring total volume, and especially with turbine meters and positive displacement meters. Unfortunately different operators use it in several different ways, and this has caused great confusion in the past. It is now generally agreed that the correct definition should be

$$F = \frac{V_T}{V_I}. \qquad (16)$$

It is the factor by which the indicated volume should be multiplied in order to obtain the 'true volume'.

5.6 K-Factor

K-factor is a term used to describe the performance of meters, such as turbine meters, whose output is in the form of a series of electrical pulses, and where the total pulse count, n, is nominally proportional to the volume passed, and the pulse frequency, dn/dt, is nominally proportional to the flowrate. It is defined as

$$K = \frac{n}{V_T} \qquad (17)$$

Characteristic curves for turbine meters customarily take the form of a graph of K-factor against flowrate, as in Figure 10.

The reciprocal of the K-factor is a factor of great practical importance, since, when a meter is used, the meter pulse count, n, must be multiplied by 1/K to derive the volume passed by the meter.

6 PROPERTIES OF MEASURING INSTRUMENTS

Any measuring instrument can only provide the user with an estimate of the true value of the quantity being measured and the user needs to know how much confidence he can have in the measurement. The value of an instrument in making a measurement depends on its discrimination, its repeatability, its accuracy, its effective range, and its linearity.

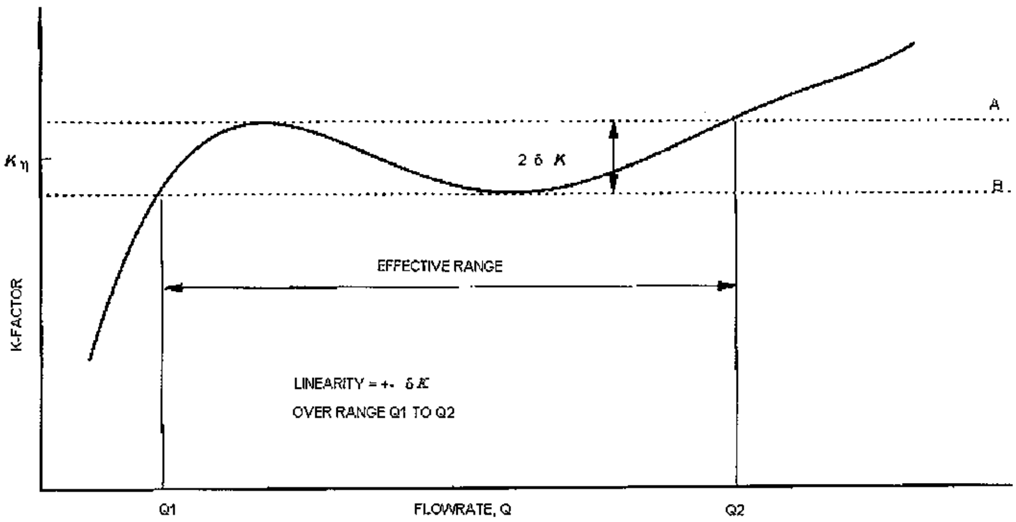


Figure 10 - Example of Characteristic Curve Based on K-Factor (Also Illustrating Meaning of the Terms, 'Effective Range' and 'Linearity')

6.1 Resolution

By international agreement the word 'resolution' is used to describe the smallest change in the display of an instrument which can be read. For example, the resolution of a digital electronic timer reading in milliseconds is a hundred times as great as that of a digital electronic timer reading in tenths of a second. Resolution must not be confused with accuracy. Resolution tells you how many decimal places you read to; it tells you nothing about how many of those decimal places you can rely upon.

6.2 Repeatability and Reproducibility

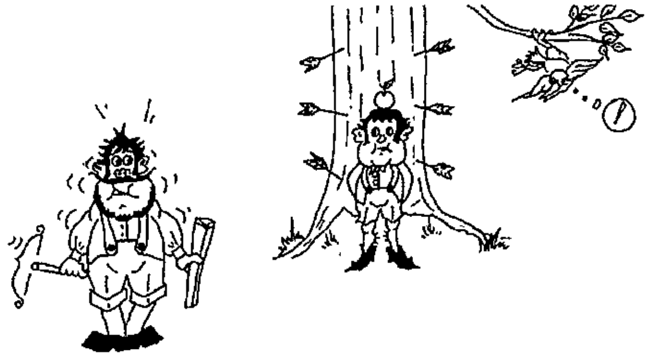
The repeatability of an instrument is an indication of its ability to give the same result when it is used to measure the same quantity several times in succession. A numerical value of repeatability can be obtained experimentally by installing two identical flowmeters in series and comparing their readings many times in succession.

Repeatability is also often confused with accuracy, which, as Figure 11 shows, is not the same thing at all. If an instrument has poor repeatability it is bound to have poor accuracy also. But if it has good repeatability that does not necessarily mean it will have good accuracy (although it might have), since it could be giving the same wrong answer time after time.

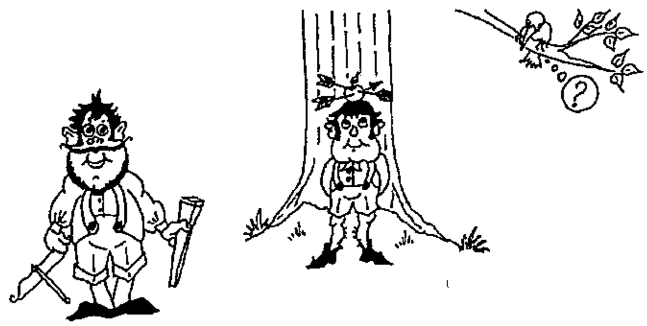
A term related to repeatability is reproducibility. This is the ability of an instrument to give the same result when it is used to measure the same quantity at different times and under different conditions.

6.3 Accuracy and Uncertainty

If we think of repeatability as the measure of an instrument's ability to stick to the same story, accuracy is a measure of its ability to tell the truth. In general, good repeatability depends upon good design and careful manufacture, whereas good accuracy depends upon those two things plus a third: accurate calibration against a standard. Where it is essential for high accuracy to be maintained over a period, recalibration at intervals may be needed.



(a) Poor repeatability means poor accuracy



(b) Good accuracy means good repeatability

(c) Good repeatability does not necessarily mean good accuracy

Figure 11 - Comparison of Accuracy and Repeatability

The word 'accuracy' is a qualitative one and should not be used quantitatively. This is because it has come to be used with many different meanings. The term now internationally accepted for 'measuring' the accuracy or inaccuracy of a measurement is 'uncertainty'. This term has a precise meaning and should be used for all measurements of flow.

Much confusion is caused by the existence of two very different methods of expressing uncertainty. Some manufacturers quote it as a percentage of full scale reading, others as a percentage of actual reading. The difference becomes highly significant when an instrument is working near the bottom of its range: for example, at one-fifth of the scale maximum an uncertainty of '1 per cent of full scale' is equal to an uncertainty of '5 per cent of reading'. **In this course, unless otherwise stated, quoted uncertainties are always expressed as a percentage of actual reading.**

Remember that good repeatability costs a lot, and good accuracy costs even more. It is wasteful to install a highly repeatable instrument where a cheap one would do; and equally wasteful to install a highly accurate and well-calibrated instrument if all you need is good repeatability - which may well be the case if you are only using it for control purposes. High accuracy is, however, needed if you are buying, selling or paying taxes against meter readings. The best way to ensure high accuracy is by using a meter of high repeatability in conjunction with a 'dedicated' (that is, permanently built-in) calibration device, as is found in many oil industry applications.

6.4 Effective Range and Rangeability

The effective range of an instrument is defined as the range over which it meets some specified accuracy requirements. This definition is illustrated in Figure 10, where the horizontal lines A and B represent the permitted limits of accuracy, and the effective range is therefore from Q_1 to Q_2. The ratio Q_2/Q_1 is often called the 'rangeability' of an instrument, or, in the case of a flowmeter, its 'turndown ratio', or simply, 'turndown'.

6.5 Linearity

The linearity of an instrument is a measure of the extent to which its performance over its effective range departs from the ideal. In Figure 10, where the accuracy limits are drawn $2\delta K$ apart, the linearity is $\pm\delta K$. It is usually expressed as a percentage of the nominal K-factor, K_n, that is, as 100 $\delta K/K_n$ per cent.

7 CONCLUDING REMARKS

There will be many more concepts introduced during the course which relate to specific aspects of flowmeters and flow measurement. The notes here are of a general nature so that the reader may have a broad understanding of the background before dealing with the particular aspects to be covered in the lectures ahead.

ULTRASONIC FLOW METERS

by

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LECTURE No 4

PRINCIPLES AND PRACTICE OF FLOW MEASUREMENT

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CONTENTS

1 INTRODUCTION

The use of ultrasound in flow measurement dates at least as far back as a German patent filed in 1928. The development of ultrasonic flowmeters has advanced significantly since the introduction of the first commercial meters in the 1950's. Modern ultrasonic meters based on the transit time principle are now capable of high performance, with some manufacturers producing 4th and 5th generation products.

A diverse variety of ultrasonic techniques are available for use in flow measurement. These range from simple flow switches to sophisticated imaging techniques transferred from the medical and non-destructive testing fields. These notes provide an introduction into what is now a very diverse topic in instrumentation theory and practice.

2 BASIC PRINCIPLES

The primary element of an ultrasonic measurement system is the ultrasonic transducer. Most transducers utilise the piezoelectric properties of crystalline, ceramic or polymer film materials to generate high frequency sound energy by converting electrical pulses into mechanical vibrations (Figure 1). The force produced at the face of the transducer gives rise to a pressure (sound) wave in the adjoining medium. If the frequency of the acoustic waves is greater than 20 kHz they are classified as ultrasonic; i.e. beyond the range of human hearing.

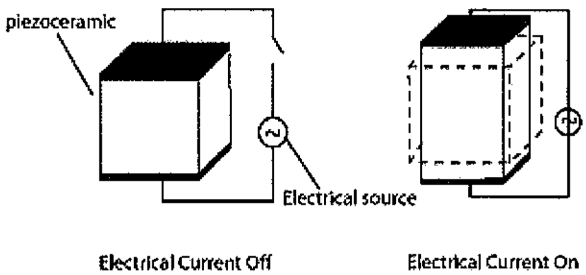


Figure 1: Schematic diagram of piezoelectric ultrasonic transducer

The component parts of a generalised ultrasonic system are the transducer elements, excitation and detection electronics, system control, signal processing, data processing and data presentation elements as illustrated in Figure 2.

A variety of forms of electrical excitation can be utilised (e.g. continuous wave, pulsed, tone burst etc.) as illustrated in the figure, and likewise, the signal detection and processing utilised to measure the flow related signal parameter can vary both in methodology and implementation.

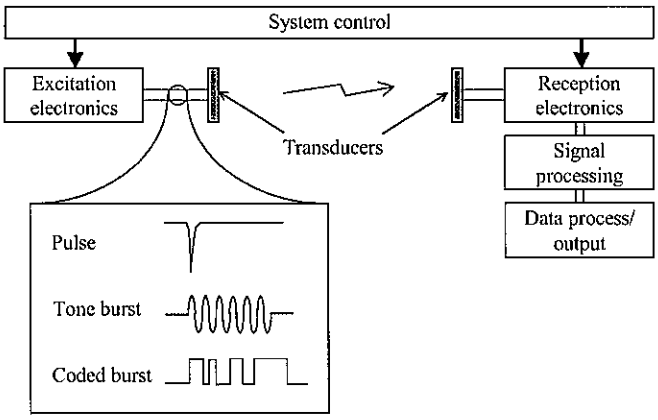


Figure 2 - A generalised ultrasonic measurement system

3 TECHNOLOGICAL BENEFITS

Ultrasonic techniques possess significant potential advantages when compared with traditional mechanical methods of flow measurement. One of the most significant advantages of ultrasound is the capability for non-invasive measurement, i.e. sensing the flow using transducers which are removed from the point of measurement. When conditions are favourable this can permit measurement of flow parameters with transducers external to the flow conduit. Such *non-invasive* instrumentation facilitates on-line maintenance, isolation of transducers from hazardous or corrosive materials and instrument portability. Even if the transducers are in contact with the fluid, *non-intrusive* ultrasonic measurement techniques have the advantage of minimising flow disturbance and the potential for fouling or erosion and impact damage from entrained materials in addition to preventing excessive pressure drop at the measurement location. Figure 3 illustrates the classification of intrusive, invasive, non-intrusive and non-invasive measurement.

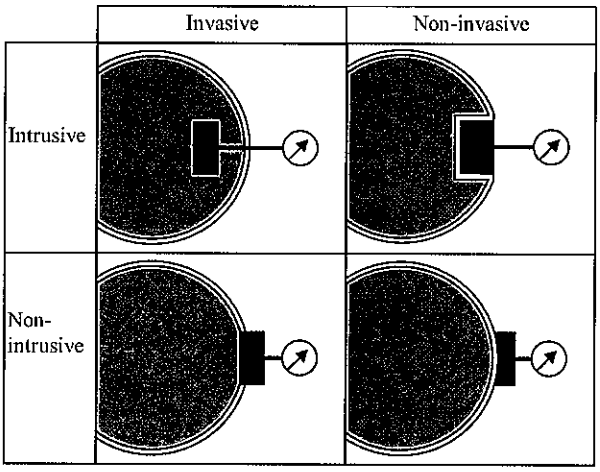


Figure 3 - An illustration showing definitions used in pipeline instrumentation

Another advantage of an ultrasonic instrument is that the components need not move (other than by acoustical vibration). This means that ultrasonic instruments can be free of the problems of mechanical inertia and progressive wear (associated with meter types such as the turbine). Furthermore, instruments for pipes of various sizes tend to use nominally identical transducers and electronics with the result that relative costs reduce with increasing meter size. For traditional mechanical meters and more recent developments such as the Coriolis mass flowmeter the opposite is true, giving ultrasonic technology a significant economic edge in large systems. For pipe diameters in excess of 3 m, ultrasonics are one of few viable technologies.

The manufacturers of ultrasonic meters claim many other potential advantages, but it must be remembered that these benefits can only be realised if the metering system is properly designed, installed and operated. Claims generally associated with ultrasonic meters are outlined below.

- Wide Turndown Ratio (ratio of maximum and minimum flow rate)

A major limitation of types such as the turbine meter is that accuracy tends to be restricted to a limited range in terms of flowrate (e.g. 10:1). The claimed turndown ratio of an ultrasonic flowmeter can be as high as 400:1.

- Fast Time Response

The short propagation times involved in ultrasonic measurements, typically only a few milliseconds, can facilitate fast and accurate instrument response in transient and pulsating flows.

- Intrinsic Calibration

As ultrasonic flowmeters are based on linear velocity relationships involving measurable parameters, the meter calibration factors can, in theory, be accurately derived under "dry" conditions without the need for wet-calibration in a flow facility.

- Bi-directional Measurement

It is sometimes desirable to transfer fluid in either direction in a pipeline. Some metering technologies require an additional metering section or a system of pipes and valves to enable the flow to pass in the same direction through the meter itself. Additional costs may be avoided by use of an ultrasonic meter since these can measure bi-directional flow (both magnitude and direction) without additional pipeline modifications.

- Diverse Applicability

Ultrasonic techniques are applicable to a diverse range of products. Extreme temperature, non-conducting, corrosive, gaseous and even some multi-component flows can be handled by ultrasonic techniques. Examples are flow measurement of nitric acid, hot bitumen, crude oil, flare gas, liquid helium, paper pulp suspensions, and pneumatically conveyed pulverised coal.

- Diagnostic and Secondary Measurements

Ultrasonic meters (and other 'electronic' meters) can often utilise secondary measurements of signal parameters for checking measurement integrity and setting fault indications. As microprocessors are utilised in most modern meters, signal parameters may also be assessed by statistical means. In the case of the transit time principle, the meters generally provide a velocity of sound indication which can be used in determination of fluid properties. Multi-sensor, multi-channel designs also have the capability for providing spatial information which is useful as a flow diagnostic.

4 PRINCIPLES

Ultrasonic flowmeters of various types have been developed over the years; indeed, new concepts and hybrid developments are still emerging. Selected measurement techniques are illustrated in Figure 4. Although each of these techniques have individual merits, the focus is set upon transit time ultrasonic flowmeters as these have been most successfully applied in industry. Doppler, cross-correlation, and level-based flow measurement techniques are also covered in these notes, but in lesser detail.

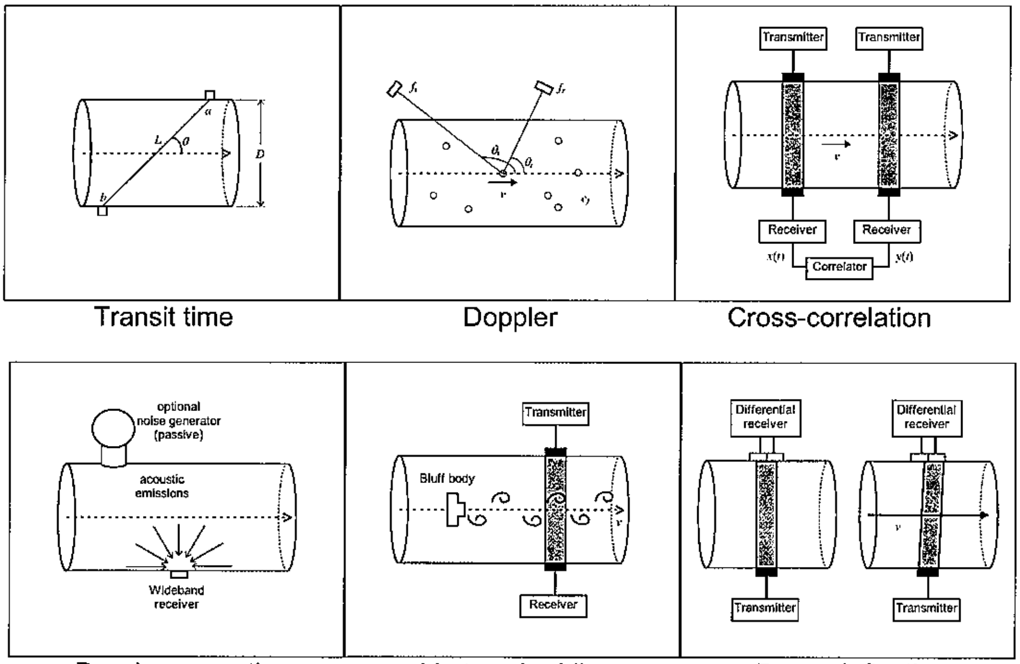


Figure 4 - An illustration of ultrasonic flow measurement principles

4.1 The Transit Time Flowmeter Principle

Ultrasonic transit time flowmeters are based on measurement of the propagation time of acoustic waves in a flowing medium. This is based on the principle that the apparent velocity along a ray is given by the velocity of sound in the fluid at rest, c_f, plus the component of fluid velocity, $\overline{v}$, along the ray. This principle is analogous to the travel of a motorised boat in a flowing current. To eliminate the velocity of sound from the subsequent derivation, transit times are determined both in the direction of flow and against it. Considering the general ray geometry shown in Figure 5, the upstream transit time and downstream transit time are given by

$$t_{ab} = \frac{L}{\left(c_f - \overline{v}\cos\theta\right)} \quad \text{and} \quad t_{ba} = \frac{L}{\left(c_f + \overline{v}\cos\theta\right)} \qquad (1)$$

$\overline{v}$ = velocity integrated over path length L from point a to b, i.e. $\overline{v} = \frac{1}{L}\int_a^b v\,dx$ (2)

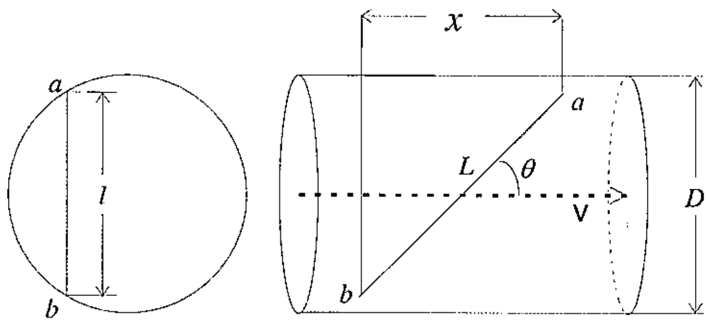


Figure 5 - General ray geometry for transit time velocity measurement

There are four basic methods by which transit time velocity measurement is performed; direct time differential, phase differential, phase control, and frequency differential[1]. In modern ultrasonic flowmeters the direct time differential method is most common. Short pulses are propagated upstream and downstream and the time interval for each excitation/detection is measured against an accurate high-frequency clock. The expressions for the upstream and downstream transit times are then solved for $\bar{v}$, independently of c_f, as follows:

$$c_f = \frac{L}{t_{ab}} + \bar{v}.\cos\theta = \frac{L}{t_{ba}} - \bar{v}.\cos\theta \qquad (3)$$

$$2.\bar{v}.\cos\theta = L.\left(\frac{1}{t_{ba}} - \frac{1}{t_{ab}}\right) \qquad (4)$$

$$\bar{v} = \frac{L}{2\cos\theta}\left(\frac{1}{t_{ba}} - \frac{1}{t_{ab}}\right) = \frac{L^2}{2x}\frac{\Delta t}{t_{ab}t_{ba}} \qquad (5)$$

The volumetric flowrate, q_v, is simply obtained by multiplying $\bar{v}$ by the cross-sectional area, A, of the flow. Thus:

$$q_v = A\frac{L^2}{2x}\frac{\Delta t}{t_{ab}t_{ba}} = \frac{\pi D^2}{4}\cdot\frac{L^2}{2x}\cdot\frac{\Delta t}{t_{ab}t_{ba}} \qquad (6)$$

The theory, in this form, neglects the fact that due to non-uniform distribution of velocity in the cross-section, the velocity measured on a finite path may not be an accurate representation of the mean velocity in the cross-section.

4.2 The Doppler Flowmeter Principle

These meters make use of the well-known Doppler effect. Consider a sound source which is moving with respect to a stationary observer. As illustrated in Figure 6 this movement produces an apparent change in frequency, and this is the cause of the tone variation observed, for example, when an emergency vehicle passes with its siren sounding.

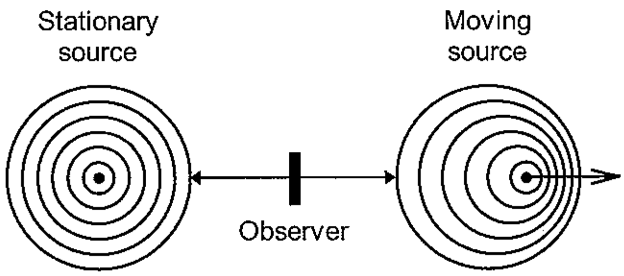


Figure 6 - An illustration of the Doppler effect

When applied to flow measurement, ultrasound of frequency f_t is transmitted into the flowing medium and discontinuities such as entrained gas bubbles or solid particles 'scatter' or reflect the ultrasound. The received ultrasonic energy is Doppler frequency shifted by an amount δf, given by

$$\delta f = f_t - f_r = f_t\left(\frac{v\cos\theta_r}{c} + \frac{v\cos\theta_t}{c}\right) \qquad (7)$$

where f_r is the received ultrasonic frequency, v is the velocity of the scattering particle with respect to the conduit axis, θ_t and θ_r are the transmission and reception angles, and c is the velocity of sound in the flow medium.

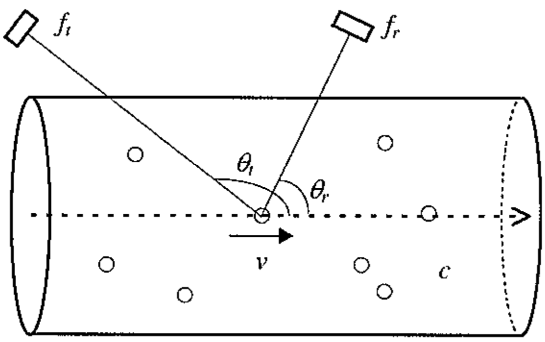


Figure 7 - A schematic diagram illustrating Doppler flow measurement

The angle θ_t and θ_r in Figure 7 depend upon the configuration of the transducers employed in the meter. Typically, Doppler meters are designed as externally mounted or 'clamp-on' devices. Therefore, the ultrasound is also refracted at each acoustic discontinuity or interface between the transducers and the flowing medium as illustrated in Figure 8.

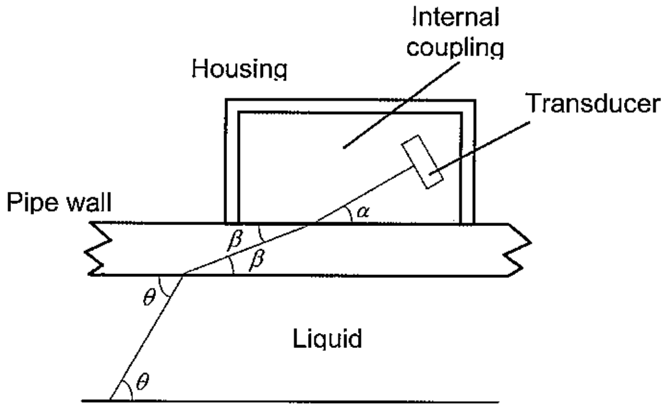


Figure 8 - An illustration of ray refraction in clamp-on transducers

This effect, while presenting problems in transit time ultrasonic flowmeters, is used to advantage in Doppler meters to effectively eliminate velocity of sound dependence as follows.

Refraction of ultrasound is governed by Snell's law, which can be presented as

$$\frac{\cos\alpha}{c_1} = \frac{\cos\beta}{c_2} = \frac{\cos\theta}{c_f} \tag{8}$$

If the transducers are configured such that $\theta_t = \theta_r = \theta$, then Equation (7) can be rewritten as:

$$\delta f = 2f_t\left(\frac{v\cos\theta}{c_f}\right) \tag{9}$$

Substituting $\cos\alpha/c_1$ for $\cos\theta/c_f$ and rearranging for v yields

$$v = \frac{\delta f . c_1}{2f_t \cos\alpha} \tag{10}$$

i.e. the measured velocity is proportional to δf and independent of the acoustic properties of the fluid and the pipe wall, assuming the angle α and velocity of sound c_1 are constant.

Again, the volumetric flowrate is obtained by multiplying v by the cross-sectional area, A, of the flow.

4.3 Cross-correlation Flowmeters

These flowmeters, figure 9, are based on the measurement of flow transit time between two sensors. Rather than relying on an injected tracer, random modulation of the signal at the upstream and downstream sensors caused by a naturally occurring feature in the flow is used. The result is two similar 'noise' signals displaced by a time $\tau_m = l/v$ where l is the axial spacing of the sensors and v is the flow velocity. The delay τ_m is determined by computing the mathematical cross-correlation function between the two signals:

$$R_{xy}(l,\tau) = \lim_{T\to\infty} \frac{1}{T}\int_0^T x(t+\tau)\, y(t)dt \qquad (11)$$

where $x(t+\tau)$ is the upstream signal delayed by time τ, $y(\tau)$ is the downstream signal, and T is the integration time. In the idealised case R_{xy} displays a distinct peak at $\tau = \tau_m$.

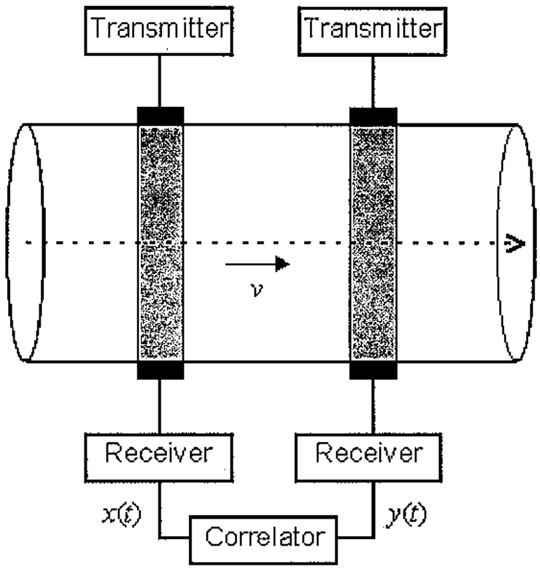


Figure 9 - A schematic diagram of a cross-correlation ultrasonic flowmeter

The use of ultrasonic sensors for cross-correlation techniques has received much attention, mainly due to the potential for non-intrusive measurement in multi-component flows. However, despite the apparent simplicity of the method, difficulties in implementation of the technique have prevented its widespread use.

Reported applications of this technique are mainly in paper manufacture and power industries. In the late 80's a meter was developed and evaluated for offshore multiphase flow measurement[2]. Although this specific development was not a commercial success, cross-correlation techniques (using other sensing principles) are now common components of multiphase metering systems.

4.4 Level-based Measurement Techniques

The principle of interface position measurement using ultrasound is based upon measurement of the transit time, t, of the ultrasonic signal as illustrated in Figure 10 which is then used to obtain the distance from:

$$d = \frac{c_l . t}{2} \qquad (12)$$

This is possible due to the fact acoustic waves reflect back from boundaries where there are large differences in acoustic impedance (i.e. the product of speed of sound and density of the medium) between the mediums either side of the boundary.

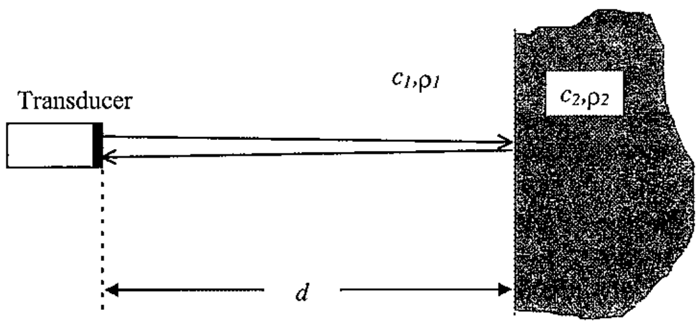


Figure 10 - The ultrasonic Interface level measurement technique

This technique generally uses short-duration ultrasonic signals transmitted and received by the same transducer (Tx/Rx), and then is commonly referred to as the pulse-echo technique.

It should be recognised that in this simple format, the measurement is dependent on knowledge of the velocity of sound in the propagation medium. Since the speed of sound is varies with temperature care needs to be taken to correct for any temperature change.

Flow measurement is realised by measuring the interface level in a flow structure in combination with a knowledge of the level/flowrate relationship or a velocity measurement. These aspects are discussed in detail elsewhere in these course notes.

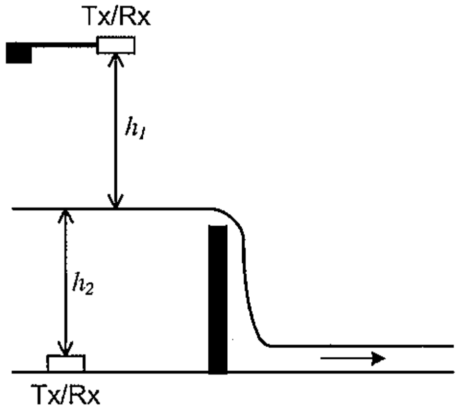


Figure 11 - Level measurement in a flow structure

Considering the simple representation of open channel flow as shown in Figure 11 it is clear that two opportunities exist for measuring the position of the interface; either through the gas or through the liquid. There are advantages specific to each means of interface level measurement, but measurement through the gas is most common in industrial applications.

5 DESIGN VARIATIONS

As the above sections illustrate, there are a range of ultrasonic techniques available for the measurement of flow and it is obvious that application conditions (e.g. flow velocity, pipe diameter, pipe material, fluid viscosity etc) and performance demands may also vary widely. In addition, there exist numerous meter manufacturers each of which, for obvious commercial reasons, have developed their products in relative isolation. The combination of these factors results in a complex situation in relation to generic discussion of ultrasonic meters but the following subsections are intended to outline some of the important generic features in ultrasonic meter design.

5.1 Transducer Configurations

'Wetted' and 'clamp-on' are commonly used classifications for ultrasonic meters. However, when discussing the transducers themselves, division into *refracting* and *non-refracting* categories is also useful in reference to flow measurement. The term non-refracting refers to a transducer construction such that the ultrasound meets each interface at normal incidence. This includes 'wetted' transducers where the transducer element is in direct contact with the fluid, encapsulated transducers where the element is housed in a protective material, or hybrid designs where the element is not in direct contact with the fluid but the pipe section has been modified. Non-refracting transducers are generally associated with better performance as uncertainties in constructional parameters tend to be controlled to a greater degree. However, if the application is a retrofit, requiring transducer ports to be made in an existing pipeline, this may not be the case.

Refracting transducers are almost exclusively of the 'clamp-on' or non-invasive type fixed to the exterior of a straight pipe section. In addition to uncertainties in the diameter, wall thickness and acoustic properties of the pipe, uncertainty is introduced in the angle θ at which the beam enters/leaves the flow. This can be partially compensated by taking advantage of Snell's law of refraction (Equation (8)) if the acoustic parameters of the transducer and fluid are known or controlled. Four principal clamp-on transducer designs are used in commercial ultrasonic flowmeters; thickness-mode, shear-mode, Rayleigh-mode and Lamb-mode. The principle difference is that the 'wide-beam' characteristic of Lamb-mode and Rayleigh-mode transducers can allow operation over a wide range of fluid sonic velocity as changes in the angle of refraction do not cause the beam to miss the receiving transducer. Shear-mode transducers permit more efficient transmission of energy at oblique angles than thickness-mode transducers.

Due to problems related to gas/solid acoustic impedance mismatch, liquid and gas transducer designs tend to be different. Generating ultrasonic waves of reasonable amplitude requires different materials and design methodologies. Transducers designed for gaseous operating environments tend to operate at lower frequencies. The acoustic impedance mismatch between gases and solids has made practical development of clamp-on gas meters very difficult. However improving transducer design has lead to the development of commercial clamp-on gas meters. A selection of practical transducer configurations is shown in Figure 12 opposite.

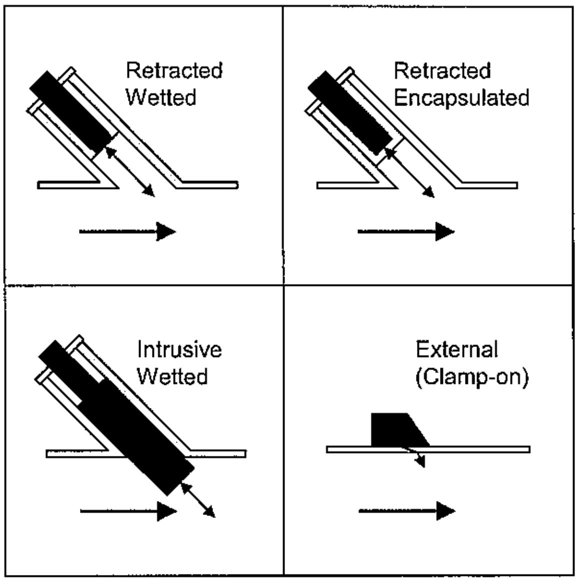
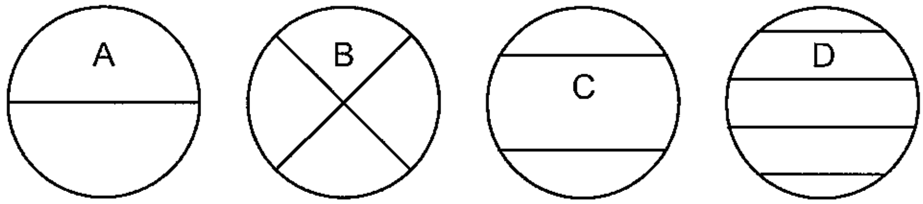


Figure 12 – Some transducer configurations used in ultrasonic meters

5.2 Acoustic Path Configurations

Commercial transit time ultrasonic meters tend to be available with a variety of path configurations. A particular configuration is generally chosen based on a requirement with respect to variations in velocity distribution (see Section 6.2.1).

A selection of commonly encountered path configurations is given in Figure 13 below.



$\bar{v} = v_1$ $\quad \bar{v} = \frac{v_1 + v_2}{2}$ $\quad \bar{v} = \frac{v_1 + v_2}{2}$ $\quad \bar{v} = \sum w_i v_i$

Figure 13 - Some typical ultrasonic meter path configurations

Configurations A and B represent those commonly used in most clamp-on meter installations and some spool piece designs, whereas configuration C represents the dual mid-radius design employed as standard in many liquid spool piece ultrasonic meters. The use of arrangement D, the multiple-chord configuration has been restricted until recently to large diameter pipelines. However, some manufacturers are now beginning to produce such multipath meters in diameters as small as 4-inch for both gases and liquids. The chordal locations used in multipath meters are often determined according to techniques for numerical integration[3].

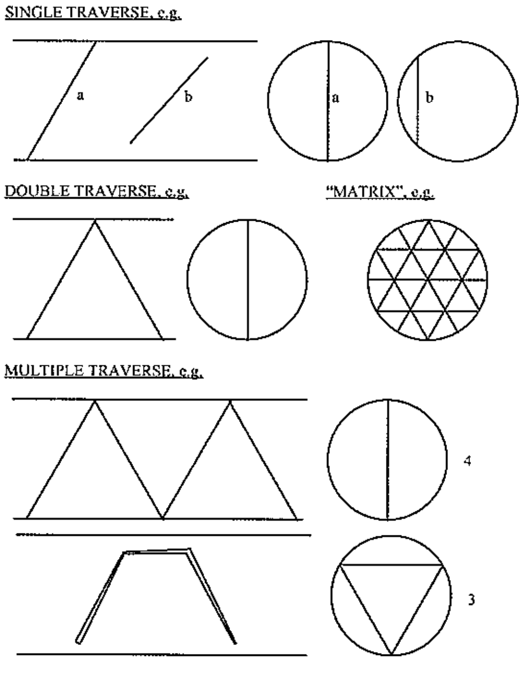


Figure 14 - Variations in path configuration

As well as variations in the chordal location of the measurement paths in the cross-section, the path configuration can be varied in orientation to the pipe axis as illustrated in Figure 14. By utilising reflection of the ultrasonic wave from the interior conduit wall, multiple traverses can be achieved and this has led to the development of meters using some fairly complex path configurations such as the 'matrix' configuration shown[4].

Overall, increasing the path number and path complexity are the primary means used to increase ultrasonic flow metering accuracy.

Accuracy of single path configurations are generally of the order of 3% but single-path clamp-on accuracy is typically no better than 5%[x].

Complex multi-path arrangements can achieve 0.1% accuracy under suitable conditions.

5.3 Transducer Frequency

The frequency of the transmitted ultrasound is chosen as a compromise between signal penetration, scattering magnitude and timing precision. Low frequencies provide good signal penetration and reduced scattering from particles of small size whereas the use of higher frequencies improves timing resolution but promotes scattering and increases attenuation. Industrial ultrasonic meters typically use transducer frequencies between 0.5 and 5 MHz for liquids and in the 50 - 500 kHz range for gasses.

5.4 Signal Processing

5.4.1 Doppler measurement

A simple, and hence frequently used, method of measuring the Doppler shift is by means of a zero crossing detection circuit. The received signal is mixed with the oscillator frequency to produce a high frequency amplitude modulated signal which can be demodulated to extract the raw low frequency Doppler shifted signal. As this demodulated signal contains a broad band of frequencies simple zero crossing analysis tends to produce a poor estimate of the mean frequency (and hence mean velocity) of the Doppler spectrum. To achieve a more precise estimate of the mean velocity more sophisticated methods such as Fourier analysis may be employed.

By using pulsed ultrasound, various options for signal processing arise. Digitisation and processing of waveforms in the time-domain has led to the development of techniques that can not strictly be classified as Doppler techniques. The main apparent advantage of these techniques over traditional Doppler meters is that they can measure lower velocities.

Another advantage of utilising short pulses of ultrasound it is that is then possible to synchronise and time-gate the reception in order to introduce positional information into the measurement.

5.4.2 Transit time measurement

A variety of signal processing methods are available for transit time measurement and there are four distinct direct methodologies which can be applied. A schematic diagram of a direct transit time ultrasonic flowmeter is shown in Figure 15a, in which the system is configured for sequential measurement of t_{ab} and t_{ba}, using single acoustic and electronic detection channels.

Other methods include frequency difference, phase difference and phase control as illustrated in Figures 15b, c & d respectively. It should be noted that the derivation presented in Section 4.1 does not apply to phase difference and phase control methods and that these methods place constraints on transducer frequency/maximum velocity and may exhibit greater sensitivity to changes in velocity of sound than direct or frequency difference methods.

Direct methods, although relatively simple in principle, can present difficulties in precise measurement of the arrival time of the signals. A relatively simple direct method detects the first zero-crossing time of the pulse waveform after it has exceeded a given threshold level. This technique is, however, prone to errors due to noise and waveform distortion. If, as a result of these problems, the zero-crossing points detected on upstream and downstream signals are out of step by only one cycle, the error is significant.

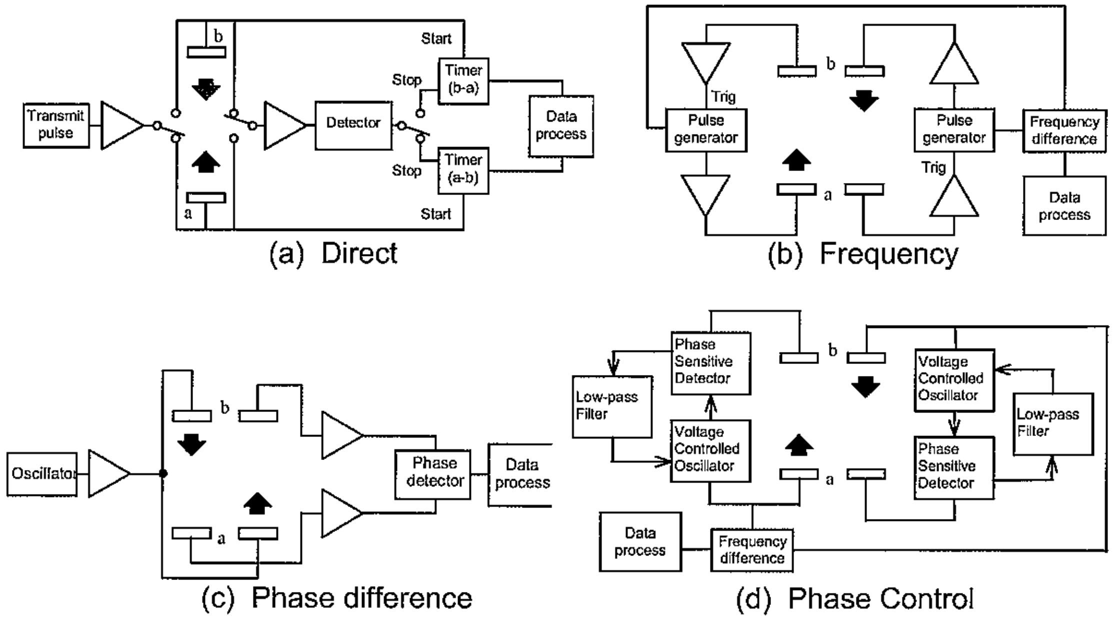


Figure 15 - Transit time measuring system schematics

In an attempt to eliminate the problems associated with noise, distortion and attenuation, complex digital signal processing methods such as correlation detection are being employed by some manufacturers. These techniques have proven to be more robust and have extended the applicability of ultrasonic transit time meters.

With the dramatic increase in recent years in computing power, advanced digital signal processing algorithms are becoming a common feature in many meters.

6 METERING PRACTICE

6.1 Doppler Meters

Up to this point in the discussion, the derived Doppler velocity has been considered as representative of the mean velocity of the flow. In realistic industrial flow situations this is rarely the case, as discussed in the following paragraphs.

The ultrasonic signal originates from the scattering centres in the fluid whose velocity may not be the same as that of the bulk fluid. This is of some importance and is likely to vary with application.

In the desirable but unlikely situation of particles that are uniformly distributed in the liquid and each making an equal contribution to the received signal, the measured velocity will be dependent on the velocity profile and the area of the cross-section that the ultrasound integrates. Therefore, sufficient knowledge of the form of the flow profile and acoustic fields is required if the mean liquid velocity is to be determined with reasonable accuracy.

In the industrial situation it is unrealistic to assume that the scattering particles will be evenly distributed. Furthermore, even if the previous assumption holds, attenuation of ultrasound in the medium makes it unlikely that all scattering centres will contribute equally to the ultrasonic signal. If, in the extreme case, we consider particles heavier or lighter than the fluid these will tend to collect at either the bottom or the top of the pipe respectively and therefore the velocity measurement will be dominated by the flow in one of these areas.

The dependence on scattering particles and resulting uncertainties due to turbulence effects, particle distribution, vibration, fluid-particle slip ratio etc. render the technique most suitable for use in low metering accuracy applications. Even in good conditions reported errors on the order of 5 to 10% are not uncommon[5].

Due to the above-mentioned factors affecting performance of Doppler flowmeters, the remainder of this section deals exclusively with transit time meters.

6.2 Transit Time Meters

The performance of transit time ultrasonic meters is dependent on a number of factors including:

- The accuracy with which the dimensions of the conduit and acoustic path are known.
- The accuracy of the transit time measurement.
- The sensitivity of the meter configuration to Reynolds number dependent variations of the flow velocity profile.
- The path number and path complexity

Assuming that the transit time difference measurement, Δt, is independent of the measurement of the upstream and downstream transit times, and that the product of these transit times can be approximated by the square of their mean, $\bar{t}$, Equation (6) can be re-written as:

$$q_v = k_h \frac{\pi D^2}{4} \frac{L^2 \Delta t}{2x.\bar{t}^2} \qquad (13)$$

where: D = the diameter of the meter tube, L = acoustic path length in the flowing fluid, x = the axial projection of the path. Note we have also now introduced the hydraulic or velocity distribution factor, k_h, given by:

$$k_h = \frac{\bar{V}_{actual}}{\bar{V}_{measured}} \qquad (14)$$

The expected performance can be quantified by determining the sensitivity coefficients of Equation (13) and estimating the uncertainties in each parameter.

Table 2 - The Sensitivity Coefficients of Equation (13)

$\delta_{kh} = \frac{\partial q_v}{\partial k_h} \frac{k_h}{q_v}$	$\delta_D = \frac{\partial q_v}{\partial D} \frac{D}{q_v}$	$\delta_L = \frac{\partial q_v}{\partial L} \frac{L}{q_v}$	$\delta_{\Delta t} = \frac{\partial q_v}{\partial \Delta t} \frac{\Delta t}{q_v}$	$\delta_x = \frac{\partial q_v}{\partial x} \frac{x}{q_v}$	$\delta_{\bar{t}} = \frac{\partial q_v}{\partial \bar{t}} \frac{\bar{t}}{q_v}$
1	2	2	1	-1	-2

It follows that, for example, a one percent error in pipe bore, D, will result in a two percent error in q_v. Such considerations are especially important in relation to clamp-on ultrasonic meters as the dimensions of the conduit may not be known with any great certainty.

The above also illustrates for a given uncertainty in Δt, as velocity decreases and the transit time difference measurement tends towards zero, uncertainty in the flowrate measurement increases.

Figure 16 below shows a 'typical' manufacturer's specification for accuracy in good application conditions.

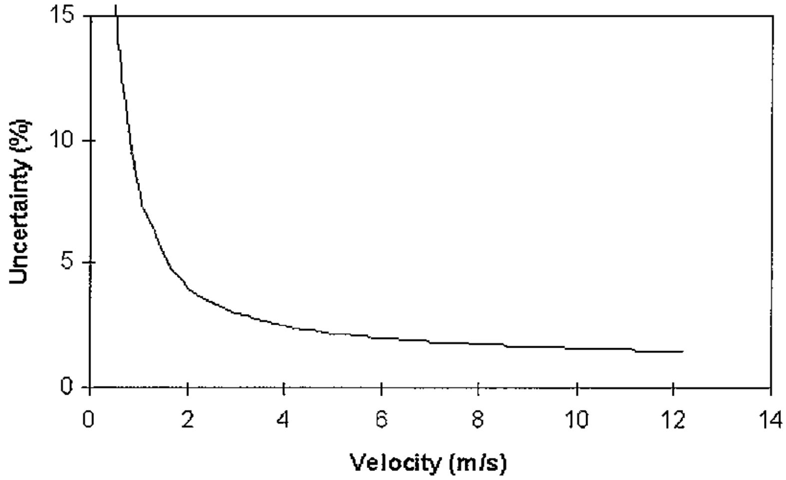


Figure 16 – A 'typical' transit time meter performance characteristic

6.2.1 Velocity distribution

Velocity distribution or profile, is of great importance in transit time ultrasonic metering. Even in fully developed flows, the measured velocity along the path of the ultrasound beam is not a measure of the mean velocity in the cross section of conduit. Diameter-path configurations are most sensitive to velocity distribution as the inherent integration of velocity along the measurement path overestimates the flow velocity due to high central velocities as illustrated in Figures 17a and 17b for laminar and turbulent profiles respectively (the plots are for smooth pipes).

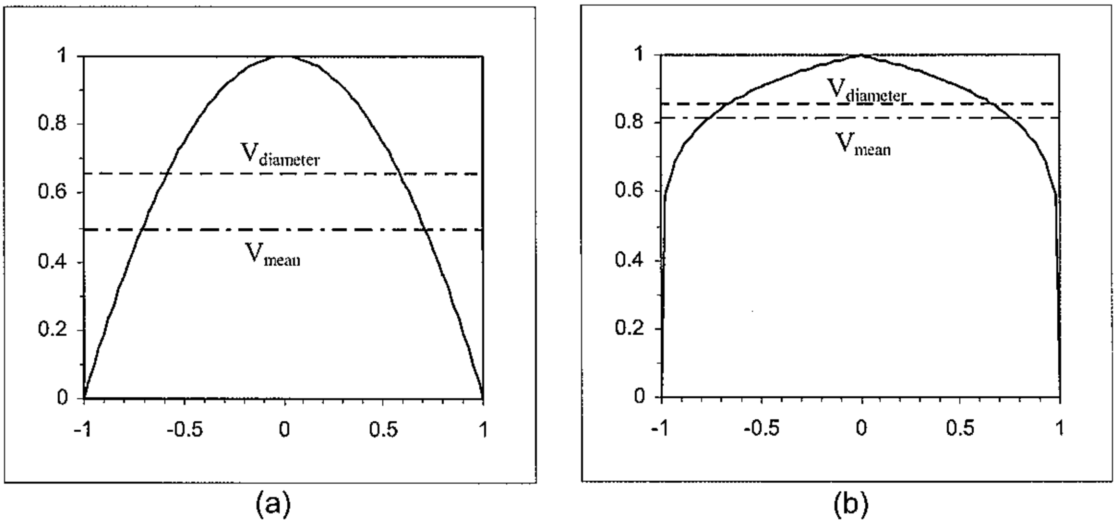


Figure 17 – A comparison of diametric and mean velocities for laminar and turbulent profiles

For the smooth pipe examples of figure 17, approximate values for k_h are 0.76 (=0.5/0.66) for laminar flow and 0.94 (=0.81/0.86) for turbulent flow.

In fully developed turbulent flows the velocity distribution factor, k_h, can be calculated as a function of Reynolds number and relative pipe wall roughness, k/r. Figure 18 shows the turbulent flow k_h function derived by Fronek[6] for meters employing diametrical paths (e.g. typical clamp-on meters).

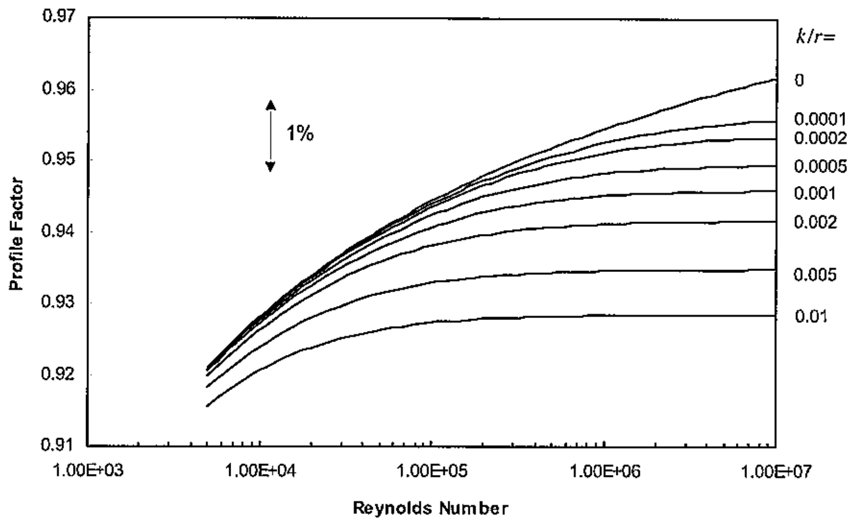


Figure 18 - Diametric profile factor as a function of Reynolds number

In Figure 19, the turbulent k_h factor is presented as a function of velocity for pipe diameters of 4, 6 and 16 inches, a constant roughness of 0.2 mm, and fluid viscosity of 1 and 5 cSt. From this figure we can see that non-linearity due to inaccuracy in k_h will be most significant at low velocities and that uncompensated changes in viscosity can easily lead to errors on the order of a few tenths of a percent. The figure also illustrates that the linearity of the k_h function is relatively independent of the pipe size.

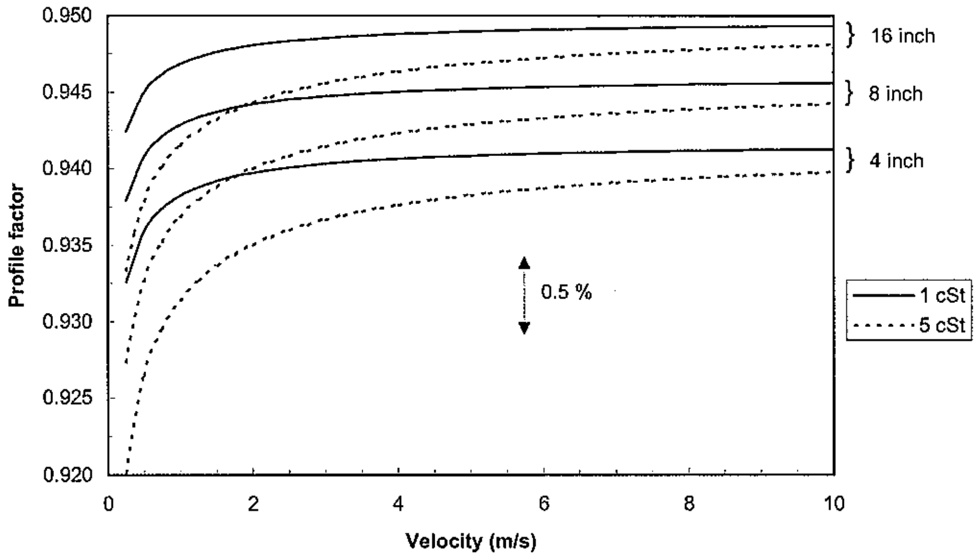


Figure 19 – Diametric profile factor as a function of velocity

Mid-radius positioning of the measurement paths is chosen to reduce sensitivity to changes of profile in fully developed flow. Figure 20 shows the variation in linearity for various radial positions, calculated using parabolic and power-law profiles[7] (illustrated in Figure 17).

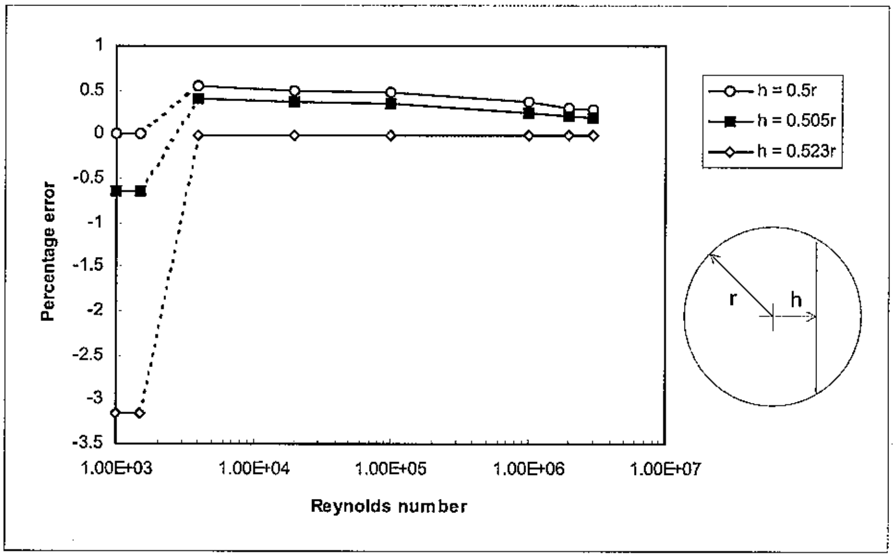


Figure 20 - Profile sensitivity dependence on the radial position of the measurement chord

By similar means of analysis, the Gaussian configuration of Figure 13(d) can be shown to be accurate to within approximately ± 0.2% uncertainty[8].

6.2.2 Distorted velocity profiles

The performance of ultrasonic meters in non-ideal installation conditions will be affected by the presence of transverse velocity components (cross-flow and swirl) and distortions of the axial velocity profile.

The influence of velocity profile distortion and swirl produced by upstream pipework is a major concern in many applications. Space and cost constraints are often prohibitive to the provision of long lengths of straight pipe. Flow conditioners or in-situ proving may be used but these methods are in conflict with two of the major incentives for using ultrasonic meters, i.e. reducing flow restriction and lowering installation costs.

Single-beam meters are most prone to installation effects where as dual-beam and multipath flowmeters exhibit lesser sensitivity to installation effects. Generally, the more paths a meter has, the more tolerant it is of adverse velocity profile effects and consequently more accurate. Typical recommended upstream straight pipe lengths are 20, 10 and 5 diameters for single, dual and multiple path configurations respectively. In general the linearity and repeatability of the instrument will not be influenced, simplifying the task of in-situ calibration. The maximum metering error expressed as a percentage of flowrate, for a sample of installation configurations is given in Table 3 below[9].

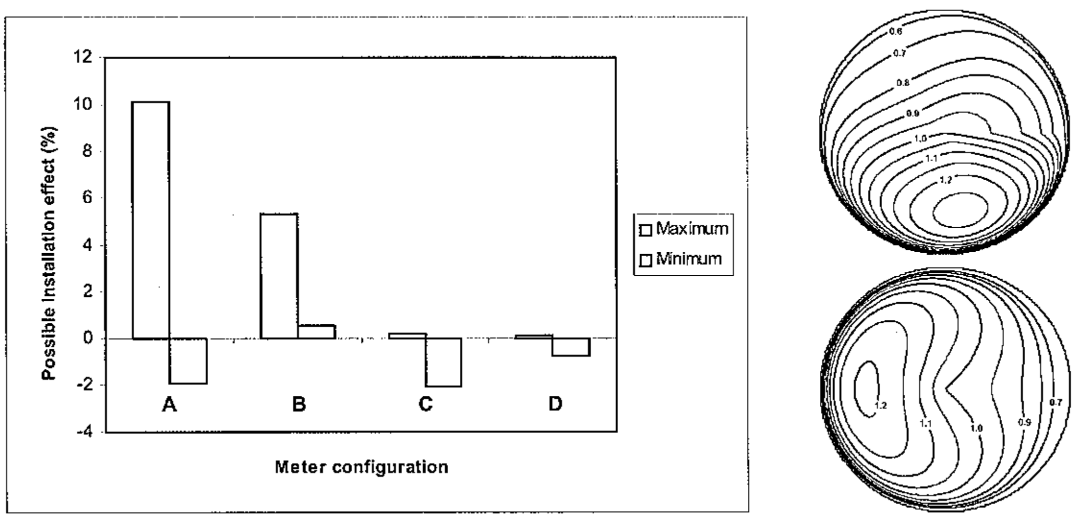
These results were obtained with meters of 150 mm nominal diameter at flow velocities of 1.6 to 4.0 m/s.

Table 3 - % Flow Metering Error for a Selection of Installation Effects

Meter type	Disturbance	Downstream position			
		2.1 D	10.4 D	20.8 D	38.8 D
Single beam (flow velocity range 3.2 to 4.0 ms^{-1})	Globe valve ($^2/_3$ open)	14.3	3.2	1.7	0.2
	Gate valve ($^2/_3$ open)	12.4	4.0	2.6	0.5
	Butterfly valve ($^2/_3$ open)	21.5	4.1	1.6	0.4
	90° bend	22.3	7.0	3.4	1.0
	Two 90° bends, perpendicular planes	9.9	6.4	4.6	2.8
	Expansion (100-150)	10.4	3.6	1.9	0.3
	Reduction (300-150)	2.3	0.8	0.9	0.9
Dual Beam (flow velocity 1.6 ms^{-1})	Globe valve ($^2/_3$ open)	4.4	0.5	0.4	0.4
	Gate valve ($^2/_3$ open)	14.9	1	1.1	0.1
	Butterfly valve ($^2/_3$ open)	8.6	0.8	0.9	0.6
Dual Beam (flow velocity 3.2 ms^{-1})	90° bend	6.7	0.3	0.6	0.6
	Two 90° bends, perpendicular planes	3.4	1.2	0.8	0.6
	Expansion (100-150)	3.5	1.0	0.6	0.4
	Reduction (300-150)	0.7	1.9	1.1	0.4

As explained in the introductory lecture of this course, pipe bends etc. can cause the flow to have cross-axis velocity components. In the case of a single-traverse single-path measurement, cross-axis components will result in errors dependent on the angle of the path relative to the pipe axis. Errors of this nature can be significantly reduced by utilising two crossed paths or a double traverse such as that shown in Figures 13 and 14. By employing configurations such as these, the effects of the non-axial component should be of equal magnitude in each traverse but positive in one case and negative in the other and hence provide some level of cancellation.

Numerical modelling has been carried out at TUV NEL using mathematical velocity profiles formulated to depict profiles encountered in practice. As the profiles can be integrated analytically, an exact reference can be determined against which the results can be compared. A summary of derived results is given in Figure 21a below which demonstrates relative sensitivity of the four configurations of Figure 13 to the distorted profiles of Figure 21b.



(a) (b)

Figure 21 - A summary of installation effects for two distorted profiles

Flow and flowmeter modelling (e.g. using CFD techniques) have already proven to be useful in improving the understanding of measurement interaction mechanisms. Modelling is also potentially useful for deriving quantitative information that could be used when installing a flowmeter.

7 DISCUSSION

7.1 Performance in Two-phase Flows

The performance of transit time meters is adversely affected in the presence of two-phase flow. In all cases, the presence of a second phase trapped in the transducer recesses will prevent normal signal propagation and is most likely to render the meter temporarily inoperable. In general, the effect of a second phase distributed within the continuous phase is dependent on the quantity, size, distribution and physical properties of the secondary component. The effects on performance can vary quite widely as outlined below.

7.1.1 Liquid meters

As the acoustic impedance mismatch between liquid and gas is greatest, the effect of scattering and attenuation is significantly higher in liquid/gas flow than in liquid/liquid or liquid/solid. Consequently, the liquid/gas condition represents the greater problem. Tests at high velocities have shown some meters to be incapable of measurement at high velocities with as little as 0.4% gas by volume. Conversely, at low velocities with approaching 25% gas by volume, some meters can perform with only moderate deviations in accuracy (~ 2-5%). These effects are also dependent on whether the flow is dispersed, separated or stratified.

Performance in liquid/gas flow may be improved by adjusting signal parameters to accommodate a wider range of gas fractions. However, as the limiting gas fraction is approached the performance will suffer in terms of accuracy. Another way in which liquid/gas performance may be improved is by operating the meter in a manner that is more suited to the phase distribution. For example in horizontal liquid/gas flow, disabling measurement chords which are in the upper half of the cross-section is likely to improve accuracy in stratified or separated flow, especially at moderate velocities where gravitational separation of the phases is more distinct.

As yet there is insufficient data to facilitate determination of more rigorous general rules regarding application in multiphase flows. Selection of a suitable meter for these duties can only be based on previous experience or up-to-date laboratory data[10,11].

7.1.2 Gas meters

Metering of wet-gas (a mixture of natural gas and a small fraction, generally <10%, of produced liquids) is of great interest in the offshore oil and gas industry. Recently work has been undertaken to develop ultrasonic meters for this duty. Tests at TUV NEL and elsewhere have shown that gas meters are capable of recovering from complete flooding, are relatively unaffected (in terms of volumetric flowrate measurement) by small quantities of liquid, and that the second-phase may be determinable from analysis of signal parameters.

7.2 Secondary, Diagnostic and Self Checking Capabilities

A measure of the velocity of sound in the fluid is inherent in all direct transit time measurements. Under certain assumptions, this can be utilised to determine fluid properties and hence can enable measurement of, for example, gas density given by

$$\rho = \frac{\gamma P}{c^2} \tag{15}$$

where is γ the ratio of specific heats, P is the absolute pressure and c is derived from Equation (1) as follows

$$\frac{1}{t_{ba}} + \frac{1}{t_{ab}} = \frac{(c + \bar{v}\cos\theta) + (c - \bar{v}\cos\theta)}{L} \tag{16}$$

$$\frac{t_{ab} - t_{ba}}{t_{ab}t_{ba}} = \frac{2c}{L} \tag{17}$$

$$c = \frac{L\Delta t}{2(t_{ab}t_{ba})} \tag{18}$$

This however is an over-simplification of the situation. Progress is being made[12] towards more sophisticated algorithms for determination of gas density, molecular weight and calorific value.

Ultrasonic meters tend to utilise propriety signal parameters to determine when the meter is functioning properly or otherwise. These tend to vary from manufacturer to manufacture in terms of the range of parameters determined and the set-points utilised in the determination of fault conditions. As understanding of the interaction of these parameters improves, greater confidence in results and wider use of the meter's capabilities will be realised (such as the wet-gas two-phase measurement application cited above).

7.3 Standardisation

Standardisation has a great impact on the acceptance and use of measurement technologies. However, the preparation of a standard for ultrasonic meters is a difficult undertaking due to the diversity within the technology area. Any attempt at rigorous definition of manufacturing specifications could exclude certain commercial products and impede further development of the technology and this has slowed progress on the standards front. It is also important that any new standard should not constrain use by over specification, but provide practical guidance to users and manufacturers.

Efforts to develop standards and best practice guides have increased markedly in recent years reflecting the growing demand and uptake of ultrasonic metering technology.

For **gas** meters the American Gas Association (AGA) has developed a widely cited reference document[13], AGA9, for measurement by Mulitpath Ultrasonic Meters. This contains a wealth of detail on meter acceptance criteria and sets accuracy limits for this type of meter. The British Standards Institution (BSI) have also published a guideline document for gas meters[14], BS7965 and includes the accuracy requirements for the four classes of gas meter; fiscal through to process. Revision of this document has been completed and publication of a 2008 version is imminent. An international standard for custody transfer and allocation meters, ISO 17089-1[15] has being developed by ISO technical committee TC30 and the DIS was published in October 2008. A companion standard, ISO 17089-2[16], for industrial gas applications is also planned but is at an earlier state of development so publication is likely to be in a few years. In addition, BS EN 14236[24] covers domestic gas meters.

For **liquid** meters the American Petroleum Institute (API) has published a standard[17], MPMS 5.8, for 'Measurement of Liquid Hydrocarbons by Ultrasonic Flowmeters using Transit Time Technology'. Currently API MPMS 5.8 is being considered for adoption by ISO, possibly as ISO18313. BSI have published a guideline on liquid clamp-on meters[18], BS8452, and this is currently going through a process of revision.

In addition to these standards, other standards and industry procedures, e.g. NORSOK_I_104r3 for hydrocarbon gas[19] and NORSOK_I-105e3 for hydrocarbon liquid[20], make reference to these basic standards.

The results of a broad study have also been published by GERG (roughly translated the European Gas Research Group) in Technical Monograph No. 8, *Present Status and Future Research on Multipath Ultrasonic Gas Flow Meters.*

Further guidance on a range of topics relevant to ultrasonic meters can be found in a collection of ten Flow Measurement Guidance notes available on the NMS Flow Programme website (www.flowprogramme.co.uk). The DTI (now DIUS) guidance note[21] also provides some additional information.

7.4 Selection, Calibration and Deployment

Even when armed with knowledge on the principles of ultrasonic flowmeters, the task of selecting a meter for a specific duty is not an easy one. Realising one specific benefit of the technology may require compromise in an area such as accuracy or ease of use.

General selection considerations (e.g. pressure rating) are not detailed here but may restrict the number of supplier options. The following paragraphs are intended to provide additional guidance on some of the important factors in selection, calibration and use of a meter.

The discussion of 'clamp-on' versus 'wetted' transducers covers many aspects of performance as well as ease of installation and maintenance. In considering high accuracy demand applications the following points are probably the most important of those which should be considered.

Clamp-on meters are susceptible to additional sources of uncertainty over wetted meters. However, by comparison of results from wetted and with clamp-on meters it is clear that if care is taken in setting up the clamp-on meter similar performance to diameter path wetted meters can be achieved. What is not obvious is that limitations of current ultrasonic technology constrain practical use of clamp-on transducers to diametrical paths. This means that for the foreseeable future, problems of dynamic profile compensation must be tolerated. This means that viscosity is required as input for clamp-on meters. This is normally achieved by user-entry of a constant into the meter software. Variable input of viscosity, either from a viscometer or inferentially by measurement of temperature and/or velocity of sound in the fluid, is one way of improving the situation.

Clamp-on meters for gases are a relatively new technical development. There is very little independent test data available at present. A rough guide to their performance can be taken from the claims of meter manufacturers. One such claim gives an uncertainty of +/- 2% for gas velocities over 1.7 m/s with a gas pressure of at least 6.2 bar. However as with all clamp-on meters the quality of installation will have a major effect on meter accuracy[22].

It is easy to see the importance of dimensional uncertainties when we consider that 1% uncertainty in the determination of the inner diameter gives rise to a 2% uncertainty in the cross-sectional area. In particular, the relevance of this should be borne in mind when utilising clamp-on meters.

Calibration of an ultrasonic meter can take two forms: "static" (dry) and "dynamic" (wet). Static calibration involves the metrology of the meter body and transducer configuration and the determination of, and compensation for, 'non-fluid delays' (i.e. those delays related to the electronics, the transducers and the transit time detection method). The execution of hypothetical correction methodologies, for example the determination of a velocity profile factor, could also be considered a part of this process.

As with orifice meters, the ability to perform a static calibration is advantageous. However, unlike orifice meters, there is no internationally agreed method of dry calibration with the result that dry calibrated meter accuracy can vary from manufacturer to manufacturer due to differences in construction, metrology and correction methodologies.

Dynamic calibration refers to a flow calibration and is generally carried out following static calibration. The aim is usually to determine a calibration factor that is entered in the meter software. In some instances, the derived calibration curve may be utilised to linearise the meter. Ideally the flow calibration should be carried out with as much similarity in end-use or field operating conditions and fluid properties (e.g. viscosity) as is practically feasible.

Where dynamic calibration is carried out at pressure and temperature conditions that are appreciably different from operational conditions, correction to account for the change in fluid viscosity (and flow profile) and those due to body geometry effects due to the ΔP and ΔT change also need to be considered. AGA9[13] contains some guidance on this correction but it is only applicable for certain types of meter. Guidance covering geometry related pressure and temperature corrections in a wider range of meters, and applicable to gas or liquid, is now included in ISO/DIS 17089-1[15] and BS 7965[14].

As a result of the capability to perform complex processing, precautions must be taken during calibration and use of microprocessor-based meters to ensure that the meter output is representative of the flow dynamics. A good general point of guidance is that the meter 'response time' or equivalent should be set to a minimum for calibration purposes.

In addition, it is known[13, 23] that certain gas meters are susceptible to interference from noise generated by certain types of control valve and care needs to be taken over their installation.

Manufacturer's meter specifications provided to the user are often insufficiently detailed in relation to pipe dimensions, transducer configurations, and calibrated versus uncalibrated uncertainties. In terms of accuracy specifications, laboratory data demonstrates that claims by vendors are often proven to be unrealistic or moderately over-optimistic and therefore caution is advised in this respect.

8 CONCLUSIONS

Ultrasonic flowmeters have been subject to progressive development. Advances in transducer technology, signal processing and high-speed electronics have all assisted in the process. In order for the technological benefits of the technology to be fully realised it is important that progress continues. This will require development and evaluation both by the manufacturers and on behalf of the end-users.

It is important that industry regulators, standards organisations and independent bodies are familiar with developments in order to enable progress. Questions regarding reliability, accuracy and performance must be revisited and new developments tested.

Collated information, from laboratory programmes, field trials and state-of-the-art reports, demonstrates that ultrasonic technology can provide a practical solution for a wide range of industrial needs.

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DIFFERENTIAL-PRESSURE METERS

by

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LECTURE No 6

PRINCIPLES AND PRACTICE OF FLOW MEASUREMENT

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CONTENTS

NOTATION

A_1	Area of upstream pipe
A_2	Area of throat or orifice
C	Discharge coefficient of flowmeter
D	Upstream diameter of flowmeter or inlet pipe
d	Throat or orifice diameter
m	Area ratio, A_2/A_1 $\{= (d/D)^2\}$
p_1	Absolute pressure upstream of flowmeter
p_2	Absolute pressure at throat or downstream tapping
q_m	Mass flowrate
q_v	Volume flowrate
U_1	Mean velocity at upstream section
U_2	Mean velocity at throat or downstream section
α	Flow coefficient
β	Flowmeter diameter ratio, = d/D
ε	Expansibility factor
κ	Isentropic exponent
ρ	Density of flowing fluid at upstream section
τ	Pressure ratio, = p_2/p_1

1 INTRODUCTION

This class of flowmeter partially obstructs the flow and hence operates by creating a difference in static pressure between the upstream and downstream side of the device. It may be installed either 'in-line', ie with pipework both upstream and downstream of it, or at the inlet to a length of pipe. The chief types of differential-pressure meters are:

orifice plate	low-loss devices (e.g. Dall tube)
nozzle	inlet flowmeter
Venturi tube	variable area meters
Venturi nozzle	drag plate

It is estimated that at least 40 per cent of industrial flowmeters in use at present are differential-pressure devices, with the orifice plate being the most popular.

The main advantages of such flowmeters are:

a simple to make, containing no moving parts,

b their performance is well understood,

c cheap - especially in larger pipes when compared with other meters,

d can be used in any orientation,

e can be used for most gases and liquids, and

f some types do not generally require calibration.

Their main disadvantages are:

i rangeability (turndown) is less than for most other types of flowmeter,

ii significant pressure loss may occur,

iii output signal is non-linear with flow,

iv coefficient and accuracy may be affected by pipe layout or nature of flow, and

v may suffer from ageing effects, i.e. the build-up of deposits or erosion of sharp edges.

2 THEORY

If a converging section of pipe, Figure 1, typical of the entry cone of a Venturi tube, is considered and Bernoulli's Equation is applied between two planes, then

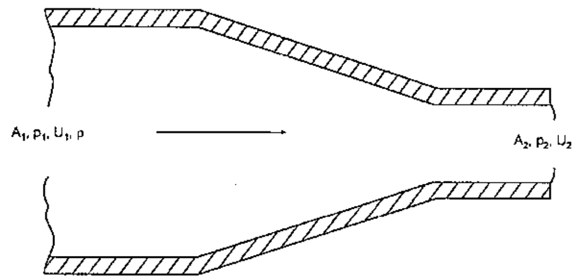


Figure 1 - Converging Flow

$$p_1 + \tfrac{1}{2}\rho U_1^{\,2} = p_2 + \tfrac{1}{2}\rho U_2^{\,2}, \quad (1)$$

where p, ρ, and U are the pressure, density and mean velocity respectively and the subscripted 1 and 2 represent the upstream and downstream (throat) planes.

From conservation of mass for incompressible flow

$$q_m = \rho A_1 U_1 = \rho A_2 U_2 \quad (2)$$

where q_m is the mass flowrate and A the area of each plane. The area ratio, m, and the diameter ratio, β, are defined by

$$A_2/A_1 = m = (d/D)^2 = \beta^2, \quad (3)$$

where d and D are the throat and pipe diameters.

From these relations it can be shown that

$$q_m = \frac{1}{\sqrt{1-\beta^4}} \frac{\pi d^2}{4} \sqrt{(2\rho(p_1 - p_2))} . \qquad (4)$$

The expression $\frac{1}{\sqrt{1-\beta^4}}$ is known as the velocity of approach factor and has usually been denoted by E. p_1 - p_2 is the differential pressure, Δp.

Hence

$$q_m = \frac{1}{\sqrt{1-\beta^4}} \frac{\pi d^2}{4} \sqrt{2\rho\Delta p} \qquad (5)$$

assuming no losses occur and the moving fluid completely fills the pipe.

In reality some loss will occur and the equation is multiplied by the discharge coefficient C to take this into account.

Thus

$$q_m = \frac{C}{\sqrt{1-\beta^4}} \frac{\pi d^2}{4} \sqrt{2\rho\Delta p} . \qquad (6)$$

The product $\frac{C}{\sqrt{1-\beta^4}}$ is sometimes referred to as the flow coefficient of the meter and represented by α.

In nozzles and Venturi tubes the flow follows the boundary of the tube closely and the value of C is usually close to unity. However, in the case of an orifice plate the flow continues to converge downstream of the plate forming a vena contracta. Bernoulli's Equation can be applied between an upstream plane and the vena contracta, but the area of the vena contracta cannot practically be measured and is thus not known accurately; therefore in Equation (6) the area of the orifice bore is used. This leads to a value of C of approximately 0.6 which, in effect, includes a coefficient of contraction.

If the fluid being metered is compressible, there will be a change in density when the pressure of the fluid falls from p_1 to p_2 on passing through the device. As the pressure changes quickly, it is assumed that no heat transfer occurs and because no work is done by or on the fluid, the expansion is isentropic. In nozzles and Venturi tubes Bernoulli's Equation is applied, and an expansibility factor, ε, is calculated:

$$q_m = \frac{C}{\sqrt{1-\beta^4}} \varepsilon \frac{\pi d^2}{4} \sqrt{2\rho_1\Delta p} . \qquad (7)$$

where

$$\varepsilon = \left(\left(\frac{\kappa \tau^{2/\kappa}}{\kappa - 1} \right) \left(\frac{1-\beta^4}{1-\beta^4 \tau^{2/\kappa}} \right) \left(\frac{1-\tau^{(\kappa-1)/\kappa}}{1-\tau} \right) \right)^{1/2}, \tag{8}$$

ρ_1 is the density at the upstream tapping, τ is the pressure ratio, p_2/p_1, and κ is the isentropic exponent. Because of the assumptions on which this equation is based, it has an uncertainty, which increases with $\Delta p/p_1$.

The theoretical values of ε do not apply to orifice plates because the effective area ratio is not readily obtained and the flowing jet can also expand laterally within the orifice. Hence empirical values are used, and for all three recognised tapping arrangements Equation (7) is used together with the equation

$$\varepsilon = 1 - (0.351 + 0.256\beta^4 + 0.93\beta^8)\left[1 - \left(\frac{p_2}{p_1}\right)^{1/\kappa}\right]. \tag{9}$$

The most significant standard for differential-pressure meters, BS EN ISO 5167, has recently been revised in four parts: the first part is a general one[1]; the other three parts cover orifice plates[2], nozzles[3] and Venturi tubes[4].

3 PRINCIPAL DIFFERENTIAL-PRESSURE METERS

3.1 Orifice Plate

There are many forms of orifice plates in the sense that various profiles of the actual orifice are used and alternative positions of pressure tappings are permitted by the standards[2,5]. The normal profile used in orifice plates is the square edge, Figure 2. The downstream edge of a square-edged plate is bevelled, unless the plate is thin.

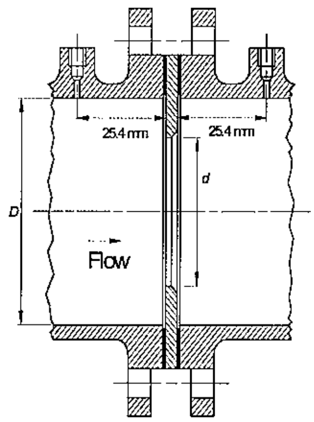


Figure 2 - Orifice plate with flange tappings

Three alternative positions of the pressure tappings are permitted: corner, flange and D and D/2, see Figure 3. Their choice is largely a matter of local custom and engineering convenience, although experience indicates that D and D/2 tappings are generally less sensitive to disturbed flow than flange or corner tappings. In industry, especially in the USA, flange tappings are commonly used.

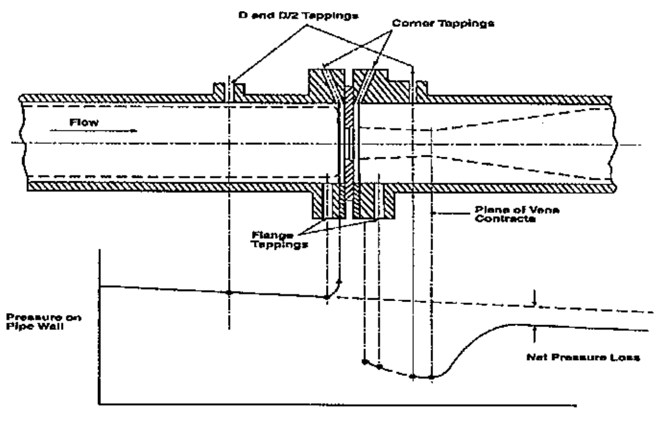


Figure 3 - Alternative pressure tapping positions

To measure pressure it is generally better to use a piezometer ring or annular groove than a single tapping. A triple-tee arrangement (Figure 4) has been shown to be the most satisfactory, especially where flow disturbances exist[6].

The outstanding advantage of a square-edged orifice plate is that, if designed and manufactured according to BS EN ISO 5167-2, the coefficient can be predicted by an internationally accepted Equation, thus obviating the need for calibration. No other type of flowmeter has quite this capability.

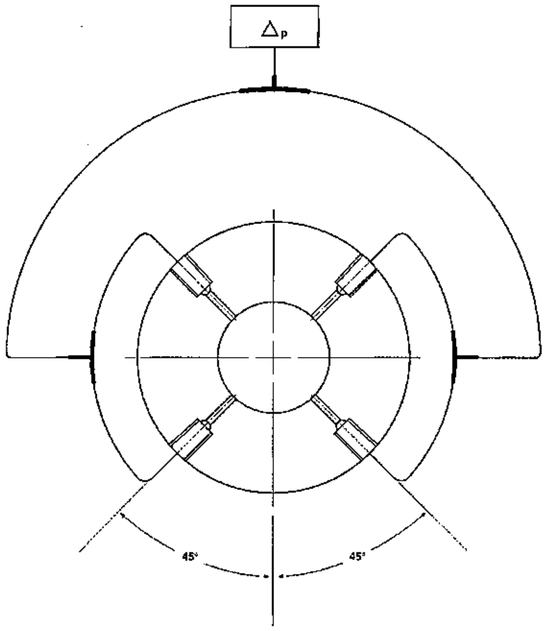


Figure 4 - Triple-tee arrangement

A very large international programme of work led to the creation of a database of orifice-plate discharge coefficients: the diameter ratios range from 0.1 - 0.75, orifice Reynolds numbers from 1700 - 7×10^7, and pipe diameters from 50 - 600 mm. As a result of this work the Stolz Equation for the discharge coefficient was replaced by the Reader-Harris/Gallagher (1998) Equation. This took place first when Amendment 1 to BS EN ISO 5167-1:1991 was published in 1998, and the same equation is repeated in BS EN ISO 5167-2:2003. The Reader-Harris/Gallagher (1998) Equation is as follows:

$$\begin{aligned} C = {} & 0.5961 + 0.0261\beta^2 - 0.216\beta^8 \\ & + 0.000521\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0188 + 0.0063A)\beta^{3.5}\left(\frac{10^6}{Re_D}\right)^{0.3} \\ & + (0.043 + 0.080e^{-10L_1} - 0.123e^{-7L_1})(1 - 0.11A)\frac{\beta^4}{1-\beta^4} \\ & - 0.031(M'_2 - 0.8M'^{1.1}_2)\beta^{1.3}. \end{aligned} \qquad (10a)$$

Where D < 71.12 mm (2.8 inch) the following term should be added to the above Equation:

$$+ 0.011(0.75 - \beta)\left(2.8 - \frac{D}{25.4}\right). \quad (D : mm) \qquad (10b)$$

In this Equation

Re_D is the Reynolds number related to D;

$L_1 = l_1/D$ is the quotient of the distance of the upstream tapping from the **upstream** face of the plate and the pipe diameter;

$L'_2 = l'_2/D$ is the quotient of the distance of the downstream tapping from the **downstream** face of the plate and the pipe diameter;

$$M'_2 = \frac{2L'_2}{1-\beta};$$

$$A = \left(\frac{19000\beta}{Re_D} \right)^{0.8} .$$

The limits of use in terms of Reynolds numbers and pipe roughness are given in BS EN ISO 5167-2. The standard also gives the straight lengths required upstream and downstream of differential-pressure meters both with and without flow conditioners.

In recent years in addition to the work on the orifice-plate discharge coefficient there has also been a significant amount of work on installation effects on orifice plates, on the effect of pipe roughness, and on the temperature correction between the downstream pressure tapping and the upstream pressure tapping, all of which have been included in the revision of BS EN ISO 5167. The new standard encourages the user to use flow conditioners and includes the new expansibility equation (9).

Square-edged orifice plates and nozzles may be used in pipes smaller than 50 mm diameter: this is covered by a British Standard[5] which also includes conical entrance, quarter-circle and eccentric orifice plates. Conical-entrance and quarter-circle plates are used especially for viscous flow. For special purposes, eccentric or even non-circular orifice plates are used; for example, in metering suspended solids a chord-type orifice plate can be used, Figure 5.

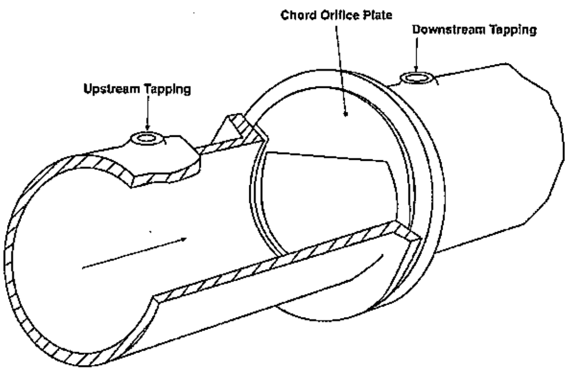


Figure 5 - Chord-type orifice plate

Further guidance on the use of differential-pressure devices is given in other British and International Standards[7-9]. Reference 7 is being revised to be consistent with the new version of BS EN ISO 5167.

3.2 Venturi Tubes

The profile of the classical Venturi tube is shown in Figure 6. Although the included angle of the conical divergent section can be between 7 and 15°, it is recommended that an angle of 7-8° be chosen where possible.

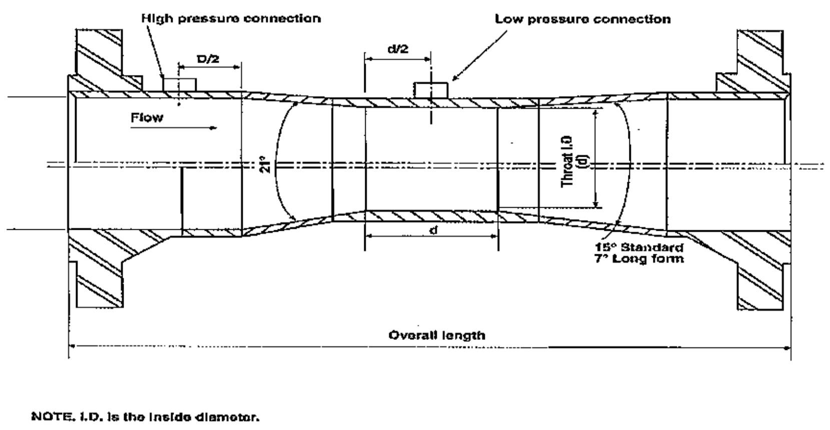


Figure 6 - The classical Venturi tube

Various forms of construction are employed, depending upon size, but all are considerably more expensive than the orifice plate. However, because of the recovery of most of the pressure in the divergent outlet section, the Venturi causes less overall pressure loss in a system and thus saves energy, Figure 7.

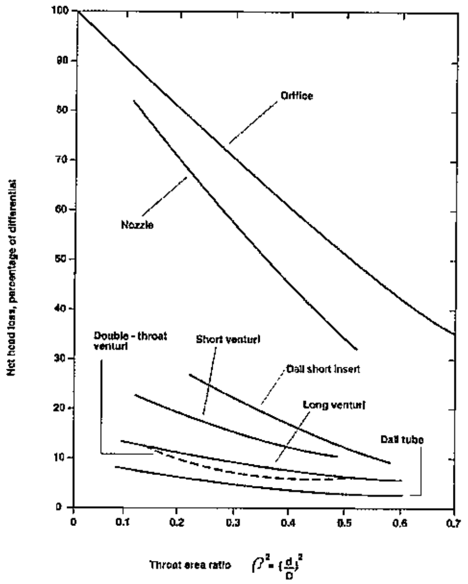


Figure 7 - Net pressure loss as a percentage of differential pressure

When the outlet diameter of the divergent section is less than the pipe diameter a Venturi tube is called 'truncated'. The divergent portion can be truncated by about one-third of its length without greatly affecting the pressure loss in the device.

The discharge coefficient of a Venturi tube with a machined convergent is typically 0.995.

Because it has pressure tappings in the throat a Venturi tube is much more affected by burrs on the tappings than an orifice plate. It does, however, have the advantage of requiring a shorter upstream straight length than an orifice plate.

There is an increasing desire to use Venturi tubes in gas flows. However, on undertaking the calibrations it has been found that on many occasions discharge coefficients significantly greater than 1 have been found (e.g. C ≈ 1.02). This problem has been described by Jamieson et al[10]. The cause of this problem is a matter of current research. It has been found that using a convergent angle of 10.5° (instead of 21°) has certain advantages[11,12], and such Venturi tubes will probably be included in the revision of BS ISO TR 15377.

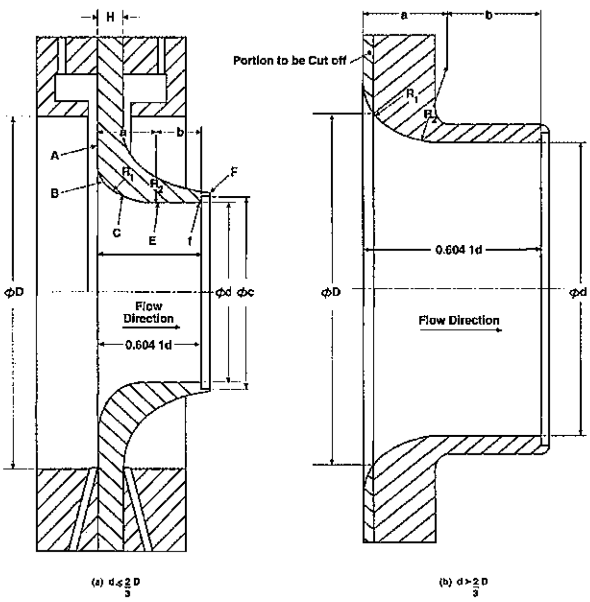


Figure 8 - ISA 1932 nozzle

3.3 Nozzles

The nozzle has a curved entry and cylindrical throat, but no divergent outlet section. Therefore the discharge coefficient is similar to that of a Venturi tube. However, the pressure loss is the same as that of an orifice plate for the same flowrate in the same size of pipe at the same pressure difference.

There are two types of standard nozzles, the ISA 1932 nozzle, Figure 8, and the long-radius nozzle, Figure 9.

The profile of the ISA 1932 nozzle depends on whether the throat diameter d is less or greater than two-thirds the pipe diameter D. Corner pressure tappings are usually used with this nozzle which may be mounted between pipe flanges or in a carrier.

Two standard designs of long-radius nozzles are used according to the value of the diameter ratio β. They are

a high ratio nozzles, where $0.25 \leq \beta \leq 0.8$, and

b low ratio nozzles, where $0.20 \leq \beta \leq 0.5$.

For values of β between 0.25 and 0.5 either design may be used.

With long-radius nozzles the upstream pressure tapping is about one pipe diameter from the inlet face. The downstream tapping is half a pipe diameter from the inlet face unless the nozzle is less than D/2 in length in which case it must be no further downstream than the nozzle outlet.

Long-radius nozzles with throat tappings have been standardized by ASME[13]. This standard is commonly used in the electrical power generation industry.

In order to reduce the pressure loss caused by a nozzle it can be fitted with a divergent section similar to that used for a Venturi tube, hence becoming a Venturi nozzle. The upstream face is identical with that of an ISA 1932 nozzle. Upstream corner and throat pressure tappings are used, Figure 10.

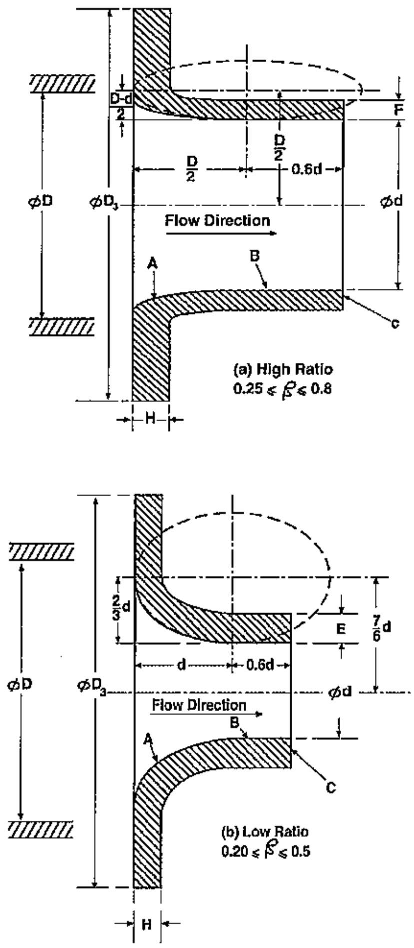


Figure 9 – Long-radius nozzle

One advantage of a nozzle over an orifice plate is that there is no sharp edge to erode, but they are more expensive to manufacture and more difficult to install and to remove from the pipe.

3.4 Low-loss Meters

With the growing concern for energy conservation there is every incentive to develop devices with a low pressure loss, and yet to retain the basic advantages of differential-pressure meters.

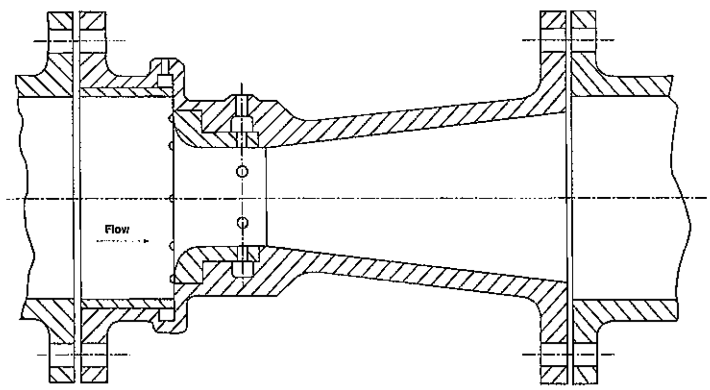


Figure 10 - Venturi nozzle

Many variations of low-loss meters have been invented, but only a few have been exploited commercially. The main problem perhaps is that to be competitive with conventional differential-pressure devices an immense amount of test data would need to be accumulated to match the installation experience on the latter.

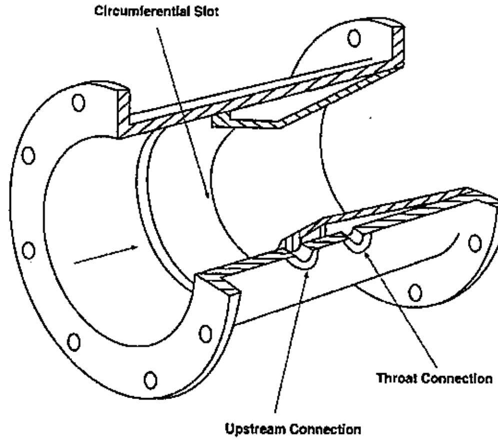


Figure 11 - Dall tube

One of the earliest such developments was probably the Dall tube[14], Figure 11. It comprises two cones, each with a substantial included angle, between which is a circumferential slot. The abrupt change of boundary contour results in flow curvature which increases the differential pressure produced. The sudden reduction in section at the upstream pressure tapping gives a local pressure increase which also augments the differential pressure produced by this device.

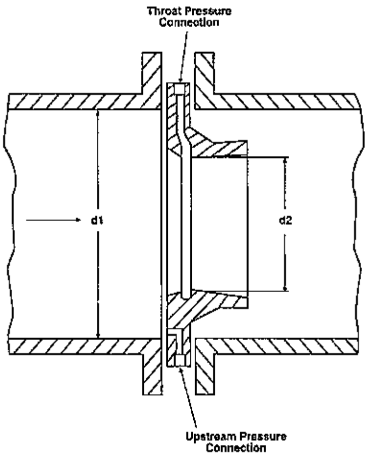


Figure 12 - Dall orifice

An interesting variation of the Dall tube is the Dall orifice, Figure 12. This is virtually a shortened version intended for insertion between flanges, but the price of this is an increased head loss.

The orifice plate has also been modified to improve its performance, and the Epiflo device[15] is a good example of this. As shown in Figure 13, it features a cylindrical ring protruding upstream and a conical diffuser downstream to obtain maximum pressure recovery.

Tests indicate that it can operate over a wider flow range than a standard orifice plate and that the pressure loss is comparable with that of a Venturi tube. However, it is cheaper to manufacture and easier to install than a conventional Venturi.

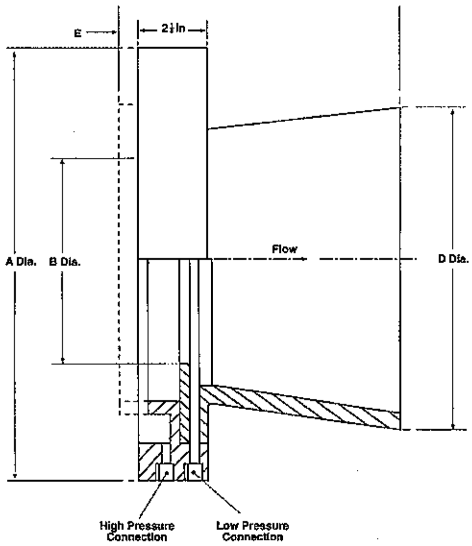


Figure 13 - Epiflo device

Another low-loss meter is the Gentile Flow Tube, named after Vincent Gentile Jr who described it in 1950[16], Figure 14.

It comprises a short length of pipe (usually about 1.5*D*) the inner passage of which is fitted with two groups of pressure-sensing holes, one group pointing upstream, the other downstream. Each group is connected to a common chamber from which connections to the manometer or pressure transmitter are made.

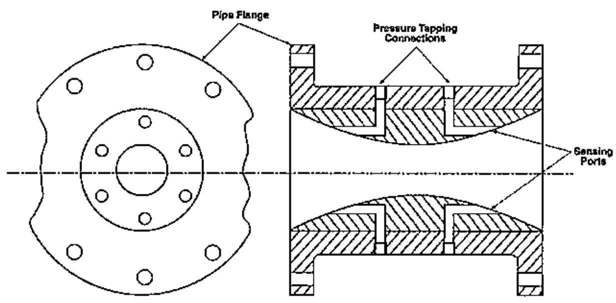


Figure 14 - Gentile flow tube

The meter measures the dynamic head near the pipe wall, static pressure being cancelled out. It will operate in gas or liquid and, being symmetrical, can measure flow in either direction. When calibrated within the adjacent pipework it is capable of high accuracy, uncertainties of about 0.3 per cent being possible.

3.5 Inlet Flowmeters

Four devices are used as a flowmeter at the inlet to a pipe: the nozzle, bellmouth entry, conical inlet and Borda inlet. Such flowmeters are most commonly used for air-flow measurements; although there is no reason in theory why they should not be used with liquid flows, there are, in practice, few situations in which they are appropriate.

In every case the 'upstream' pressure is simply that in the reservoir (normally the atmosphere) from which the air is drawn into the pipe. Details of the dimensions and construction of the devices are given in Figure 15.

The use of nozzles at an inlet is described in Reference 17. Alternatively an ISA or a Venturi nozzle can be used in accordance with Reference 2.

The design of bellmouth entries is not standardised, but any long-radius curved inlet will act as a good flowmeter provided that the walls are smooth, and the use of a discharge coefficient of 0.99 will be correct to within ±1 per cent - which is not to say that this is the uncertainty of the flow measurement, because manometer readings, density calculations etc., have their own associated uncertainties.

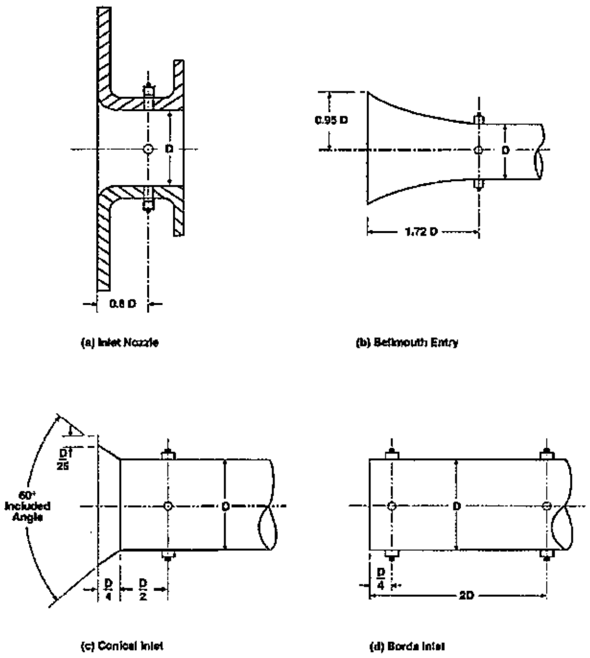


Figure 15 - Inlet flowmeters

The conical inlet has been standardised[18] and has been shown[19] to have a discharge coefficient of about 0.96, although this value can vary by ±2 per cent even with carefully made devices.

The Borda inlet has the advantage that it is easy and cheap to make, and generates about four times the differential pressure produced by a conical or a bellmouth entry with the same throat diameter (the diameter of the 'throat' being that of the downstream pipe). It does, however, have a higher head loss - about 0.5 times the velocity head. The discharge coefficient is approximately 0.5, and details of the design and use of Borda inlets are given in Reference 20.

When using inlet flowmeters, care has to be taken that the area from which the air is drawn is free from draughts or cross-winds, since otherwise significant errors can occur[21].

3.6 Variable Area Meters

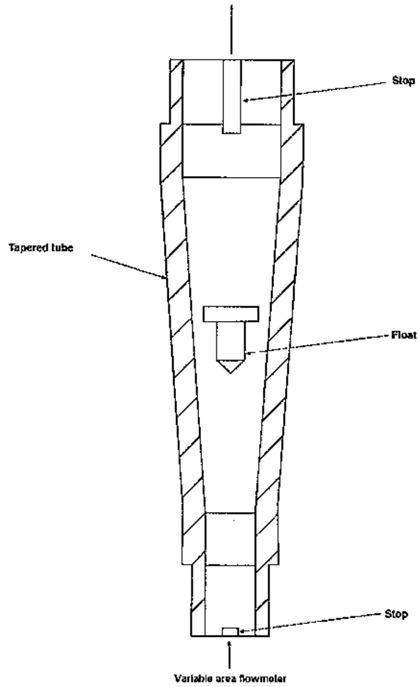


Figure 16 - Cone and float meter

So far flow through a fixed area has been considered so that the differential pressure is a function of flowrate. The variable area meter, however, operates on the principle of maintaining a nominally constant differential pressure by allowing the effective area to increase with flow. There are various types of variable area meters, but the cone and float is the most common. It is used widely for metering gas and is manufactured in forms suitable for nearly all fluids. In its simplest form it comprises a vertical tapered glass tube containing a self-centering top-like float, Figure 16. With flow upwards from the narrow end, the float rises until equilibrium is reached, and graduations on the tube opposite the top of the float indicate the flowrate.

For more arduous duties, usually involving higher temperature and pressure, a robust metal-tube design has been developed. This offers a much safer instrument that can be used with toxic or otherwise hazardous fluids. Even opaque or slightly dirty fluids can be handled by virtue of the magnetic coupling between the float and the indicator. This type of meter can also be fitted with an electric or pneumatic transmitter to operate a distant indicator.

In the most recent development, based upon the use of a series of light-emitting diodes for the opto-electronic detection of the position of the float, the variable area meter can be converted into a digital instrument.

3.7 Drag Plate or Target Flowmeter

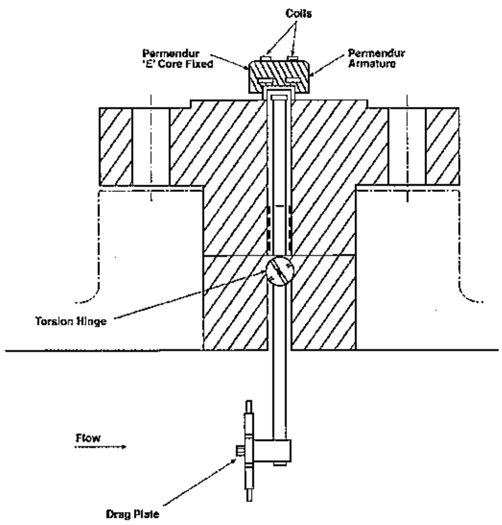


Figure 17 - Drag plate flowmeter

Although not strictly a differential-pressure device, this type of meter is included here for completeness. The principle of a unit developed by NEL[22] is shown in Figure 17. The drag plate is a thin disc mounted on a rod normal to the flow and the change in momentum of the flow past the plate produces a force which deflects the plate against the restoring torque produced by the hinge. The movement of the plate, as sensed by a displacement transducer adjacent to the armature, is related to the flowrate.

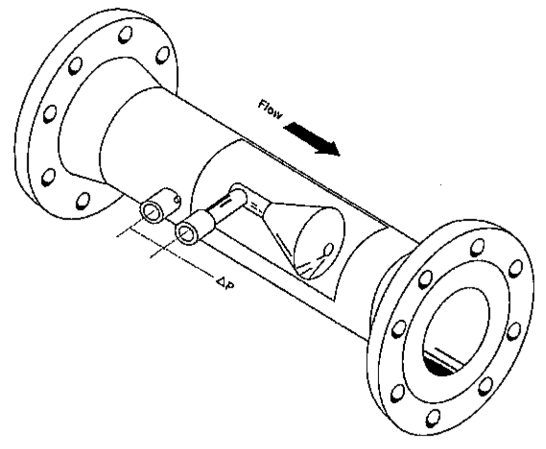


Figure 18 - V-cone flowmeter

This particular device was developed for use as a transient flowmeter in which capacity it was most successful. Other designs of the instrument are on the market for the measurement of steady flow.

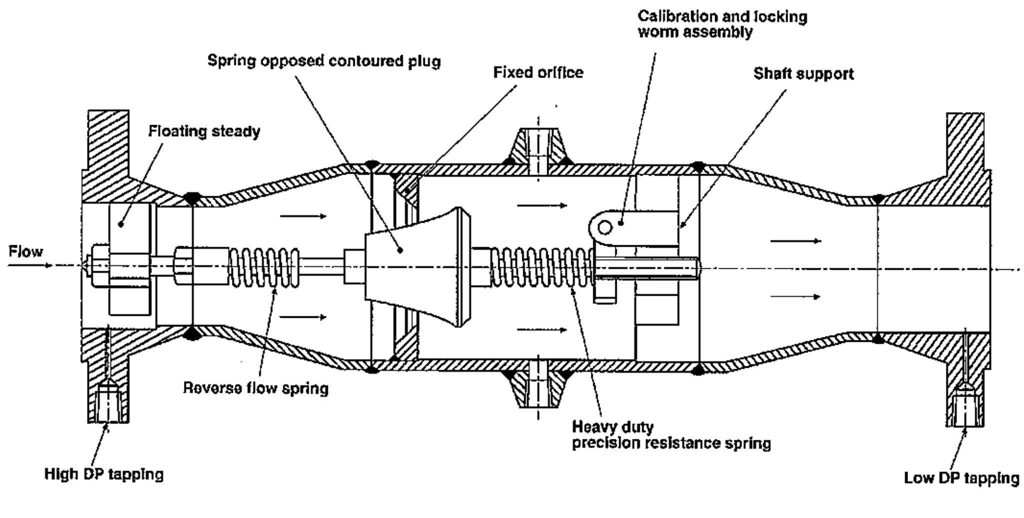
3.8 V-Cone Flowmeter

A modern patented differential flowmeter that has found significant use is the V-Cone flowmeter (Figure 18). Its advantages include a shorter straight length required upstream than that required by an orifice plate[23].

4 EXTENDING THE RANGE OF DIFFERENTIAL-PRESSURE METERS

Because of the square law relationship between pressure difference and flowrate, the rangeability of a differential-pressure meter is limited normally to 3:1 and to about 8:1 at most. The use of modern 'smart' pressure transmitters is increasing the range of the meter.

In some situations where brief interruption of the flow is permissible, a greatly extended flow range can be obtained by use of multiple orifice plates[24]. Interruption of the flow will not be necessary if multiple meter runs downstream of a header are used or a suitable orifice fitting is employed.



NOTE DP is differential pressure.

Figure 19 - Variable area differential-pressure meter

In the field of variable area flowmeters probably the most significant development was the introduction of the spring-resisted, differential-pressure, variable area flowmeter, Figure 19. The cone takes up a position of equilibrium under the combined effects of the flow, the spring and the area of the orifice. By suitable design of the profile to match the choice of spring, the differential pressure can be made a linear (or even some other) function of flowrate.

Thus it is possible to extend the range of the variable area meter several fold with the benefit of differential-pressure output and, if desired, to improve the sensitivity at the low-flow end.

5 ACCURACY

In choosing a flowmeter, there are many factors to consider, and among them the question of accuracy is very important. While it is pointless to pay for higher accuracy than is necessary, a cheap meter that is not accurate may become expensive. Similarly, unless a meter is calibrated and installed correctly, it will not achieve its potential accuracy.

If a typical orifice plate is designed and manufactured according to a recognised standard, it is reasonable to expect that an uncertainty of approximately 1 per cent (or a little less) will be obtained at maximum flowrate under ideal conditions depending on its area ratio. This could be increased by as much as 4 per cent because of the effects of inadequate upstream and downstream lengths.

By calibrating a differential-pressure meter an uncertainty of less than 0.5 per cent should be obtainable.

Because of the square root relationship between differential pressure and flowrate, the relative uncertainty of the flowrate measurement increases very markedly at low flowrates.

6 AGEING EFFECTS

Having obtained a suitable meter and calibrated it, one might suppose that to be the end of the matter. This is not so. As time goes by gradual changes may occur which eventually cause significant errors to be introduced unless remedial measures are taken. The sharp edge of an orifice plate may be eroded away causing the discharge coefficient to rise. Film growth may occur on the throat of a nozzle or a Venturi tube resulting in a lower discharge coefficient.

Unfortunately, no general rules for the rate of deterioration are available; each installation must be assessed according to its own set of circumstances and renewals or recalibrations made as appropriate. The vital thing is to be aware of the dangers. Forewarned is forearmed.

7 CONCLUSIONS

Differential-pressure meters remain the most common meters in use worldwide. They are simple to make, normally without moving parts, and well understood. They have generally accepted standards based on years of research, and the standards have been revised in the light of the latest research. They have the advantage that most differential-pressure meters, especially the orifice plate, the most common meter, can generally be used without flow calibration.

However, most differential-pressure meters have an output which is non-linear with flow; they are affected by upstream installations and ageing, and they may cause significant irrecoverable pressure loss.

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POSITIVE DISPLACEMENT AND TURBINE METERS

by

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PRINCIPLES AND PRACTICE OF FLOW MEASUREMENT

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CONTENTS

POSITIVE DISPLACEMENT METERS

1 DISPLACEMENT METERS

The most general description of a displacement meter is a flowmeter which measures the volume of fluid passing through it by separating the flow into discrete bits, and then counting the bits. In this respect a bucket lifting water out of a pool, counting the number of times, timing the operation and knowing the volume of the bucket is a simple positive displacement meter. In practice however a more continuous mechanism is normally employed.

Each type of positive displacement meter has three common components: first a working chamber of discrete and known volume; second a displacer which allows the chamber to be filled and emptied, hence transferring the fluid from one end of the working chamber to the other, and lastly a register connected to the displacer which counts the number of times the displacer moves across the working chamber. All meters have some degree of sealing preventing fluid from leaking past the displacer.

This broad description covers a very wide range of meters operating on the displacement principle, and only a few of them can be considered in this course. However general information regarding most of the others, as well as fuller descriptions of those considered here can be found in the references at the end of these notes.

2 DISPLACEMENT METERS FOR GASES

The three main types of volumetric displacement meters used in gas measurement are dealt with in this Section. The first two types of meter described, wet gas meters and diaphragm meters, are used for metering low flowrates at conditions close to ambient. Wet gas meters are frequently used as secondary reference standard meters in flow measurement laboratories and diaphragm meters are the most commonly used meters in the United Kingdom for the sale of gas to domestic and commercial consumers. Rotary displacement meters which are the third type of meter described, are used for a range of gas flow applications at higher flowrates and pressures than those covered by either wet gas meters of diaphragm meters.

2.1 Wet Gas Meters

A wet gas meter consists of a horizontally disposed drum divided into compartments as shown in Figure 1. The drum is free to rotate about its axis in a water bath which is filled to a level just above the axis of rotation. The gas to be measured enters the drum at the centre and, as it fills a compartment, it displaces the water and allows the drum to rotate. When the compartment is filled the inlet port to the compartment is sealed by water. The inlet

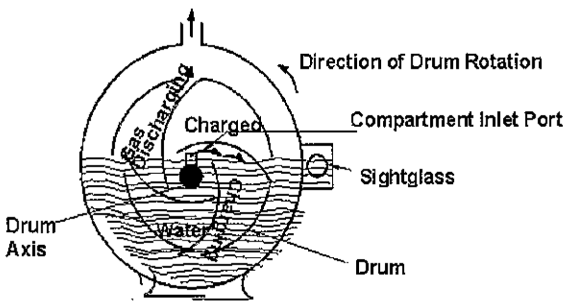


Figure 1

port to the next one then opens and the drum continues to rotate. As is rotates water enters the first compartment and the contained gas is expelled through the outlet. Thus, when calibrated, one revolution of the drum displaces a known volume of gas.

The gas passing into the meter should be saturated by passing through a pre-wetting process. This reduces errors due to humidity variations and prevents water within the meter from evaporating. The pressures within the meter should be such that no water displacement errors are caused.

It is worth while noting that for many applications it is preferred to use light oil as the sealing medium instead of water. This avoids evaporation and humidity problems The oil used must be of low viscosity and very high vapour pressure

One of the main disadvantages of this type of meter is that, to measure even moderate flowrates, meters become very large in size. As can be imagined that if the drum rotates too quickly the water level will bank up on one side of the meter and either break the seal or pump the water out! A meter rated for a maximum delivery of 9.5×10^3 m^3/s an instrument 1.2 m long and 1.05 m high must be used.

Devices of this type are used to meter gases at flowrates between 2.5×10^{-6} m^3/s and 4×10^3 m^3/s. The pressure and temperature of the metered gas are usually close to ambient, differentials in pressure across the meter being usually less than 2.5×10^3 N/m^3. Under carefully controlled conditions accuracies of some ±0.25 per cent of reading can be achieved and the meters have rangeabilities of up to 10:1.

2.2 Diaphragm Meters

This type of meter is the most commonly used meter in the United Kingdom and throughout the world for the sale of gas to domestic and commercial consumers. Some progress has been made in recent years to develop replacement meters operating on the ultrasonic and fluidic principles, however these are proving difficult to manufacture with the required stability, rangeability or more importantly low cost..

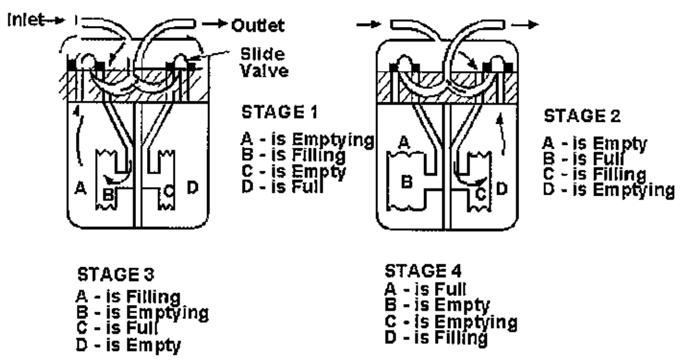


Figure 2

Figure 2 describes the meter during its four stages in the operating cycle. Two stages are illustrated. The device consists of a housing containing four chambers two of which, 'B' and 'C', are enclosed by bellows which expand and contract as they are charged and exhausted respectively. Flow into and out of the chambers is by means of slide valves. The volume of gas passed through the meter is obtained through a linkage arrangement which connects the diaphragm to a mechanical readout system which counts the number of displacements.

Provided the devices are carefully calibrated and maintained accuracies in totalised flow of ±1 per cent can be attained. These meters measure gas at rates ranging from 5×10^{-4} to 10^{-1} m^3/s. Pressures and temperatures of the metered gas are usually close to ambient and the instruments have a rangeability of grater than 20:1 and 100:1 is possible.

Diaphragm meters are popular since they can be manufactured very cheaply and they measure volume directly. They are, however, only suitable for non-corrosive gases and they cannot be used to meter large flowrates.

2.3 Rotary Meters

A lobed rotary displacement meter (Roots type meter) is shown. It consists of two 'figure of eight' lobed rotors rotating in opposite directions to each other within a casing. The rotors are driven in the direction shown by the flowing gas such that for each rotation cycle a calibrated volume is swept out. Flow is totalised by summing the number of rotor cycles.

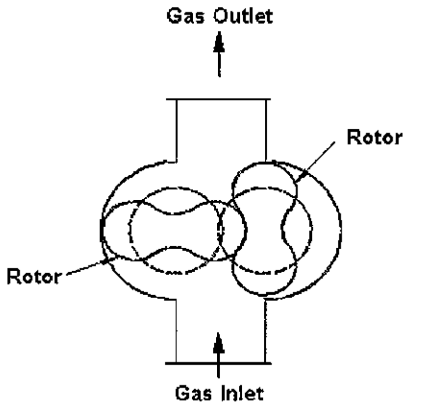


Figure 3

Roots type meters are used at pressures up to 80 bar but temperatures do not generally exceed 60°C. Rangeabilities of up to 25:1 can be achieve and flowrates covered ranges from 2×10^{-3} to 2 m^3/s at line conditions: accuracies of better than ±0.5 per cent of totalised flow are attainable with clean gases.

One of the main disadvantages of the Roots type meter is that it introduces significant pulsations into the flow. This disadvantage is largely overcome in a meter, commonly known as the CVM meter, which, because of the low inertia of the rotor introduces only very low amplitude pulsations into the flow. The meter is outlined in Figure 4. It consists of an annular measuring chamber, four freely rotating vanes X_1 - X_4 and a rotating gate. The gate allows the vanes to pass back from the inlet port to the outlet port without allowing gas to bypass the measuring chamber.

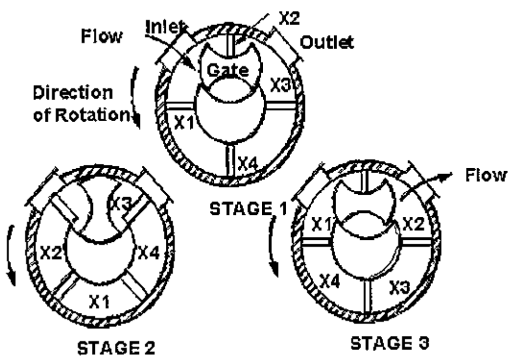


Figure 4

The drawing shows the meter at three stages in a cycle. At stage 1 the gas enters the meter through the inlet port and causes the vane assembly to rotate. This rotation of the vane assembly causes, through a set of timing gears, the gate to rotate to the position shown as stage 2. At stage 2 the vane X_2 has passed from the gate recess and the volume between X_1 and X_2 is being filled with gas. The vane assembly continues to rotate and at stage 3 the vane X_1 has returned to the recess and the gas between X_1 and X_2 is flowing through the exhaust port.

Meters of this type experience most use at temperatures close to ambient and pressures up to 9 bar. They can also be designed to operate at pressures up to 80 bar. These will be very heavy but less bulky than Roots type meters. They have a rangeability of 25:1 and can measure totalised flow at flowrates up to 3 St m^3/s to within ±0.5 per cent.

Rotary displacement meters are not greatly affected by variations in upstream pipework configurations and only severe variations in upstream velocity profiles will affect meter performance. Concerning physical properties of the metered gases the main influences are density, viscosity and different gases will give different pressure differences across the flowmeter at the same flowrate. This means that any slip of gas through the clearances in the meter will vary for different gases. This effect is greater at low flowrates although even here it is small.

Even small quantities of dirt or grit suspended in the flow can, however, cause significant errors in meter operation and if a meter jams it stops flow in the line. Filters should, therefore, always be included upstream of rotary displacement meters. Also if pulsations are present in the flow line this can have a marked effect on meter performance. Finally it should be noted that while rotary displacement meters of the Roots type can be used at pressures up to 80 bar they are seldom used at pressures in excess of 20 bar since for high-pressure work they become very bulky heavy and extremely expensive.

One comment for maintenance, the clearances inside the meter are very tight and the rotors, although heavy, rotate very easily. Introducing fingers to turn the rotor can lead to removal and of course potential damage to the meter!!

3 DISPLACEMENT METERS FOR LIQUIDS

Only three of the most common type of liquid displacement meter are considered in this section. The displacement meters find their place in measurement of liquids in petroleum distribution where their reliability for batch measurement is used extensively. They are also found in the measurement of low flows and high viscosity flows.

3.1 Reciprocating-piston Meters

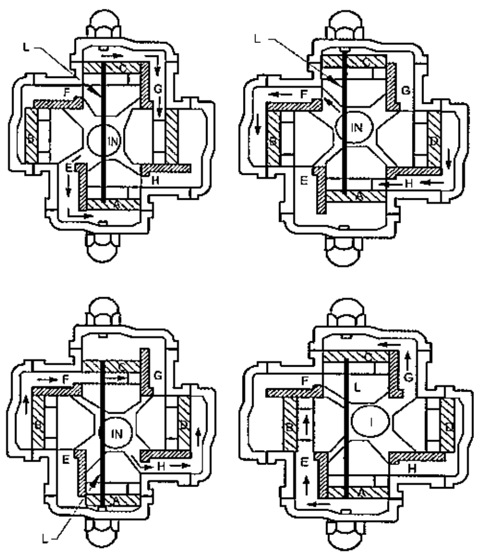


Figure 5

The reciprocating-piston meter is basically a reciprocating-piston engine which does not do any work apart from overcoming friction. Within this class of PD meter there are a number of different designs. The drawing shows the four stages of the operation and the arrangement of a four-pistons reciprocating meter.

The pistons are arranged in opposing pairs, the members of each pair being connected together by a coupling rod which, through a crank, drives the register mechanism. The pistons are arranged in their cylinders so that when one cylinder is ported to inlet, the opposite cylinder is ported to outlet. When liquid flows through the meter a reciprocating motion is set up. This is the most common flowmeter encountered by the public as it is used in the dispensing of fuel on the forecourt. The meter is not suitable for high viscosity oils and may suffer wear if lubrication is not present.

Rangeability of 10:1 with a expected accuracy of better than 0.5% is found.

3.2 Sliding-vane Meters

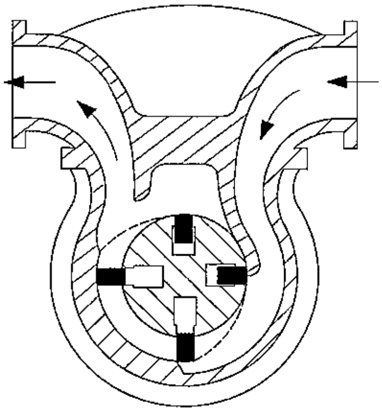


Figure 6

If the piston-type PD meter can be likened to a piston engine being driven by the fluid, then the sliding-vane type meter, illustrated has its parallel in an idling vane-type rotary pump. The rotor carries the vanes which, arranged in opposing pairs, are free to slide in and out of their recesses. The members of the opposing vanes are rigidly connected by vane rods, and the flowing fluid, acting on the exposed vanes in turn, causes the rotor to rotate. As shown, with this rotation, liquid is transferred from inlet to outlet through the space between successive blades. This is the only way liquid can be transferred from inlet to outlet and so, by counting the number of revolutions of the rotor, the quantity of liquid passed can be computed. Sealing is effected by action of the vanes on the wall of the chamber by a combination of liquid pressure and centrifugal forces and assisted by spring-loaded vanes or by close tolerance gap between vane and wall. The meters are used for most hydrocarbons from LPG through to high viscosity fuel oil (with clearance modification and trace heating).

Accuracy of better than 0.5% and rangeability of 20:1 is commonly found.

3.3 Gear Meters

There are almost as many gear-type meters as there are gear-type pumps, and lack of space precludes a detailed discussion here. Among the more important gear-type meters are the oval wheel meter on the left below and the helical gear meter on the right. The generic type have a reasonable accuracy and are particularly suitable for high viscosity fluids.

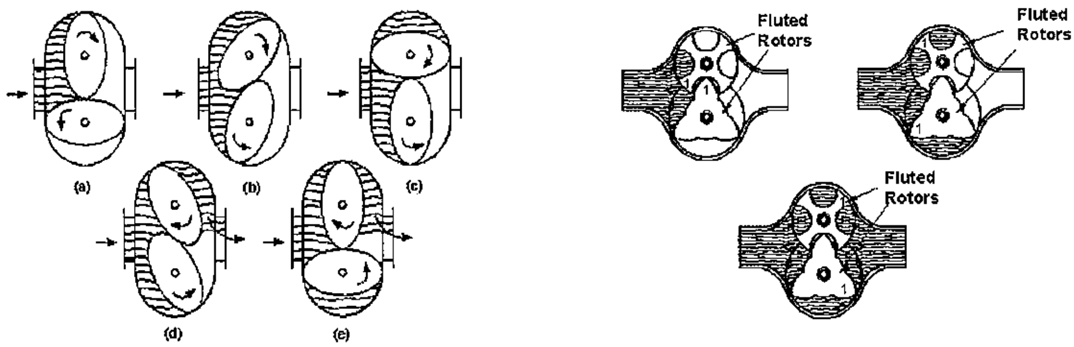


Figure 7

3.4 Metering Pumps

Because of operational similarity between PD meters and positive displacement pumps, it is often convenient to use the pump itself as a meter merely by monitoring the rotation of the shaft. Metering pumps find application mainly in the process industry where additives are required to be metered on mixing with the main stream. Metering pumps generally cover the lower flowrates and can meter virtually all pumpable liquids at moderate accuracy levels.

4 PERFORMANCE CHARACTERISTICS OF DISPLACEMENT METERS

There is such a large number of different types of displacement meters that it is impossible to generalise on their individual performance characteristics. However, certain features are common to all types, both liquid and gas. In common with all other mechanical meters, the PD meter has frictional resistance which must be overcome by the flowing fluid. At very low flowrates the fluid does not have the kinetic energy to turn the rotor against this friction (which includes, in the case of most PD meters, the resistance offered by the mechanical linkage to the register); at these low flowrates, therefore, the fluid slips past between displacement component and the casing without moving the piston or rotor. Meter error, E, is defined as

$$E = \frac{Q_{indicated} - Q_{actual}}{Q_{actual}} \times 100 \text{ per cent}$$

so that at these low flowrates the error is large and negative.

As the flowrate increases, however, this large negative error disappears rapidly, since the kinetic energy of the fluid increases as the square of its velocity. A condition of near equilibrium is then reached where the driving force of the fluid is balanced by the various resisting forces, and for a well designed meter this continues over the working range.

At the top end of the flow range the slippage tends to increase again, because of the rapidly increasing pressure drop across the meter at these flowrates.

Typical performance curves for a Roots type meter (gases) is shown in Figure 8.

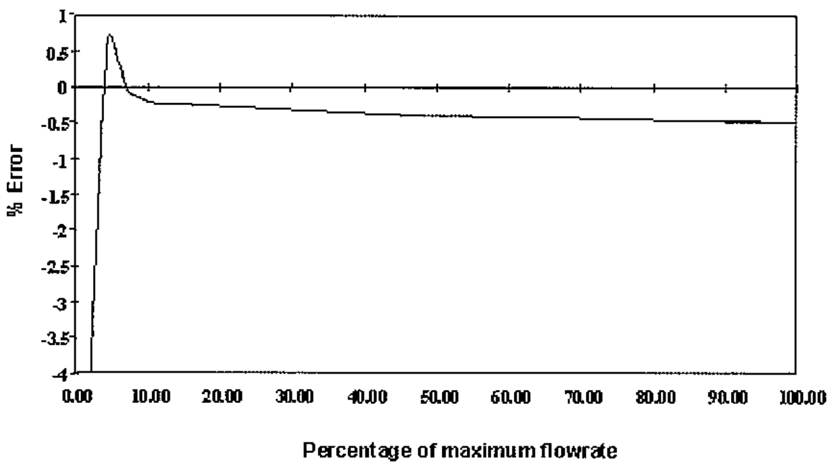


Figure 8

The performance of a sliding-vane type meter (liquids) is given in Figure 9.

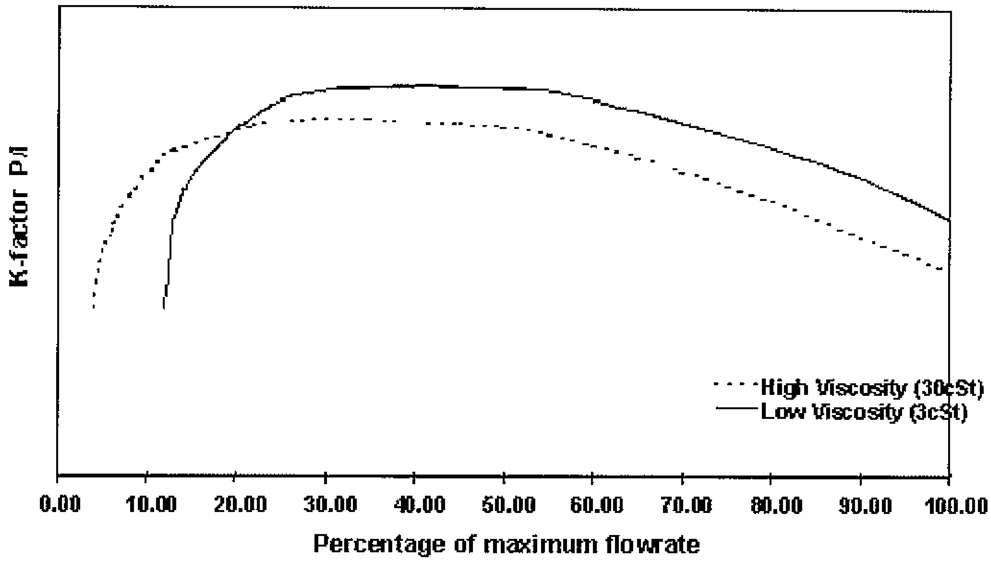


Figure 9

The performance of displacement meters, especially for liquids, is affected by viscosity while for gas meters the pressure of the metered fluid can also cause significant changes in performance. In some liquid meters adjustment for difference viscosities is provided although for the highest accuracies the meter should be calibrated in the liquid in which it is to be used.

Table 1 - Guide To Ranges and Conditions Covered By Meters Dealt With in this Lecture

Meter type	Flow	Pressure	Temperature	Pipe diameter	Rangeability	Accuracy under controlled conditions per cent
Wet gas meter	2.5×10^{-6} m^3/s to 4×10^{-3} m^3/s (at line conditions)	Ambient	Ambient	Up to 50 mm	10:1	±0.25
Diaphragm meter	5×10^{-6} m^3/s to 10^{-1} m^3/s (at line conditions)	Ambient	Ambient	Up to 50 mm	20:1	±1
Rotary displacement meters	Up to 140 St m^3/s	Up to 80 bar	Up to 60°C	Up to 0.5 m	25:1	±0.5
Reciprocating piston meters	Up to 100 l/min	Up to 10 bar	Up to 60°C	Up to 25 mm	20:1	±0.1
Sliding-vane meters	Up to 5000 l/min	Up to 10 bar	Up to 100°C	Up to 0.25 m	15:1	±0.1
Gear meters	Up to 1000 l/min	Up to 10 bar	Up to 100°C	Up to 100 mm	10:1	±0.5

TURBINE METERS

5 TURBINE FLOWMETERS

Turbine flowmeters are one of the most common flowmeters used for high accuracy measurement of both liquids and gasses. As with all flowmeters this sweeping statement has to be qualified by the limitations of the meter type and the applications for which they are suitable. Within the oil sector, turbine meters are the first choice for most liquid fiscal or custody transfer applications involving continuous or large batch flows.

5.1 Principles

A turbine flowmeter consists of a multi-bladed rotor mounted on bearings allowing it to rotate at a speed proportional to the kinetic energy of the fluid flowing across the blades. This in turn is proportional to the mean axial velocity of the fluid. This gives a flowmeter where the speed of rotation of the rotor is proportional to the volumetric flowrate of the fluid passing through it.

Two theoretical techniques have been used to model the performance of turbine meters; one technique relating the reduction in angular momentum across the meter to the resulting rotor speed, and the second technique uses airfoil theory to predict rotor speed. Both of these techniques are one-dimensional, and airfoil theory is the most popular. Recent developments in computational fluid dynamics codes are allowing more complex and precise modelling, but the codes are often operating at their limit to achieve good results.

It should be stressed that turbine meter modelling can only be indicative, as it is a well documented fact that relatively minor changes in blade design, for example filing the trailing edges, can cause shifts in meter factor in excess of 5 per cent. This being said, some of the concepts used in the airfoil modelling technique are given below.

5.1.1 Airfoil theory

The basic form of this approach treats each blade as an entity and the lift and drag torques due to aerodynamic forces are coupled with drags caused by bearings, skin friction effects, and at the tip of each blade. For steady rotation, the sum total of lift and drag torque must equal zero, and from this relationship (and some assumptions) the rotor speed can be calculated as a function of flow velocity.

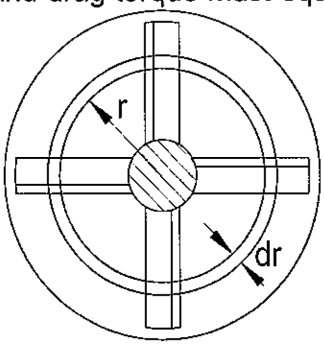


Figure 10 - A cross-sectional diagram of a turbine flowmeter

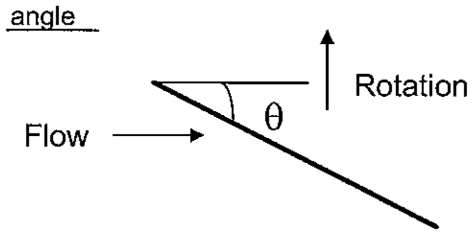
Figure 10 shows a cross section of a typical meter, and the modelling process begins by considering a radial element, dr, at a radial position, r, from the centre-line.

Figure 11(a) considers the axial flow impinging on this element of blade that is at an angle θ to the axis. For straight bladed turbine, this angle is constant (30° is typical). For a helical blade, however, the angle θ is function of r given by

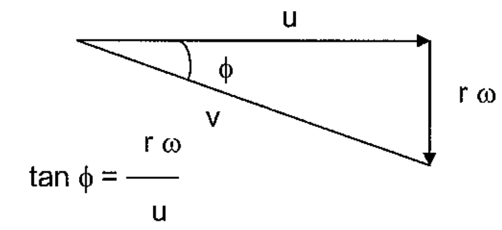
$$\tan\theta = \frac{2\pi r}{L} \qquad (1)$$

where L is the blade pitch. This shows that for the helical bladed turbine, the angle θ increases towards the tip of the blade.

In order to calculate lift and drag forces due to aerodynamic effects, the resulting angular rotation imparted is "stopped" by adding an equal and opposite rotation, which at a radial position r equates to rω, This is illustrated in a basic vector diagram in Fig 11a. From this a flow velocity diagram similar to that shown in Figure (11b) can be constructed.

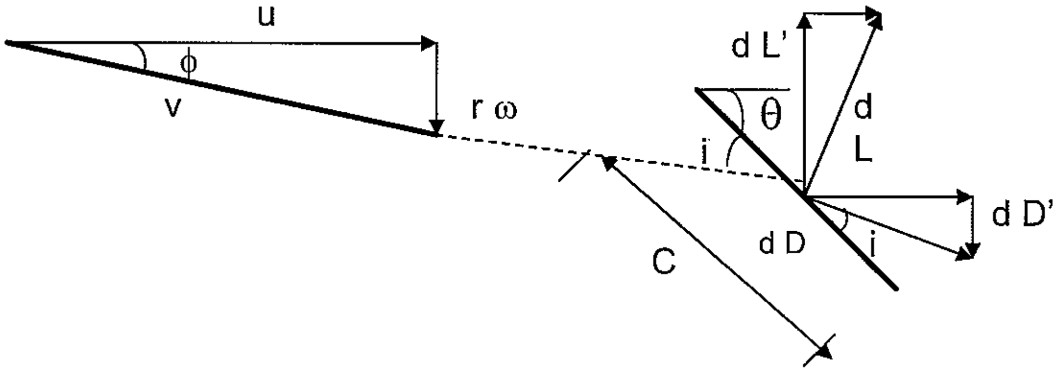


11a



11b

It is then possible to derive the angle of incidence of the flow onto the blade as shown in Figure 11(c), and from there derive the lift and drag forces using standard fluid dynamic equations for flow over a flat plate.



11c

The components of the lift and drag in the plane perpendicular to the axis of the rotor are then obtained from trigonometric calculations, and the torque obtained by multiplying the resulting force in the direction of rotor spin by the radial position, r.

$$dT = r\,(dL' - dD') \qquad (2)$$

It is then a straightforward integration process to find the total torque per blade

$$T_b = \int_{TIP}^{HUB} dT \qquad (3)$$

and ultimately the total driving torque,

$$T_t = NT_b \qquad (4)$$

where N is the number of blades.

Using similar fluid dynamic equations, it is possible to derive expressions which give approximations to the values of bearing friction, skin friction drag and tip drag. It is then a matter of setting the driving torques equal to the resisting torques, and solving iteratively to obtain ω as a function of axial velocity (or flowrate).

This simplified theoretical model is able to predict meter factor for a given geometry to within about 5 per cent accuracy, and it can also model the characteristic 'hump' in the calibration curve. More sophisticated variations to the airfoil approach attempt to make allowance for the interference effects of adjacent blades and velocity profile, and to allow for leakage past the blade tips.

6 DESIGN VARIATIONS

As may be expected from a concept that has been available for many years, the designs are numerous and each claim advantages.

An example drawing showing the main features of typical meter is given below.

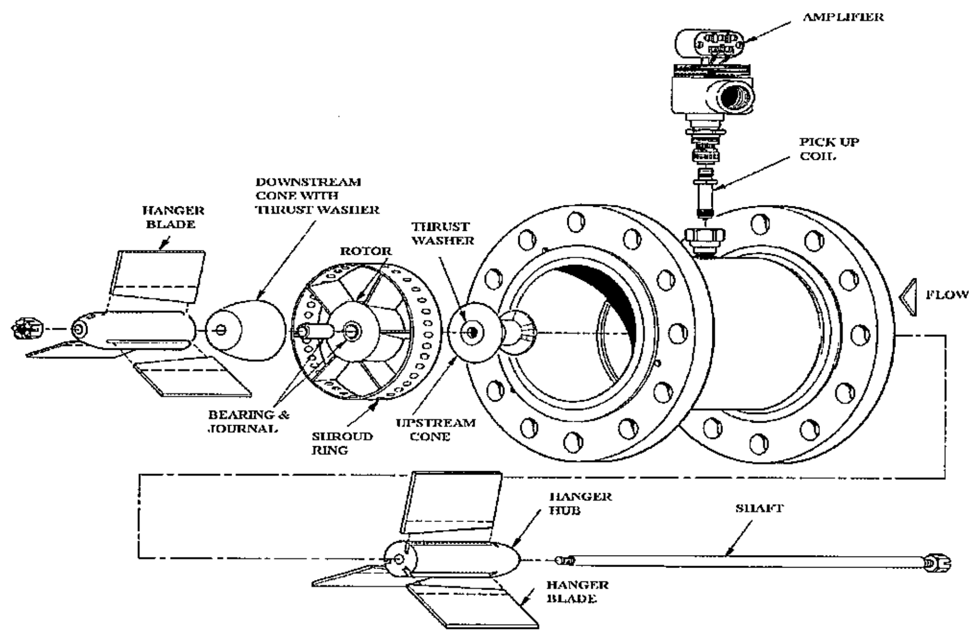


Figure 12 - A schematic diagram of a turbine flowmeter

6.1 Hub, Shaft and Bearings

Common to all turbine designs is a central hub. This is normally a solid central disk which holds the rotor shaft and the rotor blades. The shaft on which the rotor runs is fixed to the rotor and located in upstream and downstream support bearings. Alternatively a fixed shaft can support a bearing concentric with the rotor (as shown in Figure 12).

Bearings are critical to the operation of the meter. Bearing friction creates a drag that is speed dependant and changes with the viscosity and lubricating properties of the fluid. Bearing friction is less important for meters greater than 50 mm than for small meters. More important to the performance is having a bearing with long life and fully compatible for the duty. For small meters in clean fluids, ball bearings offer the best performance. For larger meters, and for most process fluids, journal bearings are generally employed. These are typically combined with a thrust bearing to take up the end float and forces transmitted by the fluid. Various hydrodynamic balancing techniques are used in the designs to ensure that the end-thrust, and hence the friction, drag and wear, is minimised.

6.2 Rotor and Blades

Rotor blades can be machined from solid bar leaving the hub in the centre, or can be located in slots in the hub and fixed by welding or other methods. Casting can also be used to produce rotors but this method is rarely employed for high accuracy meters. The blade/hub joint is critical and care should be taken to ensure compatibility with the process fluid.

Blade shape and number varies with meter design. For liquid turbines, multiple bladed designs are most common, with six, eight, ten or more blades being typical. Blades can be straight and angled to the flow, or cut to produce a helical section.

Each design concept has its adherents, but in practice no rotor design gives a universal advantage which exceeds that obtained by high-quality manufacturing.

For all meters the hub to blade-tip ratio is chosen to provide a balance between driving forces, pressure drop by blockage, and drag forces at the tips. For liquid meters hub to blade-tip ratios of around 0.4 to 0.6 are common. As the tip area of the meter can be critical to the performance of liquid meters, many designs have a shroud ring placed round the outside of the blades. Stated reasons for this addition are varied but it can reduce viscosity sensitivity, increase resolution (by allowing more pulses per revolution) and improve the mechanical strength of the blade assembly.

It is suggested from theory that straight blades will provide a more linear performance while helical blades are less sensitive to changing viscosity. Frequently proposed for high accuracy applications, two or four bladed helical designs are commercially available. The helical cut blades are continuous round the hub over 90 to 360° as in the example shown below.

Blade edges can be cut square or airfoil shaped. For all designs the shape of the blade trailing edge is particularly important and trimming can improve (or degrade) the linearity.

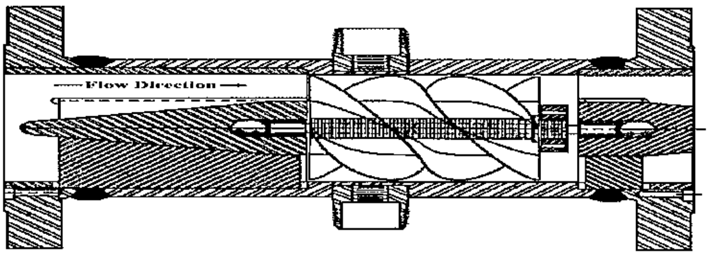


Figure 13 - A schematic diagram of a helical-blade turbine flowmeter

Alternative blade and rotor designs to those mentioned above are possible and reference to 'T' shapes, angled edges and semi-circular profiles can be found. For specialist lower accuracy duties, four conventional blades with a very low blockage factor provide performance in difficult dirty, contaminated or high viscosity duties.

6.3 Rotor Shaft Supports

The supports for the rotor shaft are usually fitted up and downstream although, again for specialist duties, a single upstream or downstream support can be employed. The supports are of two forms, either plates or tubes, aligned with the flow and set to hold the central bearing support in the centre. The plate design usually has three or four plates fitted. Less commonly, multiple plates are used but this tends to increase pressure drop to no flow or mechanical advantage. The tube design typically utilises four tubes touching the pipe walls and each other at the centre with the bearing support held in the centre of the pipe between them.

The purpose of the plates or tubes is to support the bearing. They do have some effect in conditioning the flow before the rotor, but due to their short length and proximity to the rotor, their effectiveness is limited. The central bearing support or housing is normally streamlined to some degree and shields the rotor hub from direct flow forces. It may also provide hydrodynamic forces allowing the rotor float on the bearing.

6.4 Pulse Generation

In most flowmeters, pulses are generated by the passage of the blades through a magnetic field produced by a pick-up coil mounted in a housing located on the pipe wall. For shroud ring meters the pulses are generated by slots or magnetic 'pips' located in the rim (see Figure 12). In each case this provides a signal without breaching the integrity of the pipe. Signals generated in this manner have an amplitude of around 10 mV to 1 V depending on the design of the coil. The signal is a floating a.c. signal of approximately sine wave shape. The amplitude varies with rotor speed and this has to be considered when designing subsequent counters or amplifiers. It must also be recognised that the ideal sine wave may not exist and flat portions or even secondary voltage changes may exist especially on the falling edge. Frequency maybe as low as 10 Hz for twin blade designs and as high as 2 kHz for shroud ring or multi-bladed meters.

An alternative pickup operates by generating a radio frequency field which is broken by the rotor passage. This is more expensive but for high quality small size meters, reduces the drag associated with magnetic pick-ups.

Two basic amplifiers types are available; a voltage pulse amplifier or a 4-20 mA pulse modulated type. The first type is advised for relatively short cable runs, the second being used where cable runs are significantly longer. A third option provides digital to analogue converter producing a 4-20 mA current proportional to flowrate that can be used for process control.

7 CALIBRATION

Turbine meter calibration frequency is based on the value of the product being metered, the risk of damage or calibration change, the cost of calibration and a historical knowledge of the performance. Some fiscal duty meters are calibrated daily, some weekly or monthly. Other meters operate for up to a year between calibrations. For many oil flow applications, a regulatory authority or commercial agreement may specify the calibration schedule.

Ideally turbine meter calibration should be carried out in-situ and for this the preferred method is to use a pipe prover. Many fiscal metering stations incorporate parallel meter runs with a dedicated pipe prover enabling calibration to be performed as required. The alternative is to calibrate meters in a central laboratory such as NEL where a similar viscosity product can be used. Similar installation pipework upstream of the meter should be employed where possible.

An alternative for some installations is to use a portable small volume pipe prover. Small volume prover calibration is only recommended if the turbine meter has a suitably high pulse frequency and has demonstrated good repeatability.

If turbine rotors are not central or imbalanced, signal amplitude can vary within a rotation and this can lead to missed pulses if counter or amplifier trigger levels are not carefully chosen. Furthermore, if blades are not spaced evenly, the interval between each pulse may vary (intra-rotational non-linearity) and this should be considered if pulse interpolation is to be used with any proving or calibration system.

8 PERFORMANCE IN GOOD CONDITIONS

Within the oil industry turbine meters can be divided into three arbitrary sizes:

- small — up to 50 mm;
- medium — 50 mm to 150 mm; and
- large — 150 mm upward.

The Table overleaf summarises general turbine meter performance for various meters and typical applications within the oil industry.

Size	Duty	Range	Linearity
Small	LPG's	8:1	0.2%
Medium	LPG's	10:1	0.2%
Medium	Light (<10 cSt) product/crude	10:1	0.15%
Medium	Heavy (10 - 30 cSt) product/crude	5:1	0.2%
Large	Light (<10 cSt) product/crude	10:1	0.15%
Medium	Gantries	5:1	0.2%

Under good flow conditions and with a meter in good condition, no difficulty in obtaining excellent repeatability should be found. Turbine meters can be expected to provide repeatability, at a single flowrate (based on spread of results), within ±0.01% or better. In fact the repeatability of the calibration standard is usually the limiting factor. For oil industry use, standard practice sets acceptability limits as ± 0.025% based on five test points. This is specified in IP, API, and government (DTI and NPD) guidelines.

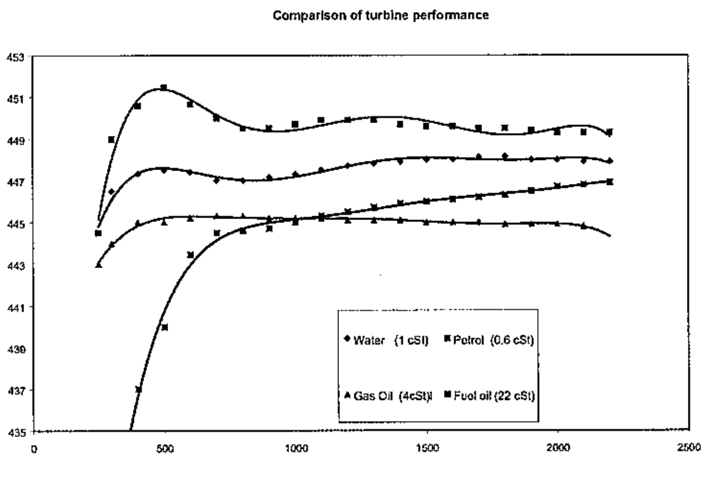
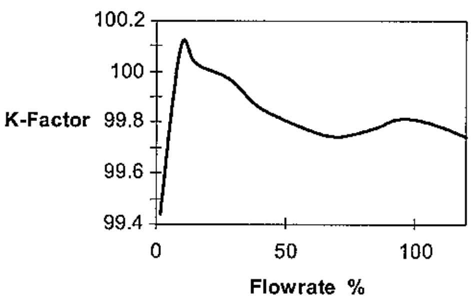


Figure 14 - Characteristic turbine calibration curves

The skill in designing a turbine meter lies in obtaining a linear performance with changing flowrate, and maintaining this across the operating viscosity range. A classic turbine meter performance curve for water is shown in top curve of Figure 14. This shows at the lowest flowrate that the resistance is high relative to the driving force. This area of slippage disappears rapidly with a hump appearing before the driving force balances the retarding force resulting in linear performance. The characteristic curves expected with increasing viscosity are also shown with the second curve for a viscosity approximately 7 cSt and the lower curve for approximately 15 -20 cSt.

Needless to say not many turbines in service will exhibit these precise curves, and Figure 11 shows some examples of curves obtained from different meters, sometimes of the same design.



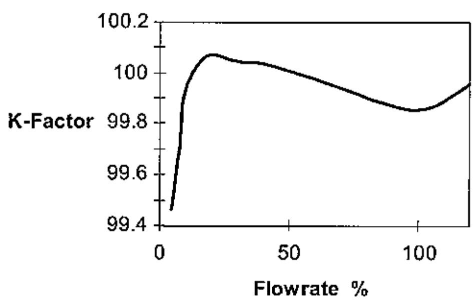


Figure 15 - Typical turbine calibration curves

Generally in the oil industry linearity across the working range (perhaps 8:1 in light refined oils) will be expected to be within 0.15 per cent. The expected linear range varies with 10 or even 15 to 1 expected for water and as little as 4 to 1 in higher viscosity products (e.g. 30 cSt). The linear range of turbine meters tends to increase with meter size.

Although good design is the key to linear performance, linearity can be improved by meter modification. For all meters trimming the trailing edges can adjust the linearity markedly but care has to be taken that this improvement is maintained at a different viscosity fluid.

Variations from acceptable performance may be evidenced by poor repeatability during calibration, indicating probable bearing damage, or changed linearity indicating bearing or blade damage. Repeatability is not always a good judge of meter health as was noted in a recent laboratory calibration where good repeatability was noted but where large step reductions in k-factor were observed. Repeatability remained good within each set of results. The step changes were found to be caused by blades falling off due to salt water corrosion at the blade root weld.

9 INSTALLATION

Turbine meters operate by integrating the kinetic energy of the fluid across the blades to produce rotary motion. If the fluid velocity is unevenly distributed across the pipe or more importantly has a rotational component (swirl), the rotational speed for a particular total volumetric flow will be altered. This is one of the main limitations of the meter. A good flow profile has to be present to provide a consistent K-factor for the meter. Any degree of swirl, asymmetry or modified flow profile can give rise to changes in calibration. Extreme distortion of the flow may even affect repeatability.

The avoidance of the effect of swirl gives the largest area of contention when standards for installation are considered. Commonly for liquid meters a minimum of 20 diameters of straight pipe of the same diameter upstream of the meter is recommended, 30 is preferred while many manufactures will suggest the very optimistic 10 diameters. Clearly, in the oil production process, space and weight savings are at a premium and hence judgement has to be used to estimate the severity of the disturbance. Double out of plane bends, followed by reducers create swirl levels which may need 100 diameters to decay while a single bend may require 20 diameters. Flow straighteners can be employed and these are best fitted 10 diameters from the disturbance and 20 from the meter. Reducing this to 5 and 10 can be acceptable if the disturbance is not severe. Five diameters of straight pipe are recommended downstream of the meters. Conventionally tube bundles are employed for flow conditioning and little assessment has been made of other types for turbine meters.

The standards documents are currently being revised indicating that proper consensus on installation effects has not yet been reached.

For the majority of industrial applications meters are fitted with an amplifier housed immediately above the pickup and integral with the meter. For measurement purposes the pulses are totalised to give a measure of volume while the frequency is used to indicate flowrate.

For fiscal duties two pickups are fitted and both signals are transmitted. The flow computer compares signals to detect electrical noise or signal failure.

10 FLUID PROPERTY EFFECTS

Assuming good inlet conditions the single most influential parameter affecting turbine meter performance is viscosity. In high viscosity liquids the velocity profile along the turbine blade is such that the angle of attack can vary significantly between blade root and tip. This means that in some cases the angle of attack may become negative towards the tip of the blade (see Section 5.1). In this region the blade will not contribute to the driving torque, i.e. the rotor is being driven only the central portion of the blades where the angle of attack is positive. The blade tip is acting therefore as a pump and increasing the flow through the tip clearance. This is one of the fundamental reasons for using helical blades for viscous fluids, in that the increasing blade angle toward the tip mitigates the near-wall velocity profile effect.

In general turbines will provide a reasonable linear performance across a viscosity range from light hydrocarbons through to around 30 cSt. At higher viscosity special designs can provide good accuracy if calibrated in-situ, but the linear range may be very restricted.

Viscosity effects vary with design and no firm guidelines can be drawn but generally above 30 cSt performance will be seriously degraded. Calibration changes are dependant on meter size and the viscosity variation but as little as 1% variation can be significant for small to medium size meters. It follows that wide variations in viscosity will have a significant effects on performance.

Pressure and temperature have little effect on turbine meters. Temperature corrections are sometimes applied to compensate for area expansion of the meter tube, however, some doubt is expressed with regard to the validity this correction methodology.

11 SECONDARY FLUID COMPONENTS

Not a great deal is known about the effects of two component flow. The meters perform reasonably well in water/oil mixtures that are homogeneous. Turbine meter output can give no indication of water content and the performance will vary with the viscosity of the mixture which can be very different from the individual components.
The presence of a gaseous or solid component will cause large errors which are

difficult to predict. The meters can indicate flow in the presence of gas in liquid but the k-factor can 10-20 percent in error for high gas fractions. Gas slugs in a liquid meter can cause over-speeding and permanent damage to the meter. Care should be taken in filling or emptying pipelines for this reason.

For fiscal metering the presence of gas or solids should not be permitted.

Erosive flow experiments at NEL have shown variable results with some meter designs eroding within hours of simulated sandy service. Others proved to be more robust and could be acceptable in sandy service conditions. No firm conclusions can be drawn at this time on predicting designs that will survive but certain manufacturers products have been differentiated.

12 CAPITAL AND OPERATIONAL COSTS

For oil up to 30 cSt viscosity the turbine meter provides the main custody transfer meter and fiscal metering system with currently unrivalled cost/performance ratio. The meters are used for all products from Liquified Petroleum Gas and Natural Gas (LPG/LNG) through to refined petroleum up to and including light fuel oils.

For large pipeline installations, the high capital costs associated with large meters and the calibration of these sizes normally results in the employment of a manifold with parallel metering runs. These meters would normally be 150 mm or 175 mm diameter and the combined flow capacity allows one meter to held on standby in event of a failure of any meter. These meters, if for fiscal use, would be designed for connection to a prover for regular calibration.

The use of turbine meters in gantry loading applications has been introduced to capitalise on the lower costs and smaller size compared with positive displacement (PD) meters. Mixed results have been reported but poor performance can often be attributed to poor installation.

The costs of meters are variable across the manufacturers and the materials of manufacture. In general small meter will cost between £800 and £2,500. Medium meters between £3,000 and £12,000, and large meters between £10,000 and £16,000. This is a guideline based on a range of manufacturers in 1998 and quoted in pound (£) sterling. One major supplier of fiscal meters with helical type blades quotes a simple formula for these more expensive meters of £2,000 per inch diameter.

Other costs to be considered are associated with the space required for the straight lengths and the costs associated with a dedicated meter prover.

ANNEX

Table I.1 - Comparison of Some Features of Displacement and Turbine Meters

Feature	Displacement meters	Turbine meters
Quantity measurement	Yes	Yes
Flowrate measurement	Convenient only if fitted with pulse generator	Yes
High pressure operation (above 10 bar)	No	Yes - limited only by rating of connectors
High temperature operation (above 100°C)	No	Yes
Pressure drop	Generally low but increases with viscosity and density at fluid	Generally low but increases with viscosity and density of fluid
Response	No data available, but probably in the region of tens of milliseconds	Few tens of milliseconds, but low rotor inertia and fast response means meter tends to read high in pulsating flow
Use with viscous liquids	Viscosity causes small change in meter error	Viscosity causes marked change in meter error at small meter sizes
Installation requirements	No need for special installation	Straight upstream pipe lengths required
Use with dirty fluids	Fluid must be clean and upstream strainer fitted if necessary	If bearings are suitable small suspensions can be tolerated - strainers generally used with dirty fluids
Meter bulk	Increases rapidly with increasing meter size	Little more than equivalent length of pipe

MEASUREMENT UNCERTAINTY

by

Alick MacGillivray
TUV NEL

LECTURE No 12

PRINCIPLES AND PRACTICE OF FLOW MEASUREMENT

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CONTENTS

"The degree of understanding of the subject of accuracy is perhaps the main criterion by which the professional quality of a test engineer should be judged……

…The first essential is to acquire as a habit of mind a sceptical attitude to all experimental observations: all instruments tend to be liars"

Plint M. A. and Martyr, A. J. Engine Testing: Theory and practice, Butterworth-Heinemann, Oxford 1995 ISBN 0 7506 1668 7

1 INTRODUCTION

As early as the 1960s it was recognized by the flow measurement community that to give a quantitative indication of the quality of a measurement it was necessary to report the uncertainty of that measurement. During the 1970s much work was done by the flow measurement community to standardize on a single method for the estimation of uncertainty in a flowrate measurement and in 1978 the first International Standards Organization (ISO) document specifically dealing with uncertainty was published. ISO followed this publication with a more general guide document relating to the estimation of uncertainty in measurement (not just flow measurement). In many industries uncertainty analysis is now a well established method and most follow the new ISO publication Guide to the Expression of Uncertainty in Measurement (1) & (2) (known colloquially as "the GUM").

The aim of this lecture is to give a general appreciation and introduction to the subject and to provide a firm basis for understanding more authoritative texts. The International Standard for the evaluation of uncertainty in flow measurement is currently undergoing substantial revision and will shortly be available as ISO/FDIS 5168(3). For those coming to the subject for the first time the Beginner's Guide to Uncertainty in Measurement by Bell(4) is a very good introduction to the concepts of measurement uncertainty. The Chapter on Uncertainty in Flow Measurement by Sattary & Boam(5) applies the general concepts to worked examples in flow measurement. The UKAS document M3003(6) is specifically written for calibration laboratories whilst UKAS document LAB 12(7) provides guidance for testing laboratories. For general guidance on statistical methods Davis and Goldsmith(8) is still a useful reference and, for more in-depth and complex uncertainty analyses, Coleman and Steele(9) provide a comprehensive and rigorous treatment of the subject.

It is not therefore the purpose of this lecture to present pages of mathematical text and statistical procedures. Instead, the various principles to follow are outlined, and these can then be used to:

- assess the uncertainty in a calibration facility
- define the range within which the true flowrate may lie relative to the indication of a meter
- to construct calibration graphs with realistic confidence limits
- to compare results from two or more meters and decide whether differences are significant or not
- to interpret correctly what the uncertainty statement in a calibration certificate, Standard or in manufacturer's literature means.

2 WHY BOTHER ABOUT UNCERTAINTY ANYWAY?

The answer lies in the increasing use of flowmeters where energy conservation is important, the use of meters for custody transfer or fiscal purposes, or the requirement to monitor a process either to improve the efficiency of the plant (and hence reduce costs) or to ensure that environmental damage is minimized (such as in the discharge of effluent to rivers or the emission of waste products into the atmosphere).

There are many other examples, but the point of carrying out an uncertainty calculation is that it identifies the reliance that can be placed on the measurement result. End users need to know the uncertainty of results based on measurements for a number of reasons. They need to know if the uncertainty of the results is acceptable for their requirements and, if not, how to reduce it. Conversely, a particular result with a very low uncertainty may involve the proposed use of expensive instrumentation or procedures that are time-consuming and costly. A less expensive option may still yield an acceptable uncertainty for a given application. Uncertainty analysis can be used to identify the most cost-effective way of obtaining an acceptable uncertainty for a particular measurement process.

A calibration certificate should always include a statement of uncertainty otherwise the calibration factor obtained from a flowmeter calibration could subsequently be used blindly without any suspicion that it is not perfect. Uncertainty statements are also relevant when calibration facilities are being set up, since these should be traceable back to national standards; this is impossible unless there is a method of judging whether or not the inevitable differences that exist between calibration results from different rigs on the same meter are consistent with the uncertainty claims of the two facilities.

3 UNCERTAINTY OF MEASUREMENT

3.1 Concepts

Measurements are always made using an instrument of some kind, for example a flowmeter, a pressure transmitter, a thermometer, a densitometer, a weighing scale, a timer or a ruler. A flowmeter calibration normally involves a number of measurements using these and possibly other instruments.

Uncertainty of measurement gives an indication of the quality of a measurement or result derived from a number of measurements. No measurement is ever absolute there is always a margin of doubt about the measurement, even in the most accurate measurement. We need to know 'how large is that margin?' and 'how doubtful are we?'. Therefore, two numbers are required in order to state an uncertainty, one is the width of the margin or interval and the other tells us the degree of doubt and is the confidence level.

For example, we might say the flowrate is reading 50 l/s ± 1 l/s at the 95% confidence level. This means that if the flowrate remained constant and the measurement was repeated a large number of times then on average the result will lie between 49 l/s and 51 l/s 95% of the time (i.e. 19 out of 20 times), in other words we are 95% sure that the flowrate will lie between 49 l/s and 51 l/s. In flow measurement the 95% confidence level is normally used and if the confidence level is not explicitly stated for a particular measurement result then it can reasonably be assumed to be 95%. If that same flowrate (50 l/s ± 1 l/s) was reported at the 50%

confidence level we would only expect repeated measurements to lie within the range 49 l/s and 51 l/s half the time (i.e. half the results would lie outside this interval).

It is clear that a reported result derived from measurements or based on estimates is meaningless without an indication of the quality of that result. It is important too that both the uncertainty interval and the confidence level are stated together with any reported results.

3.2 Error versus Uncertainty

It is essential to distinguish between the error and the uncertainty in a measurement result. The error is the difference between the measured and the 'true' value. Since the 'true value' is unknown, the error is unknown - otherwise a correction could be applied.

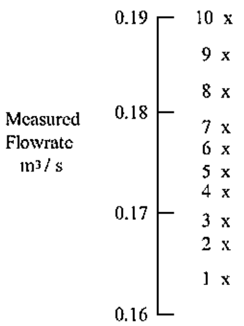
Uncertainty is defined as the range within which the 'true value' is expected to lie with a stated probability or confidence level.

When a calibration is performed the reference flowrate given by the calibration rig, instrument or device can be taken as the 'conventional true value'. Therefore, the difference between the result derived from the calibration rig and the result from the instrument under calibration can be considered as the error. This error will be given on or can be determined from the calibration certificate. Wherever possible a correction should be made to an instrument or the measurements made by an instrument following its calibration. If this is not possible then the error will contribute to the overall uncertainty in the measurement made by that instrument. It should be remembered that the correction will also have an associated uncertainty; this is normally the measurement uncertainty given for the calibration rig or instrument. It should also be remembered that the uncertainty in the calibration correction is only one component of the overall uncertainty in measurement for an instrument.

3.3 Accuracy

Accuracy is a commonly used word, but is a purely qualitative indication of how close a result is to the truth. No numbers can be associated with it, and if it has to be quantified then the uncertainty has to be stated.

3.4 Repeatability and Reproducibility



Definition of Repeatability	Value Obtained m³/s	Value Obtained % of mean
$2s\sqrt{2}$	0.0074	4.2
s	0.0026	1.5
$4s$	0.0104	5.9
$t_{95}s$	0.0058	3.3
$2t_{95}s$	0.0116	6.6
(10) - (1)	0.0250	14.1
$\frac{(10)-(1)}{2}$	0.0125	7.0
(8) - (6)	0.0060	3.4

Value varies from 1.5 to 14.1 per cent

Figure 1 – Different ways of defining repeatability

The repeatability of a measuring method can be computed numerically but the problem here is that there are numerous ways in which this can be done. This is illustrated in Figure 1, which presents a set of data points, eight possible ways of defining 'repeatability', and the value which is obtained from each of these.

In an attempt to standardize on one definition, BS ISO 11631(10) has settled for 'the value below which the absolute difference between two single test results obtained with the same method on identical test material under the same conditions (same operators, same apparatus, same laboratory and a short interval of time) may be expected to lie with a specified probability'. The numerical value, r, is then given by 2.83 s, where s is the standard deviation of the measurement results. The operative word in the above definition is 'two', since the value 2.83 s arises as follows. If a measurement is one of a series with a standard deviation s then the standard deviation of the difference between any two of the measurements is $\sqrt{(s^2 + s^2)} = s\sqrt{2}$ (see Section 4 below). The 95 per cent confidence limits can normally be expressed as $2\sqrt{2}s$ or $2.83s$. However, this expression is not a good approximation for small samples. Repeatability calculations for small samples can be found in Reference 10 or can be better approximated by the following equation:

$$r = t_{95}\sqrt{2}s \qquad (1)$$

where $t_{95} = 1.96 + \frac{2.36}{\nu} + \frac{3.2}{\nu^2} + \frac{5.2}{\nu^{3.84}}$. and $\nu = n - 1$

(t_{95} is the Student's 't' statistic and ν is the number of degrees of freedom).

Reproducibility is a similar concept, but applies when the same method is used on identical test material, in this case under different conditions (e.g. different operators, with a long time gap between the measurements, or in different laboratories). When reproducibility is stated then the conditions that have changed should also be clearly stated.

4 BASIC STATISTICS

Uncertainty estimation is based on statistical concepts. The two most important statistical calculations are the average or mean and the standard deviation for a set of measurements.

4.1 Average of a Number of Measurements

For a set of n measurements $x_1, x_2, x_3, \ldots x_i \ldots x_n$, the average value, $\bar{x}$, is given by the sum of the measurements divided by the number of measurements:

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \ldots + x_n}{n} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (2)$$

4.2 Standard Deviation

The standard deviation is a fundamental concept in statistics. Repeated measurements of a constant quantity will differ from each other as a result of random effects inherent in the measurement process. It may be that the measuring instrument does not behave in a completely stable manner or it may be due to the fact that the quantity being measured is not completely stable.

For a set of n measurements the estimated standard deviation, s, is defined by

$$s = \left(\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1} \right)^{1/2} \tag{3}$$

and is a measure of the scatter of the values about their mean value, $\bar{x}$.

The estimated standard deviation for the mean value is given by

$$s_{\bar{x}} = \frac{s}{\sqrt{n}}. \tag{4}$$

5 RANDOM AND SYSTEMATIC EFFECTS

When estimating the uncertainty in the final result it is not important to know if the individual sources of uncertainty affect the final result in a random or systematic way since all component uncertainties are treated in a similar manner.

However, it is important in many practical situations where, for example, the final uncertainty is too large and requires to be reduced.

5.1 Random Effects

Random effects can be observed in repeated measurements of a constant quantity, they cause random variations in the result of repeated measurements. In general, the more measurements that are made and then averaged, the better the estimate will be.

5.2 Systematic Effects

When sources of uncertainty arise from systematic effects every measurement is affected in the same way. So repeating the measurements will not improve the overall uncertainty. There are two kinds of systematic effect; constant and variable effects.

Constant systematic effects are those that do not vary when measurements are made under the same conditions. They do not vary with time, but can vary with the value of the measurement. Thus, for example, a zero error in the calibration of an instrument would introduce errors that are the same for all readings, but an error in the slope of a calibration graph would result in different constant systematic uncertainties for different readings.

Variable systematic effects can arise from such things as progressive wear in the bearings of a turbine meter or using a pressure transducer under environmental conditions of temperature, pressure or humidity without compensating for their effects on its calibration.

Systematic uncertainties are much harder to quantify and they are almost always underestimated, partly through human optimism and partly through the possibility of overlooking some sources of systematic uncertainty. Unless great care is taken the very existence of some of them may not be realized.

Systematic uncertainties can only be assessed experimentally by changing the instrumentation, equipment or the methods or conditions of measurement. Whenever possible this should be done but if this is not possible, it is necessary to make an educated guess at the uncertainty or a judgement on the basis of experience and consideration of the equipment involved.

6 EVALUATION OF COMPONENT UNCERTAINTIES

There are two ways to evaluate uncertainty in individual components; using a Type A or Type B evaluation.

6.1 Type 'A' Evaluation

Uncertainty estimates using statistical methods (given in Section 4) from repeated measurements.

a Calculate the average value or mean of the measurements, $\bar{x}$, from Equation (2).

b Calculate the standard deviation of the sample, s, from Equation (3).

c Calculate the standard deviation of the mean or average value, $s(\bar{x})$, from Equation (4).

d Obtain the standard uncertainty of the mean value:

$$u_i = s(\bar{x}_i) \tag{5}$$

6.2 Type 'B' Evaluation

A Type B evaluation of uncertainty is one carried out by means other than the statistical analysis of a series of observations. This could be past experience of the measurements, from calibration certificates, manufacturer's specifications, from calculations, from published information and from a judgement based on experience.

Type B evaluations of uncertainty require knowledge of the probability distribution associated with the component. The most common probability distributions are presented here; the shapes of the distributions are shown in Annex A.

6.2.1 Rectangular probability distribution

A rectangular probability distribution assumes that all values are equally likely. Typical examples of rectangular probability distributions include:

- Maximum instrument drift between calibrations
- Uncertainty due to limited resolution of an instrument's display
- Manufacturers' tolerance limits

The standard uncertainty is calculated from

$$u(x_i) = \frac{a_i}{\sqrt{3}} \tag{6}$$

where a_i is the half-range of the distribution.

6.2.2 Normal probability distribution

A typical example of a normal probability distribution is a calibration certificate quoting a confidence level or coverage factor with the uncertainty, here the standard uncertainty is

$$u(x_i) = U(x_i) / k \quad (7)$$

where $U(x_i)$ is the quoted expanded uncertainty and k is the quoted coverage factor. If k is not quoted on the calibration certificate then it is reasonable to assume k=2.

6.2.3 Triangular probability distribution

Some uncertainties are given simply as maximum bounds within which all values of the quantity are assumed to lie. There is often reason to believe that values close to the bounds are less likely than those near the centre of the bounds, in which case the assumption of rectangular distribution may be too pessimistic: in this case the Triangular distribution may be assumed as a prudent compromise between the assumptions of a normal and a rectangular distribution.

$$u(x_i) = \frac{a_i}{\sqrt{6}} \quad (8)$$

6.2.3 Bimodal probability distribution

When the error is always at the extreme value then a bimodal probability distribution is applicable.

A typical example is the uncertainty due to internal friction of a recorder.

$$u(x_i) = a_i \quad (9)$$

6.2.5 Asymmetric probability distributions

For any distributions that are known to be asymmetric, the method of evaluating the measurand should be modified to correct for the asymmetry: after this correction is carried out, there will remain a symmetric contribution to uncertainty which will take into account the uncertainty of the correction.

In some cases, when the correction is relatively very small, it may be considered economically unjustifiable to correct for an asymmetric distribution. The additional uncertainty in this case is equal to the value of correction that has not been applied.

7 SENSITIVITY COEFFICIENTS

Before considering methods of combining uncertainties, it is essential to appreciate that it is insufficient to consider only the magnitudes of component uncertainties in input quantities, it is also necessary to consider the effect each input quantity has on the final result. It is therefore convenient to introduce the concept of the sensitivity of an output quantity to an input quantity - the sensitivity coefficient.

The sensitivity coefficient of each input quantity is obtained in one of two ways:

- Analytically
- Numerically

7.1 Analytical Solution

When the functional relationship is specified then the sensitivity coefficient is defined as the rate of change of the output quantity, y, with respect to the input quantity, x_i, and the value of the sensitivity coefficient, c_i, is obtained by partial differentiation

$$c_i = \frac{\partial y}{\partial x_i} \qquad (10)$$

However when non-dimensional uncertainties (for example percentage uncertainty) are used then non-dimensional sensitivity coefficients, c_i^* must also be used, where

$$c_i^* = \frac{\partial y}{\partial x_i} \cdot \frac{x_i}{y} \qquad (11)$$

7.2 Numerical Solution

Where no mathematical relationship is available, or the functional relationship is complex, it may be easier to obtain the sensitivity coefficients numerically, by calculating the effect of a small change in the input variable x_i on the output value y.

First calculate y using x_i, and then recalculate using $(x_i + \Delta x_i)$, where Δx_i is a small increment in x_i . The result of the recalculation can be expressed as $y + \Delta y$, where Δy is the increment in y caused by Δx_i .

The increment used (Δx_i) can be equal to the uncertainty in x_i or as small as practical (taking into account the possibility of uncertainty in the result caused by not enough significant figures being used in the calculation).

The sensitivity coefficients are then calculated from

$$c_i = \frac{\Delta y}{\Delta x_i} \qquad (12)$$

In non-dimensional form

$$c_i^* = \frac{\Delta y}{\Delta x_i} \cdot \frac{x_i}{y} \qquad (13)$$

Table 1 shows how a typical spreadsheet could be set up to calculate a specific sensitivity coefficient for any function where $y = f(x_1, x_2, ..., x_i, x_n)$.

8 COMBINATION OF UNCERTAINTIES

So once the standard uncertainties of the input quantities and their associated sensitivity coefficients have been determined from both Type A and Type B evaluations, the overall standard uncertainty of the output, $U_c(y)$, quantity may be determined from

$$u_c(y) = \sqrt{\sum_{i=1}^{N}\left(c_i u(x_i)\right)^2} \qquad (14)$$

Where dimensionless uncertainties have been used, dimensionless sensitivity coefficients must also be used, where

$$u_c^*(y) = \sqrt{\sum_{i=1}^{N}\left(c_i^* u^*(x_i)\right)^2} \qquad (15)$$

Where $u^*(x_i)$ is the relative uncertainty in the form of a percentage (e.g. 1%). The above equations assume that the individual input quantities are uncorrelated.

In order to measure flowrate it is almost always necessary to compute it from the results of several subsidiary measurements. Thus, for example, if a static weighbridge system is used in a water calibration facility, it is necessary to measure the weight of liquid diverted into a weightank, the time over which the diversion occurred, and the density of the water (if volumetric flowrate is required). When an orifice plate is used, the discharge coefficient, differential pressure, areas of the upstream pipe and orifice bore, fluid density and (where the fluid is a gas) expansibility correction all most be known as a minimum.

By way of an example, taking the specific case where an orifice plate is used, the basic equation for mass flowrate, q_m, is

$$q_m = \frac{Ce A_o}{\sqrt{(1-b^4)}}\sqrt{(2rDp)} \qquad (16)$$

where C is the discharge coefficient,
ε is the expansibility correction,
A_o is the area of the orifice bore,
β is the diameter ratio of the orifice,
ρ is the fluid density, and
Δp is the differential pressure across the orifice.

Application of Equation (15) gives the percentage uncertainty in flowrate, $u^*(q_m)$, as

$$u_c^*(q_m) = [\, u^{*2}(C) + u^{*2}(e) + \left(\frac{2b^4}{1-b^4}\right)^2 u^{*2}(D) + \left(\frac{2}{1-b^4}\right)^2 u^{*2}(d) + \frac{1}{4}u^{*2}(Dp) + \frac{1}{4}u^{*2}(r)\,]^{1/2} \qquad (17)$$

This brings out the concept of the sensitivity of a flowrate measurement to a component measurement. This is the uncertainty propagated to the flowrate measurement due to unit uncertainty in a component measurement.

A 1 per cent uncertainty in each of C, d and Δp would contribute 1 per cent, $\{2/(1-\beta^4)\}^2$ per cent and 0.25 per cent respectively to the square of the uncertainty in q_m. Thus it is possible to identify which sources of uncertainty have most effect on the final result, and hence where most attention should be focused in trying to reduce uncertainties.

Although the sensitivity is important, the uncertainty in the component measurement obviously has a vital role to play in deciding if a particular source of uncertainty can be ignored in the overall uncertainty calculation. If the differential pressure has an uncertainty of 4 per cent and the orifice throat diameter measurement an uncertainty of 0.1 per cent, the fact that the flowrate measurement has a smaller sensitivity to the former than to the latter is less important. The important quantity in deciding whether or not a source of uncertainty can be ignored in an uncertainty calculation is thus the product of the sensitivity and the uncertainty. (Although percentage values have been used here for the purpose of illustrating sensitivity coefficients, it is recommended to use the absolute value of the uncertainty in the calculations to avoid calculation errors such as taking percentages of percentages.)

9 REPORTING OF RESULTS

9.1 Expanded Uncertainty

Expanded uncertainty, U, is used to describe the level of confidence associated with the uncertainty, where

$$U = ku_c(y) \qquad (18)$$

It is recommended that a coverage factor, k = 2, is used providing a level of confidence of approximately 95%.

If the random contribution to uncertainty is large compared with the other contributions and the number of readings is small then the above method provides an optimistic coverage level, a more realistic estimate can be obtained from Reference 3. A criterion that can be used to determine whether the procedure described in Reference 3 must be applied is as follows:

Generally, if an uncertainty assessment involves only one Type A evaluation and the number of readings is greater than 2 and the Type A standard uncertainty is less than half the combined standard uncertainty, then there is no need to use the method described in Reference 3 to determine a value for the coverage factor.

The uncertainty associated with an expanded uncertainty may be denoted using subscripts, for example

- U_{95}
- $U_{k=2}$

9.2 Uncertainty Budget

In reports providing an uncertainty estimate, an uncertainty budget table (similar to that given in Table 2) may be presented, (or referenced). It provides as a minimum the following information (working from the left to the right hand side of the table): symbol, source of uncertainty (text), input uncertainty (value), probability distribution (e.g. normal or rectangular), divisor or coverage factor, k, standard uncertainty, $u(x_i)$, sensitivity coefficient, c_i, contribution to uncertainty, $c_i\,u(x_i)$, square of contribution, $(c_i\,u(x_i))^2$.

At this stage it may be useful to list the contributions in order of value from the largest to the smallest; this highlights the sources of uncertainty contributing most to the overall uncertainty. The square of all the contributions are then summed and square rooted to give the combined standard uncertainty this value is then multiplied by a coverage factor (normally k=2) to give a value for the final expanded overall uncertainty.

After the expanded uncertainty has been calculated normally for a level of confidence of 95% the uncertainty can be stated as follows:

The uncertainty of the (measurement) has been estimated to be (value) per cent.

The reported uncertainty is based on a standard uncertainty multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95%.

In cases where the procedure of Reference 3 has been followed then the actual value of the coverage factor is substituted for k = 2.

10 PROCEDURE FOR EVALUATING UNCERTAINTY

The general procedure for evaluating uncertainty is, therefore:

a Decide what you need to find out from your measurements.

b Decide what actual measurements and calculations are needed.

c Clearly define the measurement process in a procedure or specification.

d Identify all known sources of uncertainty.

e Estimate the component uncertainty and decide on the probability distribution (e.g. rectangular or normal) associated with each source of uncertainty, as given in Section 6.

f Decide whether the uncertainties are independent of each other. If not then some extra calculations or information are required. When input component uncertainties are not independent of each other they are correlated; correlated uncertainties are dealt with in Reference 3.

g Calculate the sensitivity coefficient for each component as given in Section 7.

h Calculate the measurement result (making any corrections for calibration etc).

i Calculate the combined standard uncertainty from all the component uncertainties, as given in Section 8.

j Express the uncertainty in terms of confidence interval, stating the coverage factor used and the level of confidence, as given in Section 9.

k Present the measurement result and the uncertainty and state how they were obtained.

Optional

l List, in descending order of value, the product of sensitivity coefficient and uncertainty for each component.

As a general rule it is possible to ignore any product which is smaller than about one-fifth of the largest in the group.

m In certain circumstances it is useful to present the total standard uncertainty arising from random and systematic effects separately.

Although the above procedure may appear time consuming, it is usually easy to identify quickly which components can be ignored. The crucial thing is to identify all sources of uncertainty - unless a conscious effort is made to do this, it is very easy to miss major contributions to the overall uncertainty, particularly when they are systematic in nature.

Whenever the overall uncertainty is too large and needs to be reduced it may be useful to identify which uncertainties arise from random and which from systematic effects. Uncertainties arising from systematic effects cannot be reduced in any way except by repeating the test with different equipment and/or under different conditions. Uncertainties arising from random can, however, be reduced by repeated measurements, and identifying which class the uncertainties fall into will show whether an increase in the number or duration of tests is likely to be worthwhile. Conversely, it can reveal where greater effort has to be made in improving the instrumentation or test technique if the major contribution to the overall uncertainty comes from systematic sources.

11 IDENTIFYING SOURCES OF UNCERTAINTY

It is not proposed to list sources of uncertainty here, since they will depend on the particular application and are covered in various ways in the other lectures, but the following general categories should always be considered.

- The external environment - temperature, air pressure, humidity and many other conditions can affect the flowmeter or measuring instrument.
- The flowmeter or measuring instrument - instruments can suffer from bias, noise, hysteresis, linearity, changes due to ageing or other forms of drift, poor resolution or readability, and many other problems.
- The quantity being measured - for flow measurement the quantity being measurement is a very important factor. Flow is a dynamic quantity and as such may vary considerably in comparison to the required accuracy of the measurement being made. So, for example, simply assessing the static

uncertainty of weights in a gravimetric calibration rig is not enough since one of the largest uncertainties will be derived from the dynamic behaviour of the flow.

- The measuring process - the measuring process should be very well defined since any deviation from the defined measurement procedure could lead to additional uncertainty. For example, taking a different number of measurements to determine the average, changing a measuring instrument or taking the measurement over a different time interval. When a calibration laboratory has UKAS accreditation this ensures the calibration is undertaken according to a well defined set of procedures and gives traceability to the measurements.

- Calibration uncertainties - calibration of any instrument has an associated uncertainty which is then built into the uncertainty of the measurements made using that instrument.

  Do not, therefore, accept measurements from a thermometer, pressure transducer or weighing scale, for example, without assessing the uncertainty associated with its calibration.

  Remember if the instrument has not been calibrated or is out of calibration then the uncertainties will be even larger.

- Operator skill - in flow measurement operator skill and judgement is used surprisingly often.

  Whenever human judgement is used errors will occur, no matter how small. For example, everyone has their own in-built bias in reading a dial which is fluctuating or taking a reading from a digital display where the last few digits are continually changing.

  It should be noted that operator mistakes are not to be accounted for as uncertainties.

- Method or procedure - as well as uncertainty in not following the procedure correctly there may also be uncertainty associated with the method or procedure itself or the lack of detail in the procedure.

  The method of computing the flowrate from the component measurements may involve assumptions that are not strictly valid.

  The flowmeter may be placed too close to a flow disturbance (e.g. an upstream pipe bend), a flowmeter may have been calibrated at one flowrate and then used over a range of flowrates, there may be leakage past the sphere of a meter prover or if a pressure tapping hole has burrs the pressure transmitted to the transducer will be in error.

- Sampling and data processing - sampling is a very common source of uncertainty. Statistical sampling methods exist but in the practical situation it can be very difficult to determine a representative sample.

  For example, when drawing a water sample to determine the density of a sump full of water, temperature gradients within the sump will affect the measured density. The upstream temperature and pressure of a fluid will not be the same as that at the flowmeter. Flow measurement using an insertion probe placed at the mean flow position (D/8) position will only give an accurate measurement of the mean velocity if the flow profile is fully developed.

Telemetry is very often the limiting factor for data transmission and so the data from the measuring instrument is either sampled at set time intervals or the data is averaged in some way over the time interval and this average value is then transmitted.

Data processing is often a source of uncertainty, in particular rounding errors should always be identified. Also, one should be wary of errors in software but these are not to be included in the uncertainty analysis and should be corrected.

Uncertainties from each of these sources, and from other sources, would be individual 'inputs' to the overall uncertainty.

12 THE USE OF CALIBRATION GRAPHS

When assessing calibration data, the first thing to do is to decide the form of graphical presentation which should be used. We shall assume for the purposes of the following discussion that the meter which is calibrated can generate an indicated flowrate Q_{IND}, and that the calibrator (which may be a more accurate flowmeter or some kind of absolute calibration system) gives corresponding flowrate values Q_{CAL}; Q_{CAL} may be assumed for the present to be identical to the true flowrate, although in practice any calibrator is subject to errors. The most obvious form of presentation is

$$y = Q_{IND} \quad and \quad x = Q_{CAL}$$

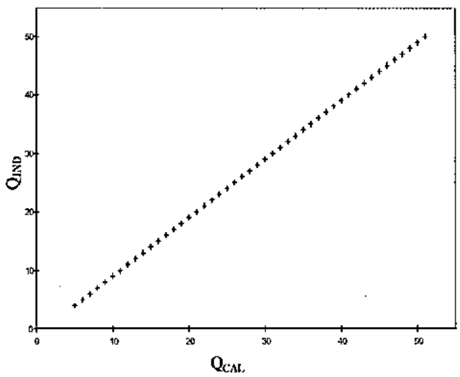


Figure 2 - Calibration Data with Indicated Flowrate Plotted Against Calibration Flowrate

Figure 2 shows calibration data presented in a graph of this form; it appears that the calibrated meter is quite accurate. If, however, the form

$$y = Q_{CAL} - Q_{IND}$$
$$x = Q_{IND}$$

is used (Figure 3), the performance of the meter can be seen in much greater detail.

From this it appears that the meter is accurate to within ±0.35 l/s or ±0.7 per cent of the full-scale reading.

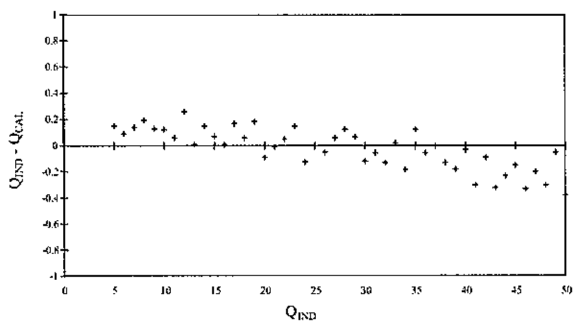


Figure 3 - Deviations of Indicated from Calibrated Flowrate

However 0.35 l/s is equivalent to 7 per cent of reading at 5 l/s: to see in detail what happens to the accuracy at low flowrates a different form of graph is necessary. Figure 4 shows a graph with

$$y = 100(Q_{IND} - Q_{CAL}) / Q_{IND}$$
$$x = Q_{IND}$$

which shows that at low flowrates errors approaching +3 per cent are possible and that the linearity error and the repeatability both become worse as the flowrate decreases.

Generally the percentage error of the flowmeter indication is of more use than the error as a percentage of full scale; graphs equivalent to Figure 4 are used to present any index of performance, such as meter factor for a turbine meter or discharge coefficient for a differential pressure meter.

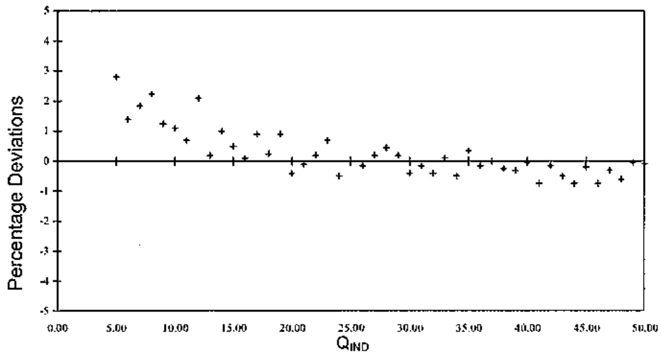


Figure 4 - Percentage Deviation of Indicated from Calibrated Flowrate

The calibration graph may be used to put a maximum value on the errors which may be expected over a specified range: for example, Figure 4 shows that the errors do not exceed 1 per cent down to 15 l/s. However, if the graph shows a trend over the range of operation of the meter, a line or curve can be fitted to the trend, and the resulting equation will allow the flowmeter to be used with significantly greater accuracy. For example, from Figure 4 an equation of the form

$$y = b_o + b_1 x + b_2 x^2 \qquad (19)$$

might be fitted: the corrected flowrate will then be given by:

$$Q_{CAL} = Q_{IND} - \frac{y \cdot Q_{IND}}{100} \qquad (20)$$

where y is given by Equation (19).

Two common examples where the above procedure is used are calibrations of turbine meters and orifice plates. For the former the meter factor, K, which is in pulses per unit volume (i.e. pulses/s divided by m^3/s), is plotted against flowrate or turbine meter frequency. When the meter is subsequently used the flowrate, Q_{IND}, is obtained from

$$Q_{IND} = \frac{f}{K} \qquad (21)$$

where f is the frequency of pulses obtained from the turbine meter.

Orifice plates are calibrated by plotting the discharge coefficient, C, against Reynolds number, Re, instead of flowrate, since in this form the calibration is independent of the density and viscosity of the fluid used. In practice there is a range of Reynolds numbers over which the discharge coefficient is constant, so the flowrate can be obtained using this fixed value of C. At lower Reynolds numbers, however, the value of C rises, so a calibration relation of the form

$$C = f(Re) \qquad (22)$$

is used. When the orifice meter is subsequently used in this region an iterative procedure has to be adopted: assume a value of C, calculate using its approximate values of flowrate and hence Reynolds number, use the calibration relation to obtain a more accurate value of C and hence flowrate, then repeat the procedure. Normally only one iteration is required, provided the Reynolds number is not unusually low.

13 CURVE FITTING

It is all very well producing nice calibration graphs, but to summarize the result of the calibration effectively it is necessary to find the 'best-fit' curve through the data and represent it by a calibration equation.

The principle of least squares is used. If an equation of the form $y = \mathrm{f}(x)$ is chosen to fit n pairs of data values (x_i, y_i) (where $i = 1, 2, \ldots n$) then the coefficients of the function $\mathrm{f}(x)$ are chosen to minimize the sum of squares of deviations

$$\sum_{i=1}^{n}\{y_i - \mathrm{f}(x_i)\}^2. \tag{23}$$

Details of curve fitting are given under the heading of regression analysis in text books such as References 8 and 9.

For the simplest case, i.e. linear regression, where the equation to be used is a straight line

$$y = b_o + b_1 x \tag{24}$$

the coefficients b_o and b_1 are given by

$$b_1 = \frac{\sum(xy) - \sum x \sum y/n}{\sum x^2 - \sum(x)^2/n}$$

$$b_o = \bar{y} - b_1 \bar{x}$$

The suffix i has been dropped from the x_i and y_i for clarity.

For a quadratic equation

$$y = b_o + b_1 x + b_2 x^2 \tag{25}$$

the coefficients are given by

$$\begin{aligned} b_1 &= (S_{22}\, S_{y1} - S_{12}\, S_{y2}) \,/\, (S_{11}\, S_{22} - S_{12}^2) \\ b_2 &= (S_{11}\, S_{y2} - S_{12}\, S_{y1}) \,/\, (S_{11}\, S_{22} - S_{12}^2) \\ b_o &= \bar{y} - b_1 \bar{z}_1 - b_2 \bar{z}_2 \end{aligned} \tag{26}$$

where

$$S_{11} = \Sigma(z_1 - \overline{z}_1)^2$$

$$S_{12} = \Sigma(z_1 - \overline{z}_1)(z_2 - \overline{z}_2)$$

$$S_{22} = \Sigma(z_2 - \overline{z}_2)^2$$

$$S_{y1} = \Sigma(z_1 - \overline{z}_1)(y - \overline{y})$$

$$S_{y2} = \Sigma(z_2 - \overline{z}_2)(y - \overline{y})$$

$$\overline{z}_1 = \Sigma z_1 / n$$

$$\overline{z}_2 = \Sigma z_2 / n$$

For clarity, x and x^2 have been replaced by z_1 and z_2 respectively.

For higher degrees of polynomial, standard statistical packages exist for many computers and calculators, as indeed they do for these two simplest cases.

14 UNCERTAINTY IN A CALIBRATION CURVE

Having obtained the calibration equation the uncertainty associated with it has to be calculated. The Type A uncertainty displays itself as a scatter of the values about the mean (if there is no variation in the calibration coefficient, i.e. the y-axis, over the range of the x-axis) or about the curve which is used to represent the variation over the range. Other, Type B, uncertainties are, however, 'invisible'.

14.1 Type A Uncertainty for a Calibration

From the scatter of the data, it is possible to make a quantitative estimate of the Type A uncertainty. An estimate derived in this way is only strictly valid, however, if the functional representation is correct; for example, an estimate based on the assumption of no variation over the range will not be valid if there is in fact some variation over the range.

When there is no variation over the range, the expanded Type A uncertainty may be expressed as

$$\overline{y} \pm U_A. \quad (27)$$

The Type A uncertainty, U_A, is normally calculated from 95 per cent probability level, and therefore, U_A is calculated as follows

$$U_A = \frac{t_{95}s}{\sqrt{n}} \quad (28)$$

If a linear relation is used to represent variation over the range, then U_A will have different values at different parts of the range. Its value at $x = x_A$ is

$$U_A = t_{95}s\left\{\frac{1}{n} + \frac{(x_A - \overline{x})^2}{\sum(x_i - \overline{x})^2}\right\}^{1/2} \quad (29)$$

$$s = \left\{ \frac{\sum (y_i - b_0 - b_1 x_1)^2}{n-2} \right\}^{1/2} . \qquad (30)$$

The value of U_A at the extremes of the range is usually approximately twice that at the mean value, $x = \bar{x}$. The 95 per cent confidence limits for the linear equation, assuming no other Type B uncertainties, are then

$$b_0 + b_1 x \pm U_A. \qquad (31)$$

The uncertainty associated with a calibration when a linear calibration relationship is used is the subject of Reference 11.

14.2 Polynomial Relationships

If a polynomial calibration relationship is used then a statistical curve fitting software routine or package is required. As was mentioned above, curve-fitting routines are widely available; however they do not in general allow the Type A uncertainty confidence limits to be obtained directly. An International Standard[(12)] includes a Fortran computer program which provides these confidence limits as well as the coefficients of the polynomial. This Standard can be used to validate results from proprietary software packages.

14.3 Choosing the Optimum Degree of Fit

If the calibration data for a meter appears to vary slightly over the range in a linear manner, but this linear variation is hard to separate from the scatter, then a statistical test can be applied to show whether the variation over the range is significant. One form of this test is to calculate the confidence limits of the slope term, which are given by

$$b_1 \pm \frac{t_{95} s}{\sqrt{\Sigma (x_i - \bar{x})^2}} . \qquad (32)$$

If these confidence limits do not include zero, then the linear dependence is significant at the 95 per cent level. A similar test[12] may be applied for the coefficients b_2 of the second degree polynomial, b_3, of the third-degree polynomial, and so on, until no significant dependence is found. The procedure should be continued until the coefficients for two successive degrees are found to be not significant at the 95 per cent level, since sometimes only the odd terms or only the even terms will be significant.

This procedure will suggest, from a statistical standpoint, what degree of fit should be used: however, before selecting this degree, a number of other factors should be considered. These factors include any knowledge of the expected shape of the curve from experience with similar types of flowmeter, the desirability of having a function that is not too complex, the range which it is necessary to represent, and the accuracy that is sought.

In assessing these factors, it is always advisable to produce graphs showing the data and the possible curves: these graphs will also highlight other possible problems. For example, if the degree is too low, the curve will fail to represent a real trend in the data: if the degree is too high, the curve may be fitting the scatter in the data rather than the underlying trend.

14.4 Type B Uncertainty for a Calibration

The Type B uncertainty associated with a particular calibration will normally be included in the calibration certificate. The Type B uncertainty for a test facility can best be estimated by arranging comparative tests with other calibration facilities, using one or more flowmeters, preferably using different methods of calibration. If this is not possible, then usually the estimate must be based on judgement.

15 CONCLUSION

The assessment of uncertainty in a calibration facility or in the calibration of a flowmeter can be a time-consuming task, and certainly it takes an effort to understand the principles involved and apply them. Without this, however, a 'calibration' is meaningless, and unfortunately too many people put a great deal of effort and money into setting up a calibration facility without examining honestly the uncertainty when it is used. Too often, sources of uncertainty are identified only when a customer complains that the meter has been checked independently and found to be 'in error', or a process goes wrong and the supposedly 'accurate' flowmeter is found to be several per cent out. The costs, in terms of both money and reputation of these situations arising, can be very much more than that of doing the uncertainty analysis correctly in the first place.

Uncertainty analysis has many benefits and can be used to determine where effort needs to be focused in order to improve the accuracy of the reported result.

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Table 1 — Spreadsheet Setup for Calculating Sensitivity Coefficients

Sensitivity Coefficient	Increment	x_1	x_2	…	x_i	x_n	y	c	c^*
	---	x_1	x_2	…	x_i	x_n	$y_{nom} = f(x_1, x_2 \ldots, x_i, x_n)$		
c_1	$\Delta_1 \approx 10^{-6}\ x_1$	$x_1+\Delta_1$	x_2	…	x_i	x_n	$y_1 = f(x_1+\Delta_1, x_2 \ldots, x_i, x_n)$	$\left(\frac{y_1 - y_{nom}}{\Delta_1}\right)$	$\frac{c_1 \cdot x_1}{y_{nom}}$
c_2	$\Delta_2 \approx 10^{-6}\ x_2$	x_1	$x_2+\Delta_2$	…	x_i	x_n	$y_2 = f(x_1, x_2+\Delta_2 \ldots, x_i, x_n)$	$\left(\frac{y_2 - y_{nom}}{\Delta_2}\right)$	$\frac{c_2 \cdot x_2}{y_{nom}}$

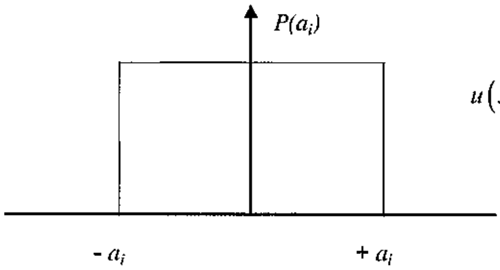
Table 2 - Uncertainty Budget

Symbol	Source of Uncertainty	Input Uncertainty U_i	Probability Distribution	Divisor or k	Standard Uncertainty $u(x_i)$	Sensitivity Coefficient c_i	Contribution to Uncertainty $c_i \cdot u(x_i)$	Contribution^2 $(c_i \cdot u(x_i))^2$
$u(x_1)$								
$u(x_2)$								
…								
$u(x_i)$								
$u(x_n)$								
$u_c(x_1)$	Combined Uncertainty							
U_c	Expanded Uncertainty							

APPENDIX

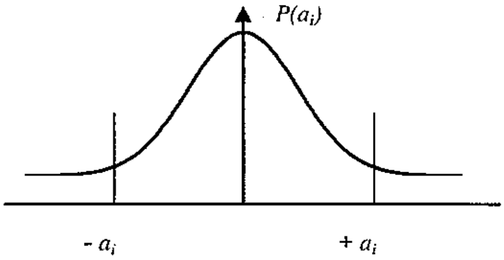
Probability Distributions

1 Rectangular Probability Distribution



$$u(x_i) = \frac{a_i}{\sqrt{3}}$$

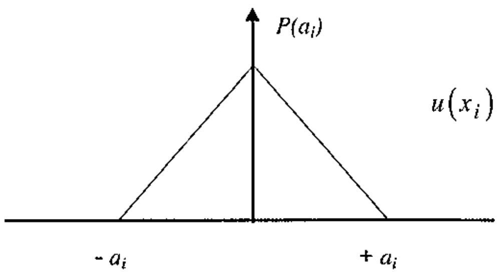
2 Normal Probability Distribution



$$u(x_i) = \frac{a_i}{k}$$

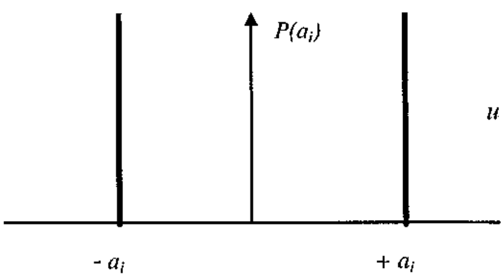
where k is the coverage factor appropriate to the range $\pm a_i$.

3 Triangular Probability Distribution



$$u(x_i) = \frac{a_i}{\sqrt{6}}$$

4 Bimodal Probability Distribution



$$u(x_i) = a_i$$

THE CALIBRATION OF FLOWMETERS

by

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LECTURE No 14

PRINCIPLES AND PRACTICE OF FLOW MEASUREMENT

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CONTENTS

1 INTRODUCTION

Calibration is the set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or system, and the corresponding values realised by standards.

The above is the international definition of calibration. For our purposes we will discus the comparison of the output of a flowmeter with some standard of known performance and uncertainty. What needs to be discussed is what consists the output of some meters, what is the range of standards used and how we define the specified conditions.

Flowmeters unlike most metrological devices are dynamic. The calibration therefore has to be defined in at least two dimensions. It is therefore normal to define the output measure in relation to a flowrate based parameter. This can be litres/second, m^3/hr, kg/min etc. Alternatively a more complex flow based parameter may be used such as Reynolds number which can add further dimensions to the performance curve by accounting for viscosity and density.

A flowmeter may have an output quantity or flowrate (in engineering units), pulses, current (ma) or pressure. How the performance is expressed becomes complex and a number of conventions can be found applied to different meter types.

Meters with electronic pulsed output will normally have the performance expressed as a k-factor (Pulses per unit quantity passed).

An alternative which can apply to meters with engineering units as well is a meter factor. Meter factor is the true value divided by the meter reading. (e.g. calibrator volume / indicated volume). A more common performance indication is 'error' which is defined as indicated value minus the 'true' value. In practice this error is normally expressed as a percentage of the true value.

To calculate the indicated value when the output is pulsed or analogue (4-20 ma) output it normal to calculate this from the straight line interpolation between the maximum and minimum values expected from maximum and minimum outputs as set for the meter.

A discharge coefficient is the normal expression used for differential pressure devices. C, the discharge coefficient, is a reflection of the differential pressure to flowrate (Reynolds number) relationship and the assumed diameter must be quoted with the final result.

The purpose of a calibration is to estimate the inherent uncertainty associated with the meter in its final application. As all flowmeters are to some degree influenced by environment, flow conditions and the fluid used, no calibration can simulate this completely, even for in-situ calibrations. It is clear that the calibration will only provide a component of the final uncertainty of the final measured flow. This puts a heavy responsibility on the user to understand the conditions of use of the meter. They also have to understand the effect of the process on the meter compared with the calibration conditions, and of course an understanding of the uncertainty provided by the calibration. Uncertainty of calibration can be expressed on the certificate as being the uncertainty of the measured quantity (flow, volume or mass), or uncertainty of the meters estimate of this quantity at each flowrate (or possibly averaged), or the uncertainty of a fitted equation to the data. It will never be the estimate of uncertainty at different time or conditions. Any estimate at a different time or condition is an estimate (or speculation) and could only be advisory and not part of the calibration.

Since calibration is generally an expensive exercise. The level of uncertainty required by the process must be assessed to define a calibration interval, the uncertainty required from the standard, and the method to be used. If, for example, high flowrates of oil attract huge tax liabilities, weekly calibrations, in product, and in-situ will be needed. Alternatively metering waste water with a Venturi may only require 5 yearly inspection of the Venturi, yearly calibration of the pressure measurement and no flow calibration. In some cases an adequate estimate of the meter's inherent error may be made from geometrical measurement or from prediction based on past experience with the meter or similar meters. The purpose of this lecture is to cover these cases where accuracy is of such importance that calibration is the only way in which the meter's performance can be estimated with sufficiently low uncertainty.

The main difference between gas and liquid flows is that all gases are compressible while liquids, for most practical purposes, may be assumed incompressible. This causes fundamental differences in the approach to calibrating in gas and liquid, and for this reason this lecture considers them separately.

One calibration method not fully considered below is the use of reference flowmeters as the standard. This is acceptable method as the reference meter shows a reliable calibration history, is calibrated to an acceptable uncertainty, and has been characterised for performance across the range of fluids, temperatures and other parameters for which it has to be used.

A number of criteria have to be considered when selecting a calibration method. The time of the test must be long enough to establish a stable condition while not too long as to create instabilities. The volume passed must be commensurate with the resolution of the meter. 1 part in 10 000 meter resolution is normally suggested which corresponds to collection of 10 000 pulses from a pulsed meter. The response time of the meter must be suitable to follow flow changes introduced by the standard.

2 CALIBRATORS FOR LIQUID FLOWMETERS

2.1 Methods

One characteristic of a liquid is that it can usually be contained in an open vessel, although if the liquid is volatile or hazardous suitable precautions have to be taken. As a result, calibration standards are usually of the 'bucket and stopwatch' type with the bucket either being weighed or the volume known. The complexity comes in achieving the accuracy required. Two concepts for calibration are used. The illustration shows a weighing system but the method can also be applied equally to volumetric techniques.

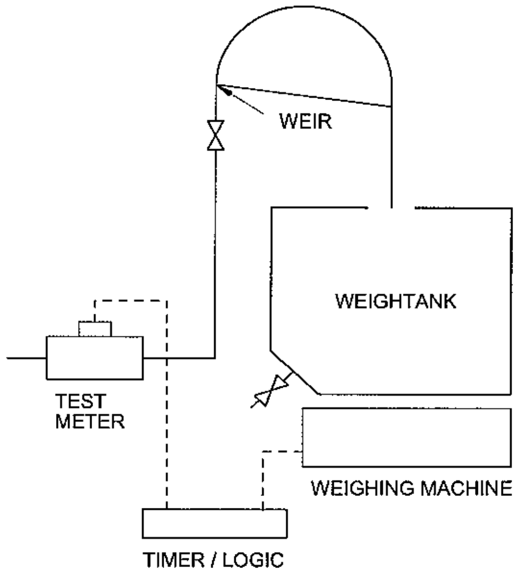

Figure 1

First is the 'standing start and stop' method which is generally preferred for quantity meters used for the accurate batch dispensing of product. The 'standing start and stop' method is the simplest and is illustrated opposite. Flow through the meter is accelerated as quickly as possible from rest to the full test flowrate. At the end of the test the flow is rapidly stopped. A number of criteria have to be met. The meter being calibrated has to have a fast response time to match the start and stop of the flow. In conjunction, the test time has to be sufficiently long in comparison with the acceleration and deceleration periods.

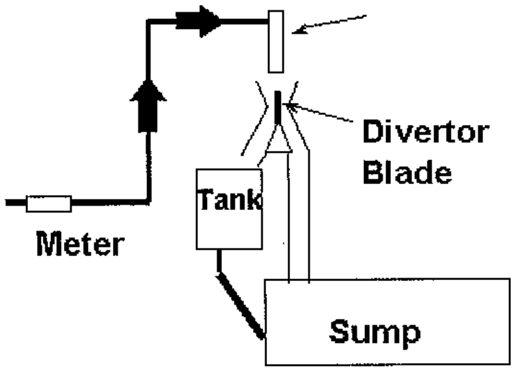

Figure 2

Secondly the 'flying start and finish' method requires some sort of diverter in conjunction with a sump or reservoir into which the liquid flows and then is diverted into the measuring vessel for the appropriate time. This technique, and the importance of the diverter timing error, is shown diagrammatically. The 'flying start and stop' method is more suitable for flowrate meters such as pressure differential devices.

Both the above methods are subject to errors at the start and finish of the collection time. These are illustrated below in the form of the end effects for standing start and finish, Figure 3, and timing error for the dynamic weighing technique (Figure 4).

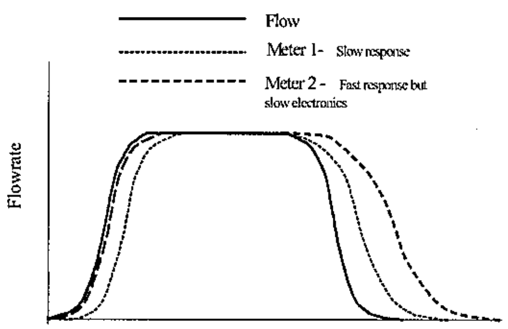

Figure 3

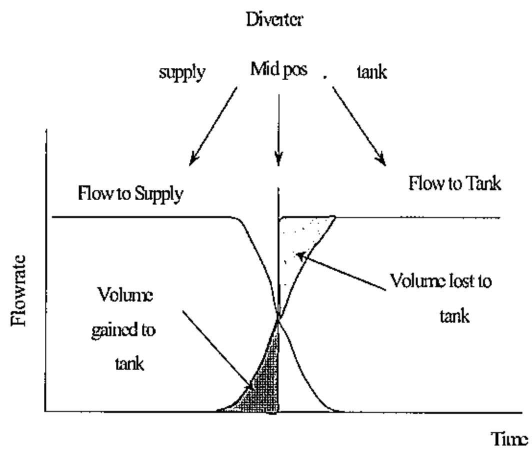

Figure 4

A third method, the dynamic measurement technique, can be used where the liquid level or the weight collected are detected and used to trigger a timer/counter connected to the flowmeter. This technique is really only used for low accuracy calibrations as repeatability is normally in the 0.5 to 1 percent at best. In saying this one particular system at NEL using an old trade mechanical scale triggering from a photocell in the pointer has shown repeatabilities of 0.005%. This has never been repeated on any other system.

2.2 Gravimetric Calibrators

A flowmeter can be calibrated gravimetrically by statically liquid weighing the quantity of liquid collected in a weighing vessel. The vessel is weighed empty and then full and the difference in readings, corrected for the effect of air buoyancy provides the mass of liquid collected. If a volume flowmeter is to be calibrated this mass is divided by the density of the liquid at the flowmeter. This is usually determined by measuring the temperature of the fluid at the meter and a knowledge of the fluid properties.

The weighing machines used must be calibrated using recognised standards of mass. Normal platform machines fitted with steelyards provide measurements of weight to high accuracy, provided they are carefully maintained. Electronic 'force balance' machines provide a better performance and the added addition of electronic output. Gyroscopic weighing gives the ultimate resolution but probably exceeds the requirements of flow measurement. Load cell weighing techniques may be used, but do not provide the resolution of the platform machines. The method can be used with both standing start and finish techniques and divertor methods.

2.3 Volumetric Calibrators

The measurement of the quantity of liquid collected may be carried out volumetrically, i.e. by collecting a known volume of liquid in a container. In the volumetric method the standard vessel takes the form of a container with calibrated volume. Normally this will be a pipette with conical ends to facilitate drainage and to reduce the risk of air entrapment. The neck of the pipette is normally fitted with a sight glass and a scale marked in volumetric units. A typical volumetric tank is shown below.

The tank is not itself a primary calibration device and its volume must be determined by calibration. This is can be carried out by weighing the water contained in the vessel, or for larger vessels, carried out using smaller volumetric measures which are themselves traceable to national standards by weighing methods.

Volumetric systems are normally used with standing start and finish methods due to the difficulty of diverting flow into the tank and controlling the finish of the fill. The technique gives a very high level of repeatability but is by necessity a bit removed down the traceability chain. Tank volumes are expressed at a reference temperature (normally 15 or 20°C) and corrections have to be applied for the expansion of the material of the tank, and the expansion of the liquid between the tank and meter. Drainage time (after the tank is empty) is vitally important as liquid clingage to the wall can be significant. Each tank has a calibrated drain time and this must be maintained. For this reason high viscosity liquids above 10 cSt start to give problems of both accuracy and repeatability due to the unpredictable quantity of liquid left attached to the walls of the tank.

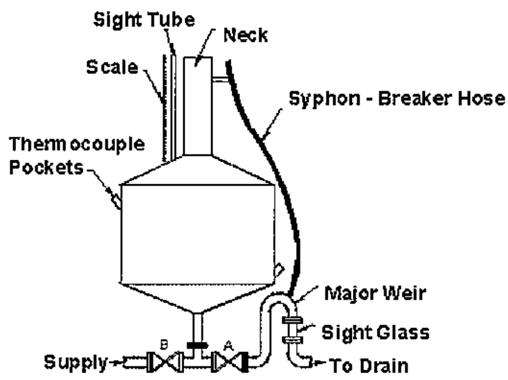

Figure 5

Pipe provers are another volumetric method and are discussed in Section 2.4 below.

2.4 Pipe Provers

The techniques described above refer to calibration systems which are in general used only in the laboratory but can, and are, used in the field for many applications. This applies particularly to volume methods where the environment is less likely to effect the measurement.

To calibrate meters on line, a device called a pipe prover has been shown to fulfil most of the requirements for field proving. The basic prover principle is shown opposite. A length of pipe is fitted with switches so that the volume between the switches is known. If a displacer, or pig is introduced to the flow, the time it takes to travel between the switches will give a measure of the flowrate. If the switches are used to gate a pulse counter, totalising pulses from a flowmeter, a measure of the meter factor (pulse per litre) can be found.

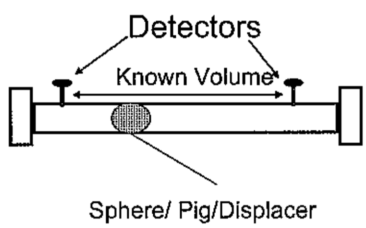

Figure 6

This concept has been refined to give the measuring device called a 'pipe prover'. These devices are used extensively to measure all types of high value fluid from LPG to high viscosity crude oil and are produced in all sizes from 3-36 inches diameters.

Four main classifications of provers are found.

2.4.1 Unidirectional sphere prover

This classification covers provers which have a displacer which only travels in one direction along the pipe. The displacer consists of an elastomer (neoprene, polyurethane, viton etc) sphere which is usually hollow. The centre is filled with liquid and pressurised to inflate the sphere until it is larger than the pipe bore. Inflation is usually around 2 per cent larger than the pipe. When the sphere is inserted into the pipe it takes up an elliptical shape and makes a good seal to the pipe wall.

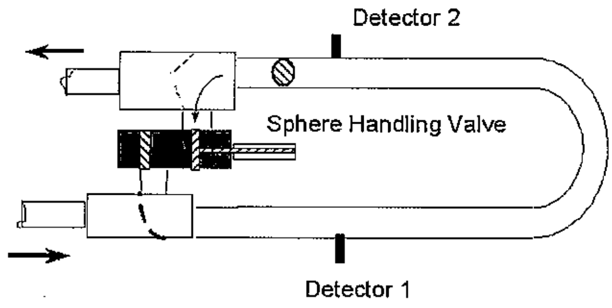

Figure 7

The pipe itself will consist of a long length of, normally, steel pipe. The internal surface is usually coated with Phenolic or epoxy resin to provide a smooth low friction lining and to protect against corrosion. As the pipe can be extremely long, it is usually constructed in a series of loops. The radius of the bends is chosen to allow the sphere to pass without either sticking or leakage.

At each end of the calibrated length of pipe a detector switch is located through the pipe wall. This usually takes the form of a plunger which triggers the switch when the sphere passes under it.

At the end of this prover is the sphere handling valve. This arrangement is designed to hold the sphere. When required the sphere can be launched into the flow and carried round the loop. At the end of the loop the sphere is captured and returned to the launch position ready for another run. The valve also has to allow for removal of the sphere, and prevent any leakage of fluid from inlet to outlet of the prover loop.

2.4.2 Bi-directional sphere prover

Because of the complexities of sphere handling and to reduce the turn round time of the sphere, the bi-directional prover was developed. Similar in layout to the previous type, the flow can circulate around the loop in both directions. A four-way valve, of very high integrity, changes the flow path without breaking the flow. The sphere is held in special end chambers which are designed to launch the sphere and absorb the shock of capture. They also provide a means of removing the sphere.

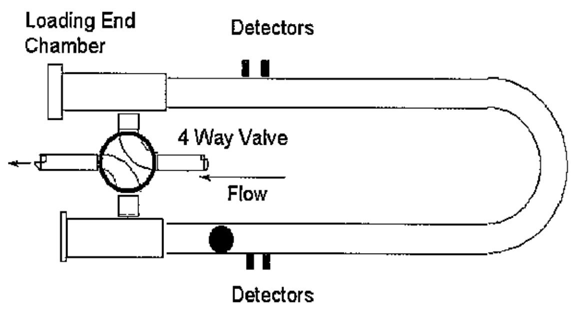

Figure 8

2.4.3 Piston provers

For difficult fluids which may destroy lining, or leak past the conventional sphere, piston provers have been produced. In this case the calibrated pipe is a smooth, perhaps honed, pipe of stainless steel or plated carbon steel. The displacer is a piston with multiple seals. Switches can be conventional plungers or a more 'high tech' non-contacting type. These provers are bi-directional and controlled using a four-way valve.

2.4.4 Small volume (or compact provers)

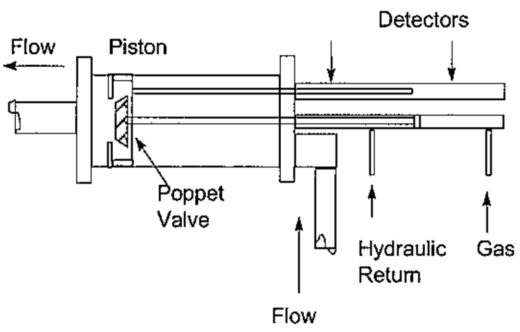

Figure 9

Depending on the definition used, these provers are either any prover smaller than a 'conventional' prover design or are a separate class of device with a volume about one-tenth of a conventional design. These are normally piston provers with the detectors mounted external to the pipe to ensure a high resolution for a small distance travelled. A technique called pulse interpolation is used to increase the resolution of the pulse counting to allow smaller volumes to be used. In other words fewer than 10 000 pulses can be collected if the pulse signal quality is suitable for interpolation.

To use a prover, the flow is directed through the prover and then the meter. The displacer is launched into the flow. When the first detector is actuated a counter and timer are started. When the second detector is actuated the timer and counter are stopped. From the known volume between the detectors, the pulses counted and the time, a calculation of volumetric flow rate and k-factor are derived. The base volume of the prover is found by displacing water into a volume (or mass) standard measure. As with volume tanks the base volume is given at reference temperature and pressure. In use corrections for temperature and pressure of the prover and liquid have to be applied.

Codes of Practice governing the design, calibration and use of pipe provers, including the small volume versions are available from ISO, Institute of Petroleum and API.

3 CALIBRATIONS FOR GAS FLOWMETERS

The choice of calibration method for any particular flowmeter is governed by the meter type, the ranges of flow and flow conditions, pressure and the accuracy of calibration required. In general all the methods have analogies with the liquid methods.

In this section only 'primary' standard methods of flow measurement are considered. A primary standard method is one in which reference flowrate is determined by measurements of the basic dimensions of mass, length, temperature and time, a secondary standard method is one in which reference flowrate is determined using a flowmeter which has been calibrated by a primary method. The principles of operation of the standard rigs dealt with here are very simple, but as might be expected, difficult problems do arise and the more important of these problems are mentioned.

It should also be noted that the uncertainties quoted refer to the uncertainties associated with the measured mean reference flowrate during the measurement period and they are applicable to tests in a well-equipped national standards laboratory staffed by highly trained specialists. In an industrial standards laboratory it may prove difficult to attain these levels of accuracy.

3.1 Displacement Methods

A number of proprietary standard devices are used for gas calibration based on the principles of the pipe prover. The biggest drawback of any prover system is the friction generated by the displacer/pipe seal and the variations in pressure caused by the weight, friction or resistance of the displacer. Mercury seal provers use a very light displacer, with a mercury ring acting as the seal sliding in a glass pipe. This type is used for low flow/pressure calibrations. Some high pressure, more conventional, provers exist where the density/pressure of the gas keep seal friction below critical levels.

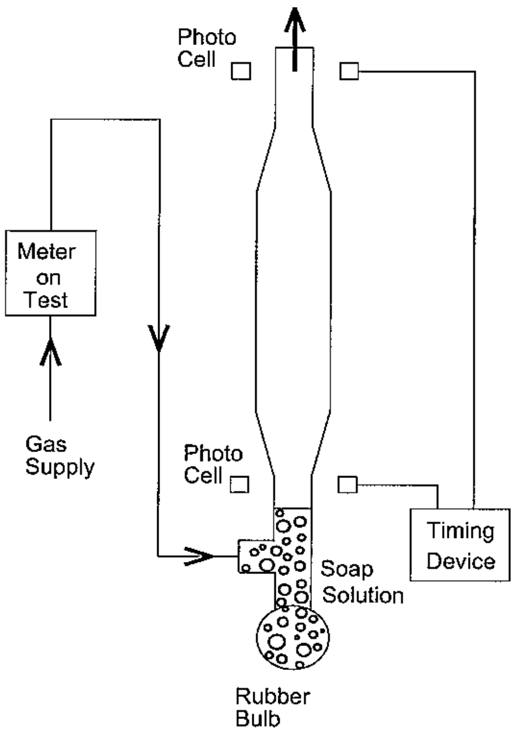

Figure 10

Soap film burettes are a common calibration device. This method which is comprehensively described by Harrison is usually used to measure gas flows within the range 10^{-7} to 10^{-4} m^3/s at conditions close to ambient. What is created is a pipe prover with the displacer formed by a soap film or Bubble.

To calibrate a flowmeter the system is set up as shown in Figure 10. Gas flow from the meter on test passes through a vertically mounted burette. As the gas enters the burette a soap film is formed across the tube and travels up the tube at the same velocity as the gas. By measuring the time of traverse of the soap film between graduations at either end of this accurately calibrated burette the rate of flow of the gas may be obtained.

Factors such as volume calibration error, volume change due to temperature effects, and timing errors are potential sources inaccuracy, but under very carefully controlled conditions reference flows can be determined to within ±0.25 per cent using soap film burettes.

Another common device is the Bell prover which is the standard method for low flow gas meters such as domestic gas meters. In this method a cylinder closed at one end in inverted over a liquid bath. The cylinder is counterbalanced by weights on a line over a near frictionless pulley such that a pre-determined pressure is created in the trapped volume. A pipe passing through the liquid communicates with the trapped volume and, as the cylinder is lowered, leads the displaced gas to the meter on test. By timing the fall of the cylinder and knowing the volume/length relationship for the cylinder, the volume flow of gas through the meter may be determined and compared with the meter reading. The liquid is often water or high vapour pressure/low viscosity oil.

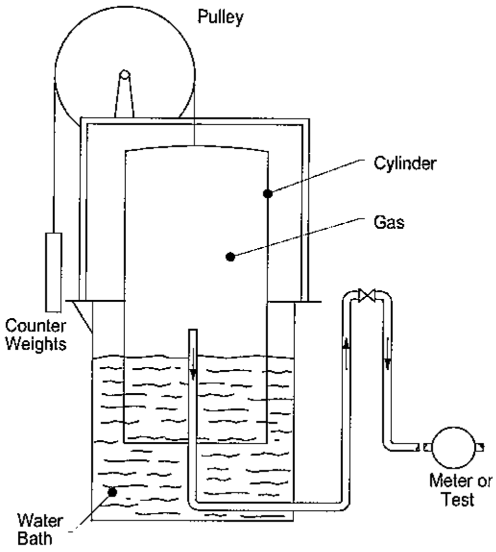

Figure 11

In order to minimise expansion or contraction of the gas, the water, gas and air temperatures should not differ by more than 1°C. Errors can also arise due to leaks, incorrect compensation for change in buoyancy on the counter-balance pulley, and the fact that the gas is not fully saturated. At present, for flows up to some 10^{-2} m^3/s this method, which is usually used to meter air flows at conditions close to ambient, can be used to measure flows to within ±0.25 per cent if strict precautions are taken to minimise the errors mentioned above.

3.2 Critical Flow Venturi-nozzle

Although not a primary method of calibration, when used alone, the method can be combined with the two primary methods outlined below as part of a primary calibration system.

If the pressure drop between the inlet and the throat of a nozzle or restriction is increased until sonic velocity is reached at the throat, then for a given value of the upstream pressure and temperature, the mass flowrate through the nozzle will be constant. The expression for the mass flowrate of the gas is

$$\frac{dm}{dt} = C_d C^* A_t P_o \frac{1}{\sqrt{RT_o}}.$$

The mass flowrate under sonic conditions is independent of downstream pressure and temperature and dependent only on the geometry of the nozzle, the properties of the gas, and the upstream pressure and temperature. This feature makes the device particularly suitable for calibrating meters, like some rotary displacement meters, which can introduce pressure pulsations into the flow. A standard sonic Venturi is shown in Figure 12.

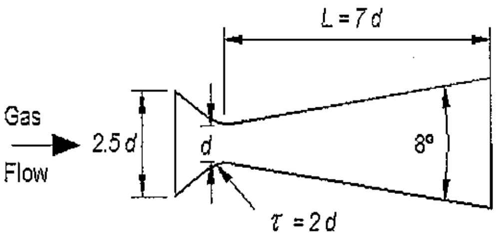

Figure 12

One disadvantage of the critical flow Venturi-nozzle is the large pressure drop, which is normally much greater than that for subsonic nozzles or other flowmetering devices. Moreover, an accurate knowledge of the thermodynamic properties of the gas is required, and this may cause difficulties in gases such as natural gas where the composition may be complex and variable. The device is however particularly suitable for calibrating flowmeters in high pressure gas flows at flowrates where the throat Reynolds number exceeds 10^5 and uncertainties of 0.2 per cent may be achieved.

One feature of the nozzle is that as pressure changes can not travel faster than the speed of sound, the nozzle effectively de-couples any downstream pressure changes from upstream conditions and hence provides a constant mass flow when upstream pressure is constant and downstream pressure changes. For measurement purposes a nozzle is used but any suitable restriction such as a valve, run at sonic velocities performs the same function.

3.3 Gravimetric / P.V.T Methods

A simple gravimetric system is outlined in Figure 13. In this system a controlled pressure, and hence flow, of gas is applied to a critical flow restriction or nozzle and diverted into a containment vessel. By weighing the vessel and timing the test, the mass flow can be derived. The meter being tested can be connected upstream of the nozzle and hence a primary calibration can be achieved. The pressure at the meter will be high and only one flowrate can be measured by any particular nozzle size. A valve can be used but sonic conditions must be maintained. Alternatively the meter can be placed downstream of the nozzle and after a divertor valve. Gas passes through the nozzle and the meter and is then diverted to the weighing vessel. What is happening is the meter is calibrated against the nozzle then the nozzle calibrated against the weight. As this occurs during one test a much lower uncertainty is obtained compared with the use of the pre-calibrated nozzle alone.

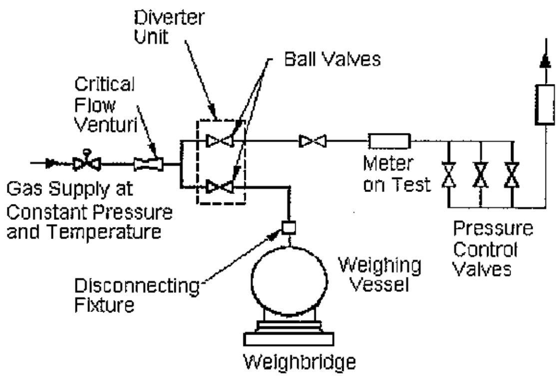

Figure 13

Alternatively, the weighing vessel is replaced by a pressure vessel of known volume. By application of the equations of state of the gas, the mass of gas collected can be calculated from the volume, pressure and temperature.

Due to gas compressibility effects, problems encountered in maintaining a closely controlled flowrate are considerably greater in gravimetric gas flow systems than in liquid flow gravimetric systems. Also since gases are very much less dense than liquids further difficulties are encountered in accurately weighing the diverted mass.

The NEL gravimetric system can be used to measure air flowrates of up to 4 kg/s, at pressures of up to 50 bar, to within an estimated uncertainty of 0.15 per cent.

3.4 On-site Testing

In this Section three methods, suitable for calibrating flowmeters on site, are described. These are in addition to using reference meters or pipe provers which have been described elsewhere. These methods, particularly velocity traversing, are also used in flow measurement test laboratories, but the uncertainties quoted for the methods in the following sub-sections refer to the best attainable uncertainties in the field. To obtain an estimate of the uncertainties attainable under laboratory conditions the uncertainties given should be halved. It should also be noted that these uncertainties refer to instantaneous flowrate measurements.

3.4.1 Tracer methods

Tracer techniques can be divided into two methods,

a transit time (velocity methods), and

b dilution methods.

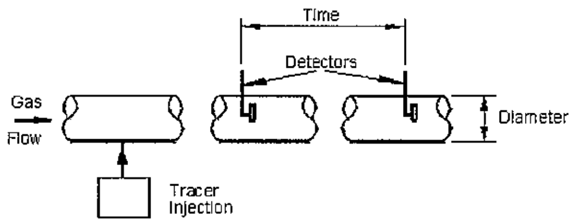

Figure 14

In transit time methods a pulse of tracer fluid is injected into the main flow stream, and the time taken for the tracer to pass between two detection points is noted. If the volume of pipe between the detectors is known the volumetric flow of the flow can be determined. At present, tracers used in this method are usually radioactive isotopes, and radiation detectors are used to determine the tracer transit time.

For the dilution method a tracer fluid which is detectable in low concentrations, is injected into the flow (Figure 15) at a known rate q m^3/s. The mainstream flow is then sampled at a distance downstream of the injection point far enough to have allowed homogeneous mixing to have taken place, and the concentration, C, of the tracer is measured. Since the rate q is usually very small compared with the main flow Q, the flowrate can be derived from

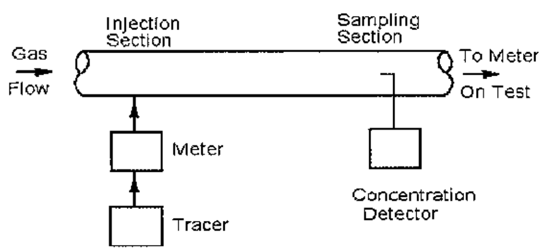

Figure 15

$$Q = \frac{q}{C}.$$

Tracer methods are not suitable for sluggish, slow moving flows. In dilution methods the main source of error occurs in obtaining accurate determination of the tracer concentration, and in tracer velocity methods, difficulties are encountered in determining the volume between detectors. However it is claimed that, by incorporating recently developed radioactive techniques, an experienced team can determine the flowrate under the most favourable conditions to within 0.5 per cent using tracer methods.

3.4.2 Velocity traversing methods

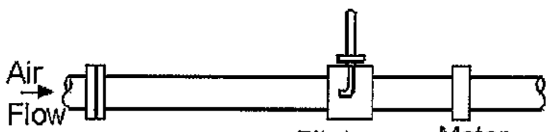

Figure 16

In these methods, the flowrate in the pipeline is estimated by measuring a number of point velocities at discrete positions in a cross-section of the flow, and then integrating these over the flow cross-section. A typical fan test-line set up for calibrating a meter is shown in Figure 16. The most commonly used instruments for determining point velocities flows are anemometers insertion meters and pitot tubes.

The main disadvantages of these methods are that they are time consuming, and serious difficulties are encountered with unsteady flows. For gas velocities in the range 0.3 to 3.0 m/s uncertainties of 4 per cent are attainable using vane anemometers and for velocities in the range 6-120 m/s uncertainties of within 2 per cent can be achieved using pitot tubes.

3.4.3 Clamp on Ultrasonic Meters

Clamp on ultrasonic meters can also be used for in-situ calibrations but many factors have to be considered such as flow profile, pipe material and internal condition and fluid properties. Uncertainties of no better than 5-10% can be assumed.

4 CALIBRATORS IN USE

A calibrator for flow, unlike a standard for mass or length, involves a number of different measurements, associated hardware, test procedures and the conditions of use. All of the above aspects can adversely affect the accuracy of a calibration.

4.1 The Importance of Calibration Fluid

In general terms the performance of most flowmeters depends to some extent on the properties of the fluid being metered. For this reason it is often important, especially for liquid flowmeters, to calibrate in the same fluid as that in which the meter will normally operate. For some meters, for example some pressure difference devices, the performance of which may be simply related to Reynolds numbers, the calibration may be carried out in a fluid different to the meter's operating fluid provided the Reynolds numbers are the same. This can even apply between liquid and gas. A calibration of performance against Reynolds number will then enable the meter to be used in different fluids over the flowrate range. Careful attention should be paid to the comparable conditions used to describe Reynolds number.

For liquid meters, especially those required to meter hydrocarbons, the choice of calibration fluid is particularly important. Turbine meters, for example, are notoriously viscosity sensitive, and Figure 16 shows some typical calibration results from a large turbine meter for water and three petroleum products of different viscosities. It is important therefore to calibrate these meters using the actual working liquid and for this reason, among others, turbine meters for crude oil are often calibrated on site using a dedicated pipe prover and the actual operating liquid.

When volumetric tanks are used the choice of liquid is limited to those of low viscosity (normally 5 cSt and below) because of the errors introduced by drainage.

For gas meters, air, for obvious reasons, is most often used as the calibration fluids. When used with other gases the Reynolds number similarity holds for a wide range of meters, the notable exceptions being variable area meters (for which another simple correlation applies) and certain thermal flowmeters. If the gas viscosity is significantly different from that of air, then the performance of some positive displacement meters may be affected, and in these cases calibrations should be carried out in the gas on which they are to be used.

4.2 Calibration Conditions

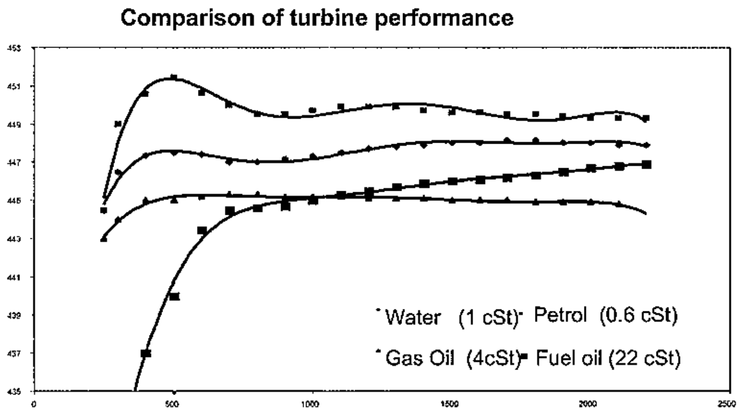

Figure 16

The pressure and temperature at which a flowmeter is to operate are important factors, particularly in the case of gas meters, and must be taken into account. Pressure and temperature not only affect the dimensions such as the throat diameter of a nozzle or the clearances in a positive displacement meter, but in the case of gas flow can have a significant effect on the gas density and viscosity as well. Unless the gas density is measured directly the composition of the gas must also be considered, including the humidity, which can cause significant errors if ignored.

Most flowmeters are sensitive to the velocity profiles of the approaching flow, and to ensure that this profile is fully developed and symmetrical it is essential that the calibration system should provide adequate straight pipe upstream of the test meter. It is normal also to provide some straight pipe downstream of the meter although this is not so important as the upstream pipe.

Good calibration systems usually provide the facility for reproducing the actual installation conditions under which the meter has to operate. For example, the meter may be installed in practice close to a partially opened valve which will almost certainly affect its performance. The error due to the proximity of this valve will however greatly be reduced if the calibration is carried out with this valve in the same position as in normal operation. Calibration with long lengths of upstream pipe would in this case have little resemblance to the actual operating conditions.

4.3 Calibration Accuracy

The calibration curve of a meter applies to that meter only, operating under the conditions with which it was calibrated. If in service these conditions are changed the calibration may not apply. What then are the real orders of uncertainty which might be reasonably obtained from calibrated meters?

First, the meter cannot be calibrated to an uncertainty level better than its repeatability and the uncertainty of the standard. The random uncertainties of a calibration can be calculated statistically from the results of a calibration, whereas the systematic uncertainties can only be estimated from a knowledge of the calibration system and its method of traceability. The absence of systematic errors can often only be checked by an intercomparison of facilities using a transfer standard.

Liquid flowmeter calibration facilities, having a known traceability path, should be able to measure flowrates to uncertainty levels between 0.5 and 0.05 per cent depending upon the size, cost and complexity of the system, and to measure volumes with a somewhat higher accuracy.

Calibration systems for gas flowmeters should be able to measure flowrate to uncertainty levels of 0.5 per cent. A primary gravimetric system such as that at NEL can be used with an uncertainty of 0.15 per cent, and when critical nozzles, directly traceable to the gravimetric system are used as working standards, the uncertainty level drops to 0.25 per cent.

DATA TRANSMISSION, ACQUISITION & FLOW COMPUTERS

by

Brendan Robson
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LECTURE No 16

PRINCIPLES AND PRACTICE OF FLOW MEASUREMENT

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CONTENTS

1 INTRODUCTION

Once we have a device that can measure some physical property in which we are interested, such as temperature, pressure or flowrate, we need to be able to do something useful with it. Before we can, the signal must be 'conditioned' into a form suitable for further processing or recording. In many instances the signal conditioning functionality is built into the transducer/transmitter, which generates a standard signal such as a 4-20 mA current output, which can be directly input into a display instrument, a controller or a data acquisition system. Alternatively sensor-driven signals are fed directly back to the data acquisition system for conditioning. Pulse signals from flow meters need special consideration.

The signal from the measuring instrument must be transmitted from the actual point of measurement to a control room, for example, and this must be accomplished with minimum loss or signal degradation (Figure 1). In the control room the signal can be processed to represent something meaningful in engineering units such as the level of liquid in a storage tank or the flow of oil through a pipeline. The data received can be stored and analysed by computers to produce information about the performance of the plant as a whole as well as that of individual processes or items of equipment. Here we will look at issues related to signal transmission, signal conditioning, data acquisition and finally consider flow computers.

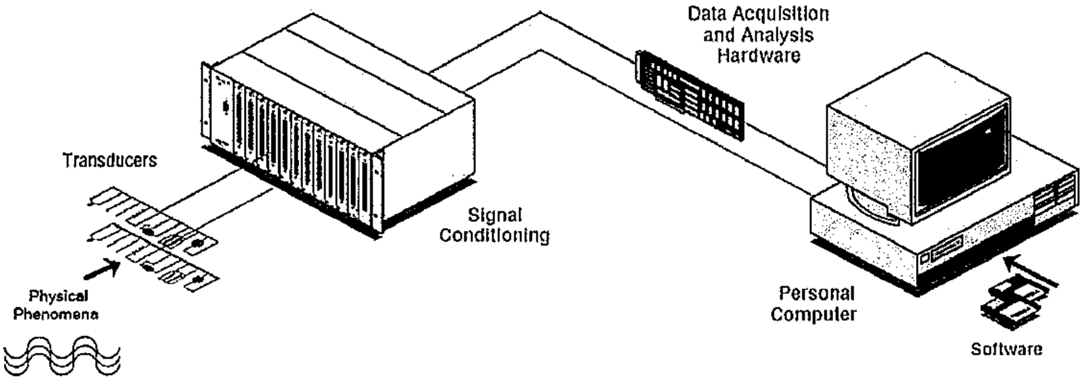

Figure 1 Example of a PC-Based DAQ System

2 SIGNAL TRANSMISSION

2.1 Transmitters

Transmitters are instruments designed to be mounted adjacent to the point at which the measurement is made. Pressure and differential pressure transmitters are connected to the process fluid using suitable tapping points, isolation valves and small-bore piping, whereas temperature transmitters are electrically connected to a temperature element. These devices produce electrical signals, which represent the measured process variable, in a form suitable for transmission over a long distance to remotely mounted monitoring instruments.

The majority of transmitters in use at the present time produce *electrical analogue* output signals, varying between 4 and 20 mA (Figure 2). These values represent the lower and upper values of the calibrated measuring range.

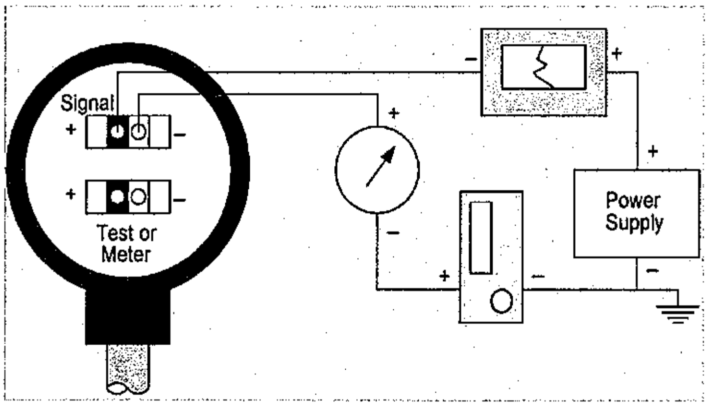

Figure 2 Electrical analogue transmitter

By using and controlling current the cable length becomes irrelevant. Only two connecting wires (generally a twisted pair) are required so the name **'2-wire transmitter'** is commonly given to these devices. The 2-wire transmitter obtains its power from the 4 mA and the use of a 'live' zero means that transmitter failure or an open circuit in the connecting cable can be detected by a zero reading. A 'live' zero also avoids noise pick-up. The load resistor at the monitoring instrument is usually of 250 ohms value, producing a signal varying between 1 and 5 volts.

2.2 'Smart' Transmitters

Smart transmitters are conventional instrumentation transmitters with the addition of an *embedded microprocessor* which can control the operation of the instrument sensor. The microprocessor can carry out correction and linearization functions, accept inputs from other sensors, and carry out calculations. More importantly it can support *communication protocols* allowing remote integration of the unit, transfer of digital information and the setting of calibration factors. Smart transmitters look like their simpler versions and are connected to the process in the same way and to achieve their full potential, have to be properly calibrated, correctly installed and satisfactorily maintained. The digital signals are transmitted using a 4-20 mA loop.

2.3 Fieldbus

Another advantage of having transmitters with digital communications capability is that large numbers can be connected in a 'multi-drop' configuration (Figure 3), to be used by a master computing system without having to use interface units which, by their very nature, introduce errors in the measurement loop. This facility however is not fully exploited because a common industry standard, acceptable to the various instrument manufacturers, has **not** been determined. To this end a number of initiatives are going on throughout the world to develop a **Fieldbus** standard. The International Fieldbus Consortium (IFC) has been established to demonstrate the feasibility of a single international standard for process control and factory automation. Fieldbus is interpreted by IFC as a digital communications system operating at the lowest level of data communications in automation systems.

Specifying a *single* Fieldbus will allow communication and interoperability among smart field devices and control system devices from a multiplicity of manufacturers. Other Fieldbus type systems include Profibus, Modbus and HART. FOUNDATION fieldbus is an all-digital, serial, two-way communications system that serves as a Local Area Network (LAN) for factory/plant instrumentation and control devices.

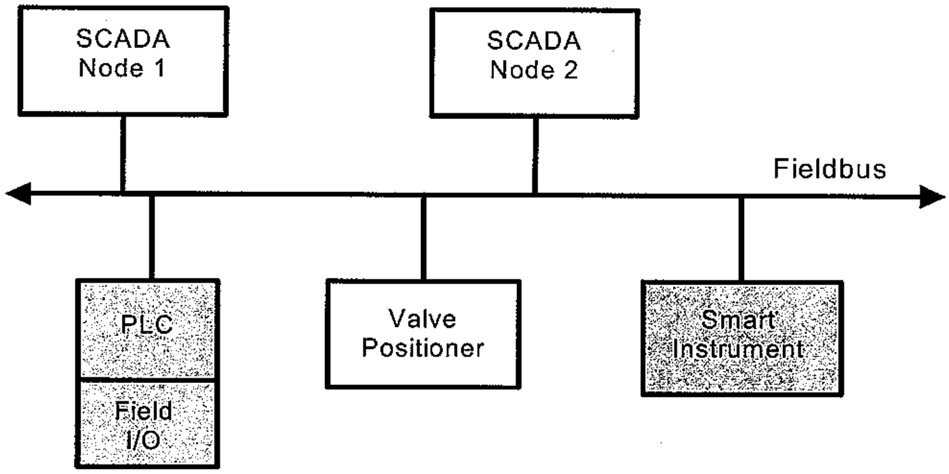

Figure 3 Intelligent instrument networks

The HART (Highway Addressable Remote Transducer) protocol is gaining wide acceptance and already there are a number of readily available PC-based process control software packages that allow digital communication to field instrumentation using this method.

Not as sophisticated as Fieldbus, the local GPIB (IEEE 488.2) communication standard is still used for secondary instrumentation; although not for flow signals.

3 SIGNAL CONDITIONING

Signal conditioning is the term given to the manipulations applied to the primary sensors electrical signals to prepare them for measurement by the Data Acquisition System. Instrument transmitters perform signal conditioning by transforming the sensors output into a 4-20mA current. In general common types of conditioning include amplification, isolation, linearization and filtering (Figure 4).

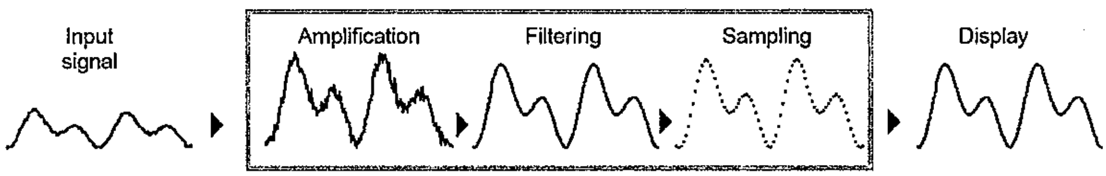

Figure 4 Conversion of analogue signal to digital data

3.1 Amplification

Amplification is usually applied on data acquisition boards to improve the resolution of the analogue-to-digital converter (ADC) by maximizing the analogue signal to match the ADC's voltage range. Amplification can also be applied to low voltage signals near to the sensor. This allows the signal to be amplified before it is affected by environmental **noise.** In this way the signal-to-noise ratio is greatly increased.

3.2 Filtering

Filtering can remove unwanted noise such as "mains hum"; it cannot be eliminated by other methods (Figures 5). However there must be a sufficient difference between the frequency of the process signal and that of the interference. As a very rough guide for a simple first-order filter, the frequency of the signals should differ by a factor of ten or greater.

Many transducers, such as RTDs (resistance thermometer devices, such as PRTs), strain gauges and thermocouples, generate non-linear voltages with respect to the parameter they measure. Signal conditioning can scale, or **linearize**, a transducer voltage to the correct units.

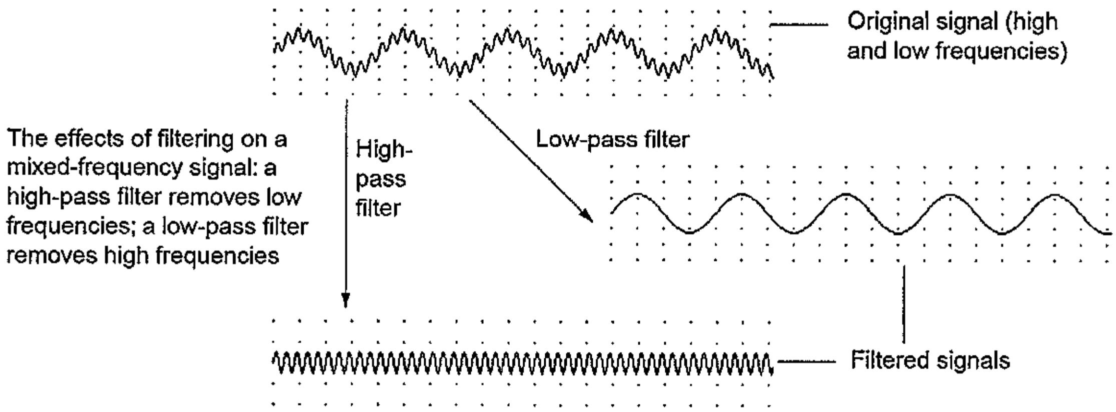

Figure 5 Effects of filtering

A word of caution: the HART protocol superimposes a fluctuation on a 4-20 mA signal, which a filter may confuse with a noise ripple. So your signal conditioning may remove your communication signal!

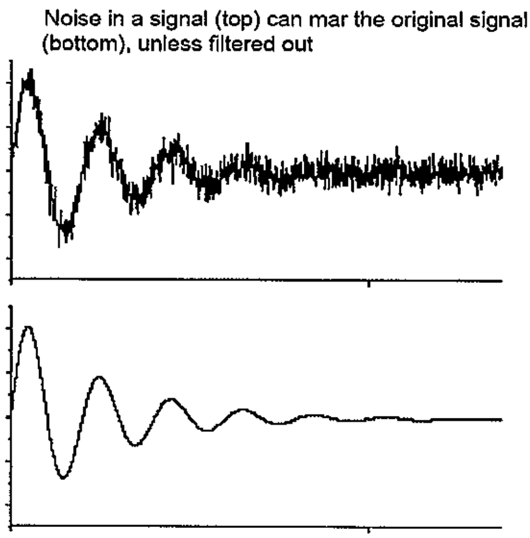

Figure 6 Example of noise

Isolation is often included when the signal being measured could potentially contain large voltage spikes, which could damage the data acquisition unit or harm the operator. Isolation devices generally use optical, transformer or capacitive coupling techniques to pass on the signal *without a physical connection.* Isolation can also be used to resolve grounding problems as is discussed in the next chapter.

3.3 Signal Interference

By interference we are not talking about fluctuations in the process variable but something directly affecting the signal on its route from the transmitter to a controller or data logger (Figure 6). The most common medium for the transmission of data is of course an *electric cable* which, as well as carrying the signal from the transducer, may also be used to provide the power to its internal signal conditioning circuitry.

If incorrectly installed, a cable can act as an *aerial* to any electromagnetic interference in the vicinity. The best example of this is "mains hum" where a signal at the frequency of the local electricity supply (50 Hz in the UK for a single-phase supply) is superimposed onto the instrument signal. Some other sources of interference include power cables, electric motors on pumps or overhead cranes, fluorescent lights, static electricity, lightning, welding equipment, radio transmitters and unfiltered power supplies.

The simplest way to reduce or eliminate interference is to *avoid the possible sources* by routing any instrument cables away from them. Instrumentation cables should never be laid in the same trunking as power cables. As well as being a safety issue this can also result in electrostatic interference affecting the signal. If a signal cable has to cross the path of a *power cable* it should do so at an angle of 90° to reduce any interference to the absolute minimum.

There are probably very few installations where interference is not a potential problem, therefore using instrument cables with a *braided or foil screen* that is earthed at *one end only* can prevent or greatly reduce the effects. By connecting the screen at only one end we are avoiding another cause of interference: an **earth loop**. This can cause unwanted currents to flow in the measurement circuit, which, in turn, can affect the measurement signal. Another simple way of reducing the effect of electromagnetic interference or inductive coupling is to *twist* the pairs of wires from the transducer together. This is known as "**twisted pairs**" and very simply the voltages induced in each successive loop of the cable *cancel* each other out so that the resultant induced voltage is greatly reduced.

4 GROUNDING

If not thought out properly the grounding of a measurement system can have severe impact on the measurement accuracy. Current flow through unintended paths known as **ground loops** can generate significant measurement errors. Consideration should be given to the type of signal source and the grounding of the data acquisition device.

There are two types of sources, **grounded** or **floating**. Grounded sources have their voltage signal referenced to the *system ground*, whereas floating sensors are *not referenced*. Grounded sources are usually devices that are plugged into a wall socket.

There are also several types of *measuring system*:

1. Differential (Diff),
2. Referenced Single Ended (RSE)
3. Non-Referenced Single Ended (NRSE)

In a **Differential** measurement system the source inputs are connected to the inverting and non-inverting inputs of the instrument amplifier with no reference to a fixed ground. It measures *only the potential difference between the two inputs*. Any voltage that is common between both inputs and ground (i.e. the **common mode**

voltage) is rejected. However in reality there is a limit to the level of common mode voltage that the amplifier can reject. If there is a possibility that this limit could be exceeded then the common mode voltage must be restricted by the use of **bias resistors**. Differential measurement has the advantage that it tends to reject *environmental noise* because the noise on the high lead closely resembles the noise on the low lead.

In a **Referenced Single Ended** system the measurement is made with respect to a *common system ground*, whereas in **Non-Referenced Single Ended** the measurement is made against a *common voltage* that is not tied to the system ground.

When measuring **grounded sources** a Differential or NRSE system should be used. Using a RSE system will result in a **ground loop**. The ground loop is created because, as shown in Figure 7, the signal is grounded *both* at the source and at the amplifier. Each ground has a unique potential resulting in a potential difference (Vg), which can be in the range of millivolts to volts. The measured voltage is the sum of both the sensor voltage and the potential difference. Differential or Non-Referenced Single Ended systems avoid this problem because in these systems the *signal* is not referenced to ground. Hence the signal is only referenced to ground *at the sensor* and the ground voltage appears as a common mode voltage, which is rejected by the instrument amplifier (Figure 8).

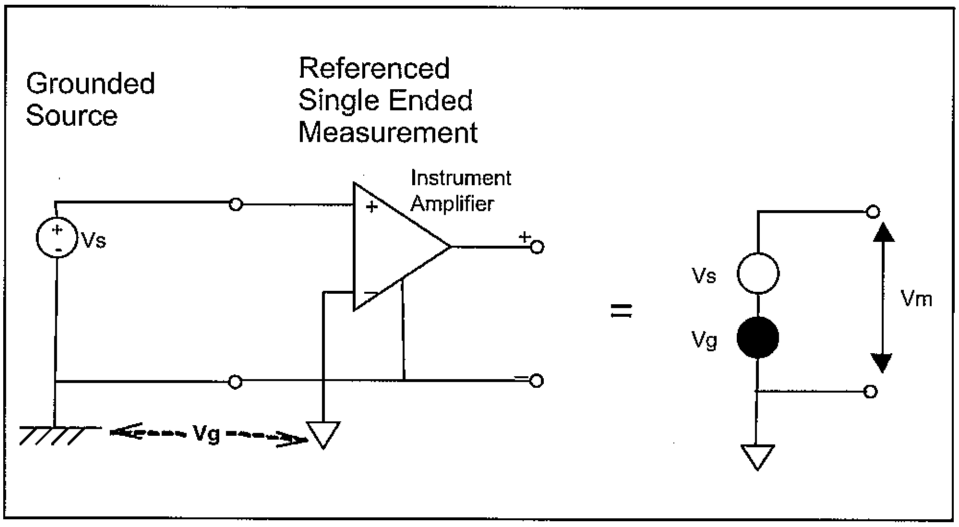

Figure 7 RSE ground loop

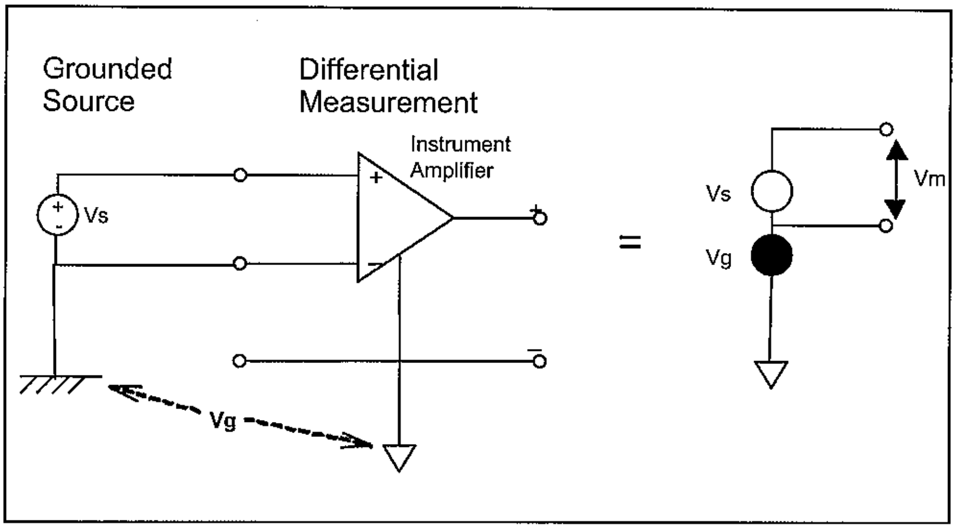

Figure 8 Differential measurement with ground loop

Floating sources can be measured by either differential, RSE or NRSE systems. However if differential or NRSE measurement is used then the *whole system* will be floating and limiting the floating voltage should be considered. This is done by connecting **bias resistors** between each line and the instrument ground as shown in Figure 9. The resistors should be of equal value and have a resistance large enough not to load the source and small enough to keep the system voltage within the **range** of the data acquisition device. A value in the range of 10kΩ to 100kΩ should be sufficient for low impedance sources.

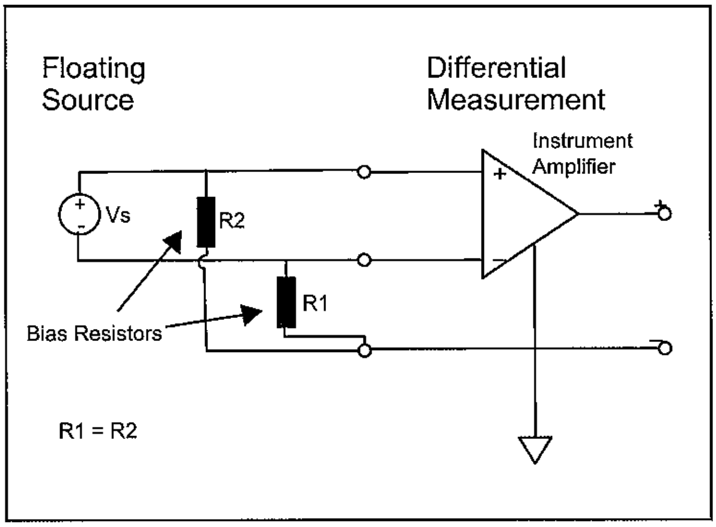

Figure 9 Using bias resistors in Differential Measurement

5 DATA ACQUISITION OF SIGNALS

5.1 General

Data acquisition is the process of collecting and recording data so that it can be analysed and/or displayed. In its simplest form this might involve taking a reading by eye and writing it down on a piece of paper. Traditionally the signal could be fed into a chart recorder where the variations in the signal cause a pen to be deflected across a moving strip of paper with a scale printed on it. More commonly a PC is now being used with the aid of an electronic data logger or one of a large variety of data acquisition cards, which can be installed in the expansion slots inside a PC or a laptop. This section considers data acquisition using PC data acquisition cards.

5.2 Data Acquisition Converters

Before a computer can measure an analogue signal it must first be converted to a *digital* signal by an **Analogue-to-Digital Converter** (ADC). This is performed on the analogue input card. Figure 10 shows the typical analogue input circuitry found on a data acquisition card. It consists of a multiplexer, instrument amplifier, sample and hold circuitry, the ADC and a buffer.

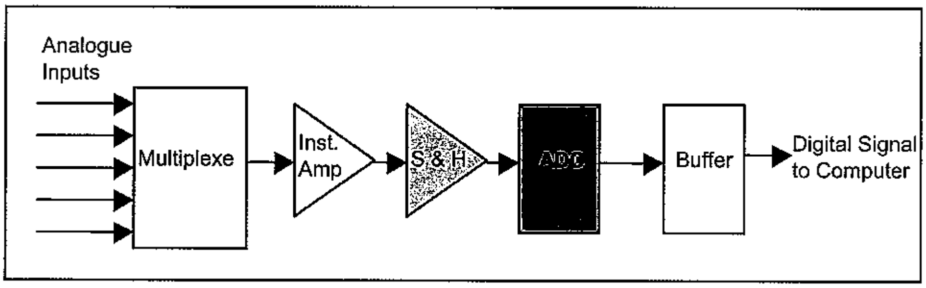

Figure 10 An Analogue to Digital Converter

The card can read multiple analogue inputs, hence a switch (or **multiplexer**) is used to connect one of the channels to the instrument amplifier. The computer controls the operation of the multiplexer to ensure that the required channels are measured. The **amplifier** applies gain to the input voltage in order that the *full voltage range* of the ADC is utilised. This improves the accuracy of the conversion. It takes a finite time for the amplifier output to stabilize. This time is called the **settling time** of the amplifier and varies between different types of amplifier. The settling time affects how fast the data can be accurately measured and hence the maximum **sampling rate**. The signal is then accepted by the sample-and-hold stage and is provided as a steady input to the ADC. The digital output of the ADC is then held in the buffer until it can be passed to the computer memory.

5.3 Analogue-to-Digital Converters

ADCs work in many different ways, one such is the successive approximation converter (Figure 11).

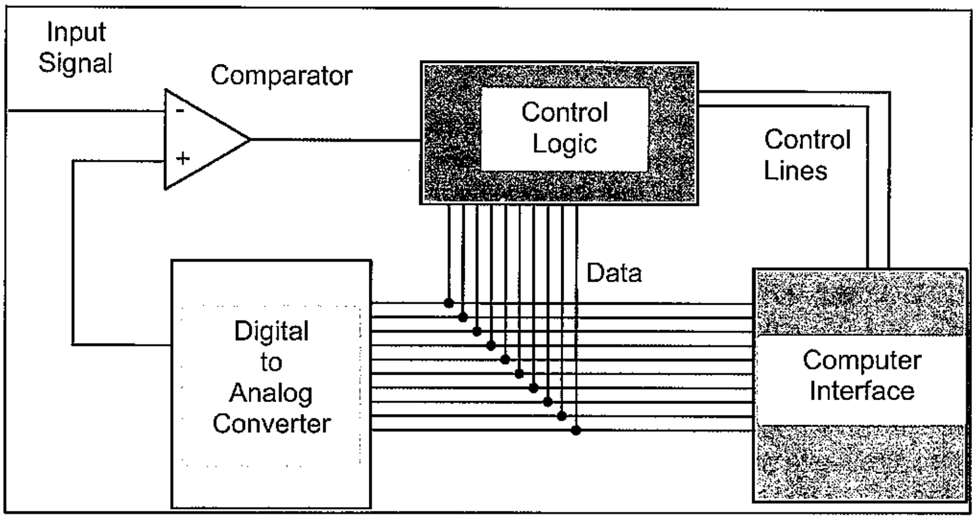

Figure 11 The successive approximation converter

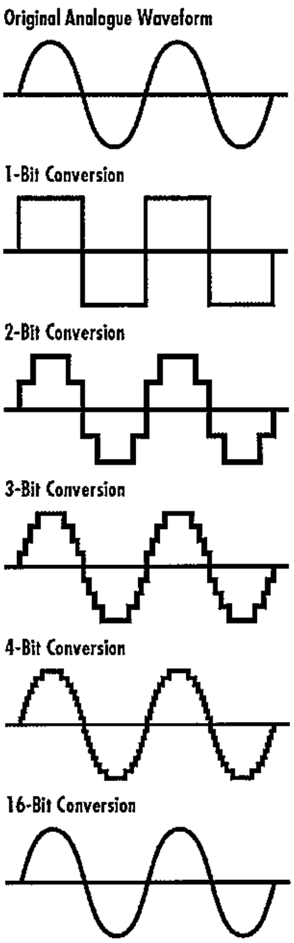

Figure 12 Resolution

This type of ADC takes a sample of the input signal and makes successive *guesses* at its value. The first guess it usually half of the full scale input. The control logic for the ADC then outputs this as a binary value which is fed into a digital-to-analogue converter. The output from the circuit is compared with the original input signal and the control logic then decides whether to make its next guess higher or lower. This process continues until the value generated by the DAC is the same as that of the input signal. The control logic then tells the computer that it can take the reading.

Other types include the **flash ADC** and the **integrating ADC**. The flash ADC applies the input voltage to many comparators *simultaneously*. It operates much quicker than the successive approximation ADC; however this speed comes at a cost due to the number of comparators required. The integrating ADC has *high resolution* but is rather *slow*, so it is normally used in slow measurement devices such as digital multimeters.

5.4 Resolution

The resolution of a digital system is defined as the voltage represented by the least significant bit. It determines how well the analogue voltage can be represented in digital form. For example a 3-bit ADC can only represent 2^3 or 8 discrete values and for a full-scale input to the ADC of 0-10 volts, this gives a resolution of

$$\frac{10}{8} = 1.25\,Volts$$

In order to achieve the best resolution consideration must be given to the size (in number of bits) of the ADC, the voltage range of the ADC, the gain applied at the instrument amplifier and the expected voltage range of the applied input signal.

The greater the number of bits used in the ADC the better the resolution (Figure 12). A 16-bit ADC has 65536 (2^{16}) discrete values.

It is important to match the ADC's **voltage range** to that of the signal to take full advantage of the ADC's discrete values. Hence the instrument amplifier is used to apply gain to the analogue signal. By applying a gain to the signal the range of the ADC is effectively *decreased*, allowing it to use as many of the discrete levels as possible. For example consider Figure 13, a 5-volt peak-to-peak signal is applied to a 3-bit ADC with an input range of 0-10 volts. With a gain of one applied the resolution is 1.25 volts. However if a gain of two is applied then the signal uses all the discrete values available. This effectively *re-ranges* the ADC to 0-5 volts, and hence improves the resolution to 0.75 volts. A balance must be achieved since choosing a large gain will give higher resolution but may result in the signal *exceeding* the voltage range of the ADC, while a smaller gain will accommodate larger signals but will result in poorer *resolution*.

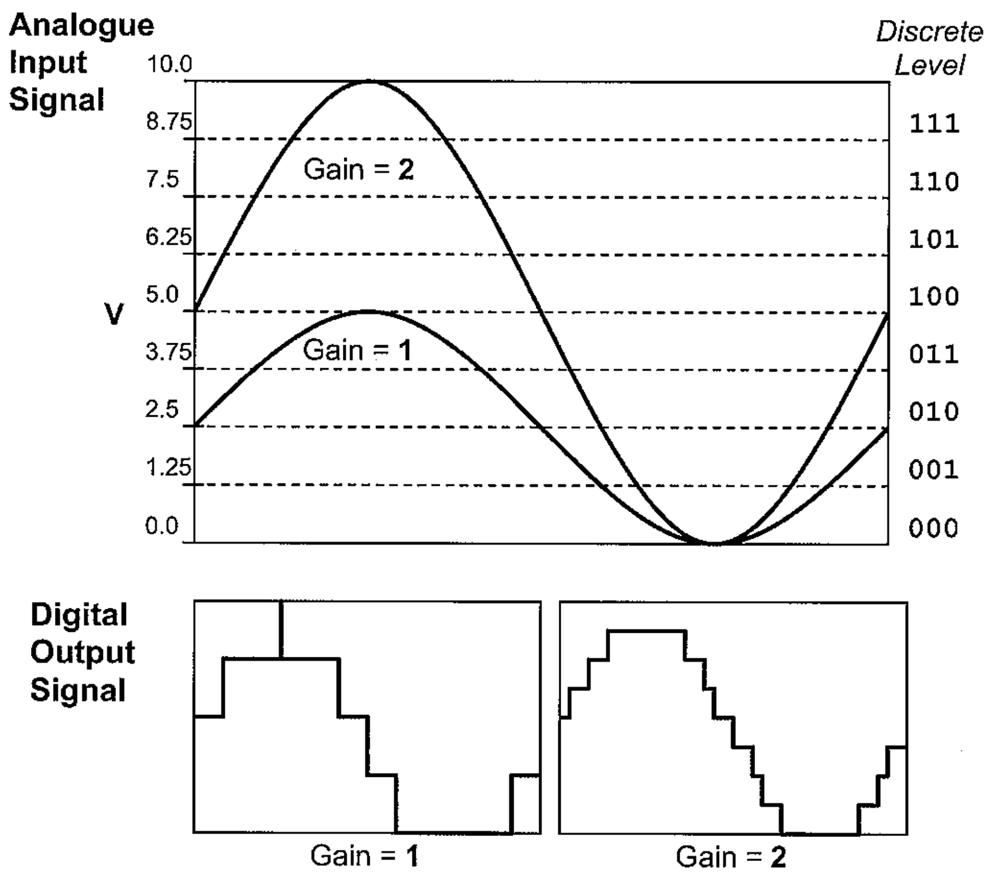

Figure 13 Gain affecting Resolution (& Range)

5.5 Sampling Rate

The sampling rate of a data acquisition system specifies how often a sample of the input signal will be taken (Figure 14).

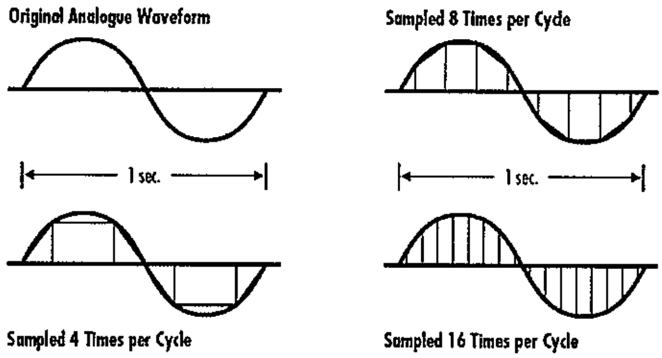

Figure 14 Sample Rate

Care must be taken here to ensure that the sampling frequency is **at least twice** that of the input signal in order to guarantee an accurate representation of it. This threshold is the Nyquist frequency and sampling at a lower rate causes an effect known as '**aliasing**', which can make the frequency of the input signal appear to be far lower or even DC as shown in Figure 15. Alternatively specifying a sampling rate that is too high can cause the generation of lots of useless information, which can easily fill up system memory, a hard disk or other storage medium. As with most things, common sense and experience are the best guides.

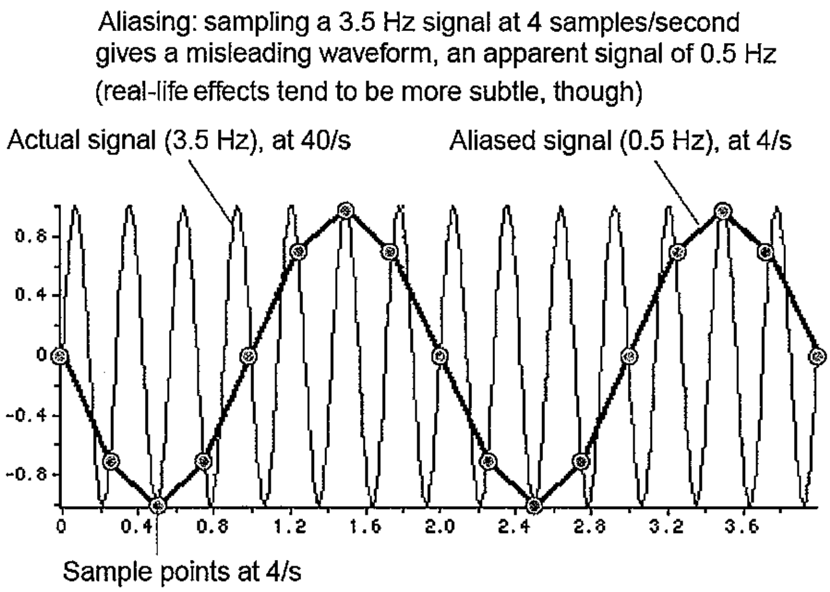

Figure 15 Aliasing

5.6 DAQ Timer/Counters

Counter/timer circuitry is useful for many applications, including counting the occurrences of a digital event, digital pulse timing, and generating square waves and pulses. Thus counter/timers are especially useful in flow measurement. A typical device may offer eight 32-bit counter channels and TTL/CMOS-compatible digital I/O. The device should have sufficient built-in data processing power and not rely on the DAQ computer resources. The counter/timer channels can have many measurement and generation modes which can be configured through the DAQ software.

Counter/timers use essentially three types of signals: **gate**, **source**, and **output**, as shown in Figure 16.

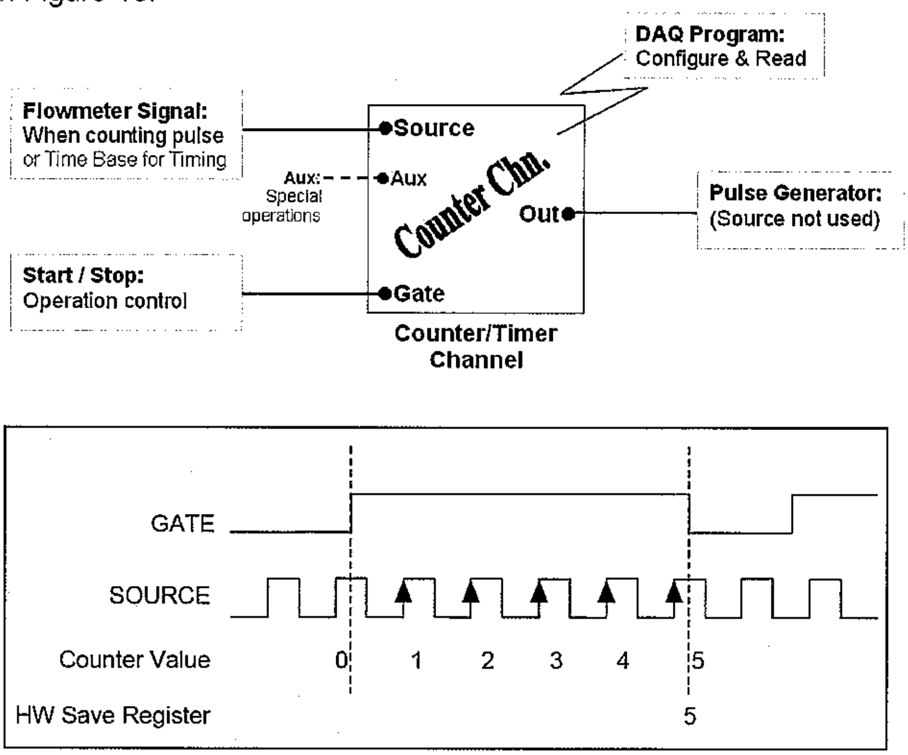

Figure 16 Pulse counting using Timer/Counter

For the example shown, the *well conditioned* flowmeter pulses are the Source and the Gate signal is controlled by a valve position. The number of pulses are counted during the open duration of the valve (5 in this illustration). The **DAQ software** is used to configure the counter/timer channel, arm it (to wait for the starting gate), read the count during acquisition (*without affecting the counting*), and to read the final count. Note, for this case, the channel is configured *not* to re-start counting pulses if the gate re-opens.

Other DAQ functionality worth mentioning is: Triggering, Digital I/O (DIO), and Analog Output, which employs a Digital-to-Analog Converter (DAC). These can be used for controlling external instruments or devices.

5.7 Data Acquisition of Turbine Pulses

Turbine meter signals are a good example of signal conditioning and analysis in flow measurement. The signal quality can be poor and difficult to process correctly.

Turbine flow sensors rely on the energy in the flow stream to spin the rotor. As liquid or gas flows through the turbine, it turns an impeller blade that is sensed by a coil, magnets, infrared beams, or photo-electric sensors. An electrical pulse is then generated and converted to a frequency output proportional to the flow rate. Some units have amplifiers on the head that supply square waves.

The waveform created by the magnetic pickups from the rotating turbine can suffer specific effects (Figure 17). The signal can form an irregular waveform that changes in amplitude and period as the flow varies (F, in Figure 17). Incorrect signal processing will lead to wrong pulse counts and calculated flowrate.

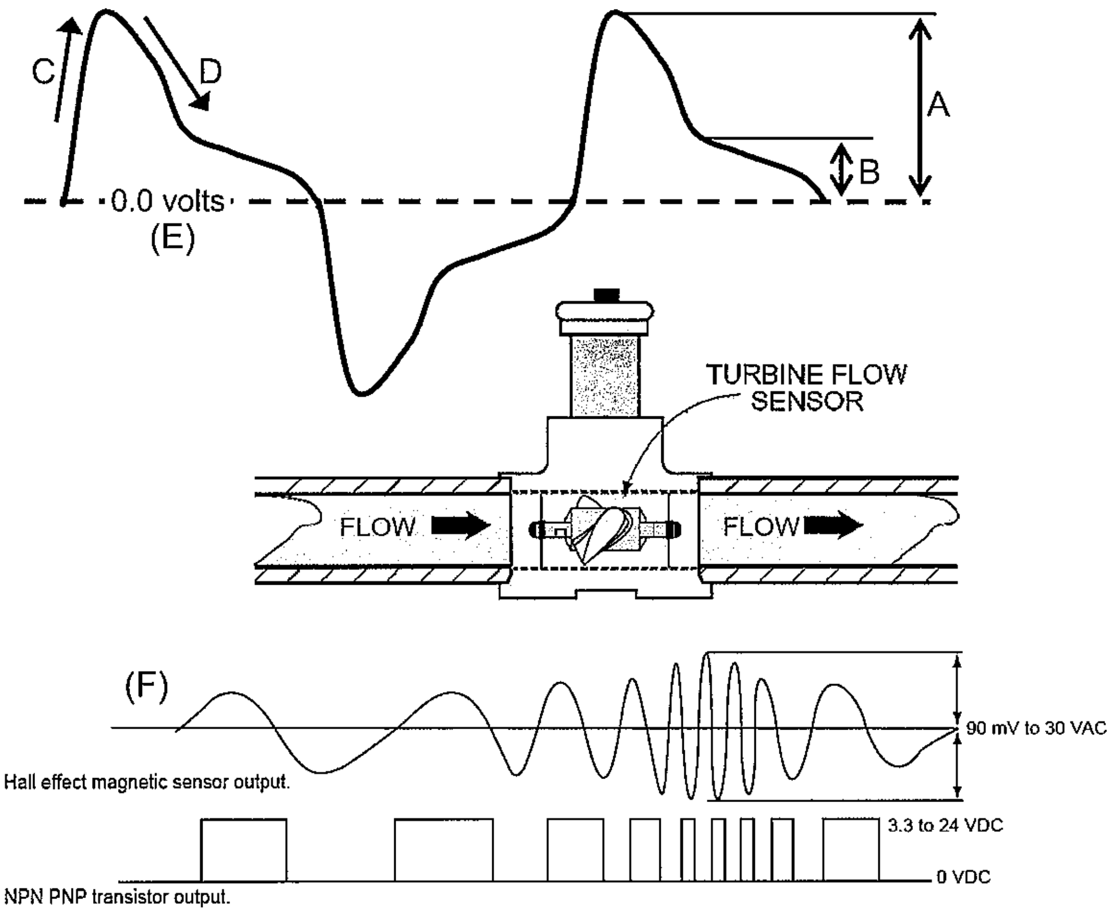

Figure 17 Example of turbine signals

Some considerations, based on this example signal:

- Filtering:
  - At higher flowrates the filtering may need to be adjusted to avoid corrupting the signal.
- Range:
  - If the signal amplitude exceeds the range, there will be severe loss of information. (This is the same as '*clipping*' in a stereo system where music is severely distorted when

the amplitude exceeds the capabilities of the amplifier.) Any signal exceeding the range is '*out of range*'; a condition indicated where no amplitude can be given. If there is any possibility of this condition occurring, the range should be set to a larger value.

- Triggering:
  - The shape of the waveform must be considering for trigger configuration. In Figure 17, the *rising edge* (C) is better than falling edge (D), since there are three falling edges, per cycle.
  - If triggering on amplitude be careful since it changes with speed! The difference between (A) and (B) may be sufficient at high flows, but not at low.
- Base line:
  - The zero base line (E) may be better offset.

A typical turbine waveform can be sensitive to the usual signal conditioning & processing of interference, resolution, range and filtering.

6 DAQ HARDWARE & SOFTWARE

6.1 DAQ Hardware

There are two basic types of PC data acquisition hardware: **plug-in** boards and **external** boxes (Figure 18). Until recently, plug-in boards have been the dominant type of hardware for PC-based data acquisition. These boards plug into an expansion slot in the computer. A separate, external terminal panel is connected to the plug-in board.

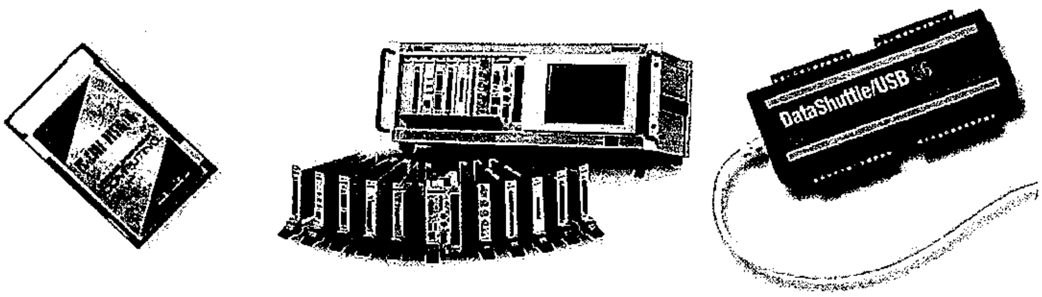

Figure 18 Some DAQ hardware

Recent technological developments in data acquisition hardware have focused on external boxes. These plug into the external parallel, USB, serial, PCMCIA or IEEE 1394 (FireWire) port of a PC. Terminal panels are either built-in or added to the peripheral as an additional box. The most important advantage of the external box is its **portability**. Unlike plug-in boards, external boxes will work with most laptop computers. They are also much easier to install on laptop or desktop computers.

In flow measurement a combination of DAQ types can be used. For example a plug-in card communicating with an external chassis that houses counter/timers and connection via serial ports to secondary instrumentation.

Limitation of communication methods must be appreciated. For example a standard **serial** port (RS-232) may only be effective up to 30m. Alternatives are available such as RS-422 and RS-485. RS-485 allows multipoint communications, similar to RS-422, but can support more nodes per line because it uses lower-impedance drivers and receivers. These are replacing the older RS-232 standard because they support higher data rates and greater immunity to electrical interference. Cable runs can easily extend to 1000m.

Data Acquisition Units, DAU, (Figure 19) allow flexibility of measurement by allowing interchangeable 'cards'. The user can choose from an extensive library of cards based on his requirements and budget. The device can be programmed locally or allow communication with a controlling PC. For flow measurement, DAUs are typically used for secondary instrumentation.

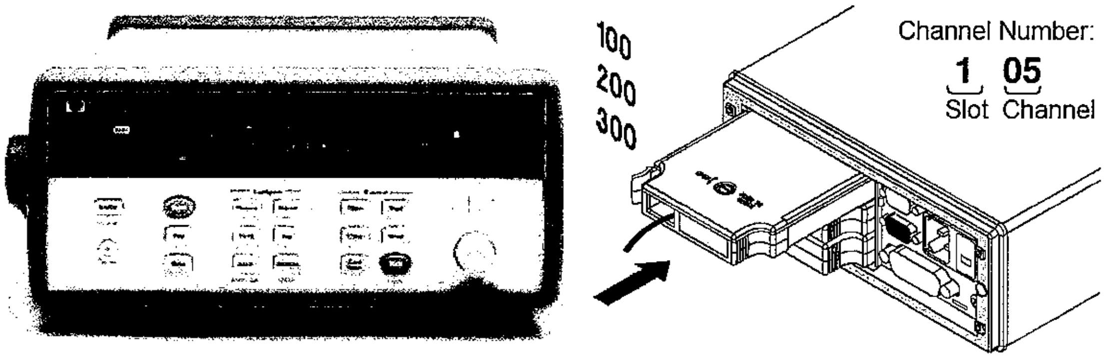

Figure 19 Example of a Data Acquisition Unit

6.2 DAQ Driver Software

Data acquisition software can be divided into two types: driver and application software. Both types must be present to allow a proper user interface. DAQ hardware without software is useless and DAQ hardware with poor software is almost useless!

DAQ **driver** software provides the communications link between the data acquisition hardware, the operating system software, and the application software. Driver software hides the low-level, complicated details of hardware programming, providing the user with an easy-to-understand interface. Driver software can usually be purchased with the DAQ hardware, but you should be aware of how to assess it (are you getting what you need?).

The increasing sophistication of DAQ hardware, computers, and software continues to emphasize the importance and value of good driver software. Properly selected driver software can deliver an optimal combination of flexibility and performance, while significantly reducing the time required to develop the DAQ application.

When assessing driver software, there are several factors to consider:

- *Which functions are available?*

Driver functions for controlling DAQ hardware can be grouped into analog I/O, digital I/O, and timing I/O. Although most drivers will have this basic functionality, you will want to make sure that the driver can do more than simply get data to and from the device. Make sure the driver has the functionality to:

- Acquire data in the background while processing in the foreground
- Use programmed I/O, interrupts, and DMA to transfer data
- Stream data to and from disk
- Perform several functions simultaneously
- Integrate multiple DAQ devices
- Integrate seamlessly with signal conditioning equipment

These and other functions of the DAQ driver, which are included with National Instrument's NI-DAQ package, can save the user a considerable amount of time.

- *Which operating systems can you use with the driver?*

Make sure that the driver software is compatible with the operating systems you plan to use now *and in the future*. The driver should also be designed to capitalize on the different features and capabilities of the OS. You may also need the flexibility to port your code easily between platforms, say from a Windows PC to a Macintosh.

- *Which programming languages can you use with the driver?*

Ensure that the driver can be called from your preferred programming language and is designed to work well within that development environment. A programming language such as Visual Basic, for example, has an event-driven development environment that uses 'software controls/objects' for developing the application. If you develop in the Visual Basic environment, be sure that the driver has custom controls to match the methodology of the programming language.

- *Are the hardware functions you need accessible in software?*

A problem occurs when a developer purchases DAQ hardware, and then attempts to use the hardware with software, only to find that a required hardware feature is *not* handled by the software. The problem occurs most frequently when the hardware and software are developed by different companies.

The answers to these questions will give you an indication of the effort that has gone into developing the driver software. Ideally, you want to get your driver software from a company that has as much expertise in the development of the DAQ software as they do in the development of DAQ hardware.

A well-established example of driver software is National Instrument's NI-DAQ. This (and similar products) protect your software investment because you can switch between hardware products or operating systems with little or no modification to your application.

6.3 DAQ Application Software

An additional way to program DAQ hardware is to use **application software** (Figure 20). However, even with application software, it is important to know the answers to the previous questions regarding driver software, because the application software also uses driver software to control the DAQ hardware. The advantage of application software is that it adds *analysis* and *presentation* capabilities to the driver software. Application software also integrates instrument control (GPIB, RS-232, and VXI) with data acquisition.

For any flow measurement system, DAQ application software is an essential component and its selection must reflect this.

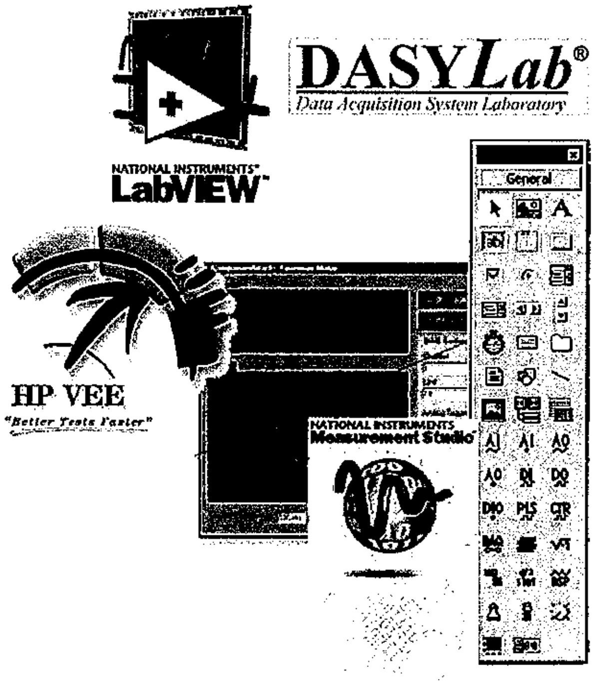

Figure 20 DAQ Application Software

Application software can be packaged with DAQ hardware or measurement device, but this may be specific only to that item and not provide the functionality or interface successfully with a flow measurement system, especially if you are acquiring multiple instruments.

General-purpose DAQ application/development software is classified as **graphical-based** (or icon-based), and **text-based**. Examples of graphical software are LabVIEW, DASYLab and Agilent VEE. Text-based software includes NI Measurement Studio (Visual C++ and Visual Basic), communication libraries (DLL, OCX), and software direct linking with Microsoft Office (eg DAQ-View XL for MS Excel).

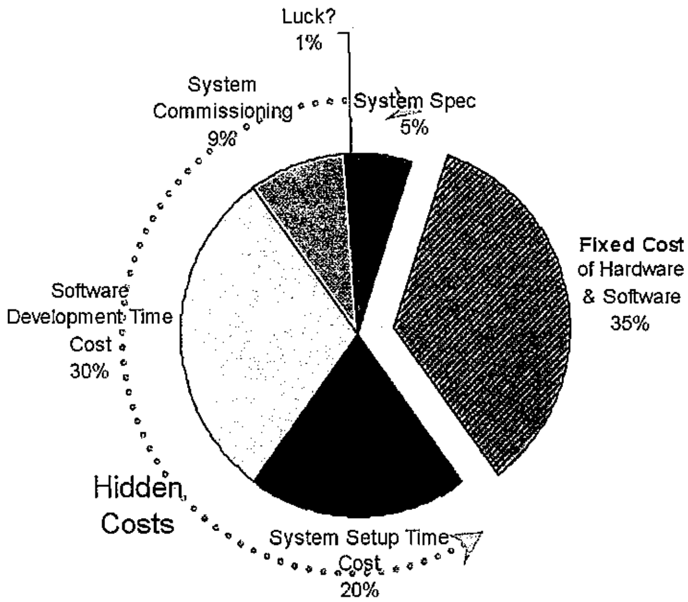

Figure 21 DAQ fixed vs hidden costs

Graphical languages can be quickly learned, but can suffer with larger, more complicated programs. Text languages are professional platforms, used in all areas of software development (not just DAQ), and are therefore more flexible. Selection of application program depends on your current experience and requirements.

The fixed cost of DAQ hardware and software (Figure 21) must be balanced with the less visible time costs of software development, system setup and commissioning, and proper system specification. These costs are very difficult to quantify and control. Any strategy to decrease such costs is obviously beneficial. **Standardisation** is the key factor in hardware, software, procedures and training.

7 FLOW COMPUTERS

To obtain high measurement accuracy it must not be assumed that the pressure, temperature and density of the fluid remain constant. Continuous measurements of the fluid conditions are essential and these measurements used to compute the flow.

It may also be necessary to calculate the effect that the process pressure and temperature have on the physical dimensions of the primary devices and make suitable corrections to these dimensions on a continual basis. Present-day instrumentation makes extensive use of the power and capability of microprocessors to carry out the tasks associated with high-accuracy metering systems.

Present-day **flow computers** are complex and powerful. These dedicated DAQ systems calculate flow in process plants and are common in the oil and gas industry. The fiscal requirements of these industries highlight the need for accurate flow measurement. *"Flow is money"*.

The philosophy adopted by most manufacturers is to produce a range of instruments, each model having sufficient hardware and software capability to cater for most likely applications. The advantages of this approach are fairly obvious:

- Manufacturing costs are lower.
- Instruments are made for stock and allocated as required.
- Spares holdings by the user may be reduced.
- Operator and engineer acceptance is easier.
- Instruments can be converted to suit a different application.

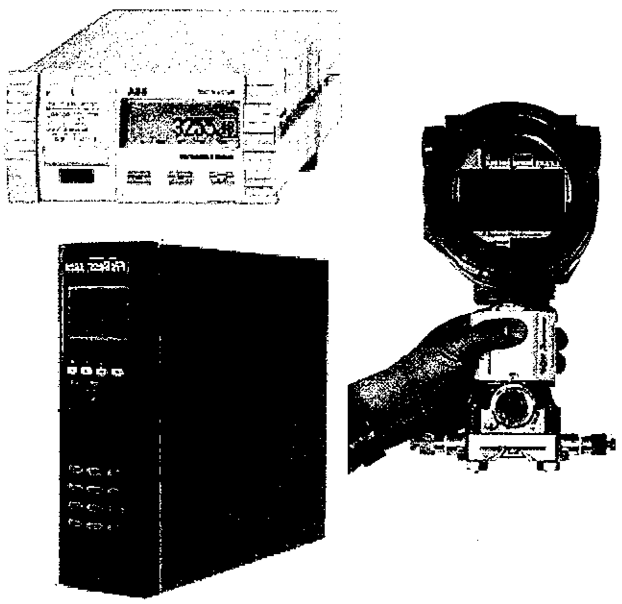

Figure 22 Examples of Flow Computers

The part that defines the particular use of the flow computer is the application software. Manufacturers have libraries of software to cater for conventional applications and most will produce software packages to suit the particular needs of a user. It should be borne in mind, however, that even a relatively small change or modification in flow computer software may have a significant increase in the cost of the device.

A distinction should be made between such software modification and software configuration capability. Configuration capability is used to describe a feature of an instrument which is available within a standard software package and permits the user to select the function of the designated feature.

For example, an instrument may be shipped in accordance with the user's specification in which analogue input No 1 is a 4-20 mA input scaled 0 to 100 bar. Since most instruments currently available have configurable analogue inputs the user would be able to re-scale the above input to other than 0 to 100 bar by a few simple keystrokes.

Security is a requirement in flow computer design. Access to the flow computer to change a parameter that is critical to the measurement is usually made via some method of protection such as passwords, key switches etc.

The software in the flow computer is fundamental, apart from carrying out the necessary calculations without adding a significant error, the calculations have to be updated every few seconds. It is essential that corruption of stored data does not occur so continuous checking of the memory contents has to be carried out as part of the software cycle. The flow computer incorporates self-checking features and detected failures are brought to the attention of the user via the alarm management system.

The inputs and outputs of such a flow computer comply with industry standards to permit operation with other manufacturers' equipment.

The flow computer hardware is designed to interface with the field-mounted measuring instruments, to provide an interface with the operator, and to have the facility to pass the results of the measurement to other devices such as supervisory computers and data acquisition equipment.

Communication with supervisory computers is done over high-speed serial data links and, for integrity, dual data links are used with the cables for these links being run on different routes.

When using analogue signals from field instruments, an extremely important part of the computer is the analogue-to-digital converter. Its performance directly affects the accuracy of measurement so its resolution and accuracy must be of a high order. To maintain this accuracy the A/D converter is automatically calibrated every program cycle against stable reference voltages.

Using a well-designed and properly installed metering system with accurate field instrumentation and a flow computer as described above, a total measurement accuracy within ±1% can be obtained.

QUALITY ASSURANCE & STANDARDS

by

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TUV NEL

LECTURE No 17

PRINCIPLES AND PRACTICE OF FLOW MEASUREMENT

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CONTENTS

1 INTRODUCTION

This lecture could be described as a vocabulary lesson more than technical discussion. The terms described are used extensively in metrology and in industry and as such will be familiar to most. Being familiar is not the same as understanding or using the words and concepts correctly.

The first of the vocabulary lesson is the definition of 'calibration'. This is a word which is used loosely by everybody but now and again needs the precise definition to explain what is meant.

Calibration: Set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring system and the corresponding values realized by standards.

Note that this definition allows for the different meanings to be accommodated. Calibration is the comparison of the measurement of the same quantity between the instrument or system and a standard. The establishment of the relationship can be the production of an error figure, the definition of corrections, or indeed the adjustment of the instrument to provide agreement between the instrument and the standard.

Be under no illusion that requesting a calibration with no other information will provide the answer that is required. The nature of the 'relationship' must be specified if it is not clear.

Another word used in this context, particularly in the oil industry is 'Proving'. This does not carry a precise agreed definition. Proving is normally meant to be a calibration where the 'relationship' is a proof of conformance to a specification. This proof of conformance may involve a simple pass /fail test or a complex pass/fail and if fail, actions to be implemented which may involve further calibration and/or adjustment.

2 TRACEABILITY AND 'HARD' STANDARDS

In the definition of calibration the term 'standard' was used. This is a word used in English with two meanings. One meaning being the written standards or 'soft' standards discussed later, the second being the more pedantically named measurement standard or 'hard' standard.

A (measurement) standard is the material measure, measuring instrument or measuring system intended to define, realize, conserve or reproduce a unit or one or more values of a quantity to serve as a reference.

In the hierarchy or measurement the term standard is often prefixed by a number of qualifiers. These are given below. Clearly there is overlap between terms, differences between industries and applications, and even situations where the application or use of a system or artifact defines the type of standard it acts as for any particular purpose. As can easily be seen from the definitions below, the exceptions and variations can easily be discovered but the base definitions have been provided to avoid gross misuse of the terms.

Standard	Definition
International	Recognised internationally as the standard to assign the value of other standards
National	Defined Nationally as the standard to assign the value of other standards within the country
Primary	standard with the highest metrological quality without reference to other standards of the same quantity.
Secondary	standard established by comparison with a primary.
Reference	standard of highest quality within a location or organization
Working	standard routinely used to calibrate or check materials or instruments. Usually calibrated against reference
Transfer	standard used as intermediary to compare standards

In general what can be seen from above the hierarchy of measurement starts to become clearer. This hierarchy is normally achieved through traceability. As the term 'Traceability' has sometimes been used to cover slightly different meanings in different technologies, the definition below explains in exact terms the accepted usage of the word as it applies to National Standards:

Traceability: The property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually, national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

This ensures that that each standard or measure used for calibration purposes has itself been compared against a standard of higher quality up to the level at which the higher quality instrument is the accepted National Standard. This is usually a unique item or instrument system held in a National Standards Laboratory, but could in some cases be a local standard of equivalent quality built and operated to a national specification and confirmed as operating to that specification.

An example of the traceability of mass , and volume, is shown below.

– International Standard	• The kg in Paris
– National Standard	• Copy no 18 at NPL
– Primary Standard	• Tertiary weights at NWML
– Secondary Standard	• Working standard at NWML
– Reference Standard	• Local Trading standards Office
– Working Standard	• Inspectors weights

Figure 1

For all primary base measurements, international agreement as to the definition of the quantity and the traceability or dissemination of this quantity has been agreed.

The relevant primary base measurements of mass, length, time, and temperature used in flow work are given below. Primary measurement implies the designated or recognised standard having the highest metrological quality. This applies to the parameter being measure as well as to the fundamental base quantities.

2.1 Mass

Mass is the last base measurement which is defined as being an artifact and not a physical, reproducable physical phenomenon. This is being addressed by the National laboratories around the world and realizations in terms of electrical or molecular references are being explored. For now the ultimate primary standard of mass is the international prototype of the kilogram, a solid cylinder of platinum-iridium preserved at the International Bureau of Weights and Measures at Sévres, Paris. All standards of mass in use in the UK are derived from the secondary platinum-iridium copy (No 18) of the prototype kilogram, and kept at NPL. Other reference mass standards of platinum-iridium can be compared with copy 18 with an uncertainty of one part in 10^9 and standards of other materials such as stainless steel with an uncertainty of one part in 10^8.

Reference standard weights are held by many organisations to accuracy levels commensurate with there requirements e.g. local trading standards, NEL etc. All are traceable through comparison to NPL copy 18 of the International Standard via traceability chains shown in Figure 3.

Of more practical interest is the definitions of the quality of weights used in metrology as defined by Bureau International Poids et Measures (BIPM) and commonly used to specify weights for metrology. This is shown in the Table below.

Table 1

Nominal value g	Class E1 ± mg	Class E2 ±mg	Class F1 ±mg	Class F2 ±mg	Class M1 ±mg
50 000	25	75	250	750	2 500
10 000	5	15	50	150	500
1 000	0.5	0.15	5	15	50
100	0.05	0.06	0.5	1.5	5
10	0.020	0.030	0.2	0.6	2.0
0.1	0.005	0.015	0.1	0.3	1.0

2.2 Length

Length was initially define as being an artifact of defined length from which reference standards were defined. From King Henry's finger to thumb or the Egyptians length rods each National and finally International meter length bar was established. Within the last decade or so, stabilised lasers have provided the definition of length in terms of wavelength standards through interferometry. Since the reproducibility in wavelength of particular lasers now greatly excels that of the original krypton-86 source, a new definition of the meter was adopted by the General Conference of Weights and Measures in 1983 to replace the previously accepted definition. In this regard perhaps the concept of an International standard becomes a definition realised by National and primary standards throughout the world.

The UK standard is held by NPL and is based on the 633 nm red light helium-neon lasers stabilised by saturated absorption by iodine. When the operating conditions are specified in detail a reproducibility of wavelength of 1 part in 10^{11} can be achieved. All advanced countries have established their own standards of length and intercomparison ensures international agreement.

Traceability passes from the NPL lasers to secondary lasers to length bars to and down to the lowest levels of measurement instruments and outwards to the measurement of both long and short lengths. The quality of the instrument being chosen for both the reference and the actual application is chosen to meet the metrological need.

2.3 Time

The UK National Standard for the second, the interval of time, and for frequency is the long beam Caesium resonator developed at NPL. Again intercomparison with other similar high quality standards ensures international agreement and definition of the measure of time. Standards of frequency are disseminated from NPL by a number of comparisons but the most common through a transmitted frequency on the 200 kHz band from Rugby transmitter. Receivers of this can produce frequencies and time intervals accurate for all flow measurement purposes.

2.4 Temperature

Temperature is defined by fixed physical state changes of specific elements or compounds. Temperatures between the fixed points are defined by the resistance of platinum wire and its know change with temperature between the fixed points. In January 1990 NPL adopted a new International Temperature Scale ITS-90. This replaced the former scale of 1968 - IPTS-68. New values have been given to the fixed points of the scale to bring them closer to their true thermodynamic values.

Approximate fixed points on temperature scale.

Equilib. State	Temp °C	Equilib. State	Temp °C	Equilib. State	Temp °C
Triple pt Hydrogen	-259.3	triple pt mercury	-38.8	FP Zinc	419.5
BP Hydrogen 0.3 bar	-256.1	**triple point water**	**0.01**	FP Aluminium	660.3
BP hydrogen 1bar	-252.9	MP Gallium	29.8	FP Silver	961.8
Triple pt Neon	-258.6	FP Gallium	156.6	FP Gold	1064.2
Triple pt oxygen	-218.8	FP Indium	231.9	FP Copper	1084.6
Triple pt Argon	-189.3	FP tin	419.5		

The differences between ITS-90 and IPTS-68 are shown below as examples from a complex correction chart.

Temperature	Difference °C
-100	+ 0.01
0	0
100	-.025
200	-.04

This has given a problem as so many equations describing the behaviour of materials are based on IPTS 68 and re-definition is needed when used with thermometers calibrated to ITS 90. All calibrated thermometers will now be to ITS90, so check your equations! In general little practical difference is found but this can only be proved by checking this also ensures the correct equations can be adopted.

2.5 Derived Measurements

In terms of traceability all other measurements (except electrical) are based on the above basic parameters. Pressure, viscosity, volume etc can all be traced back to the base measures. Flow is also a derived measurement and is based on volume and time traceable to mass but corrected through temperature.

3 FLOW STANDARDS

Flow standards are very difficult to describe in the terms outlined above. Volume is a length measurement, but for most flow related applications it is realized through mass. Flow is a dynamic measure meaning that a standard is actually a system comprising the fluid, its pumping source, its temperature measurement and the final quantity measure. Added to this is the effects of temperature, fluid properties, end effects related to the collection of the volume etc.

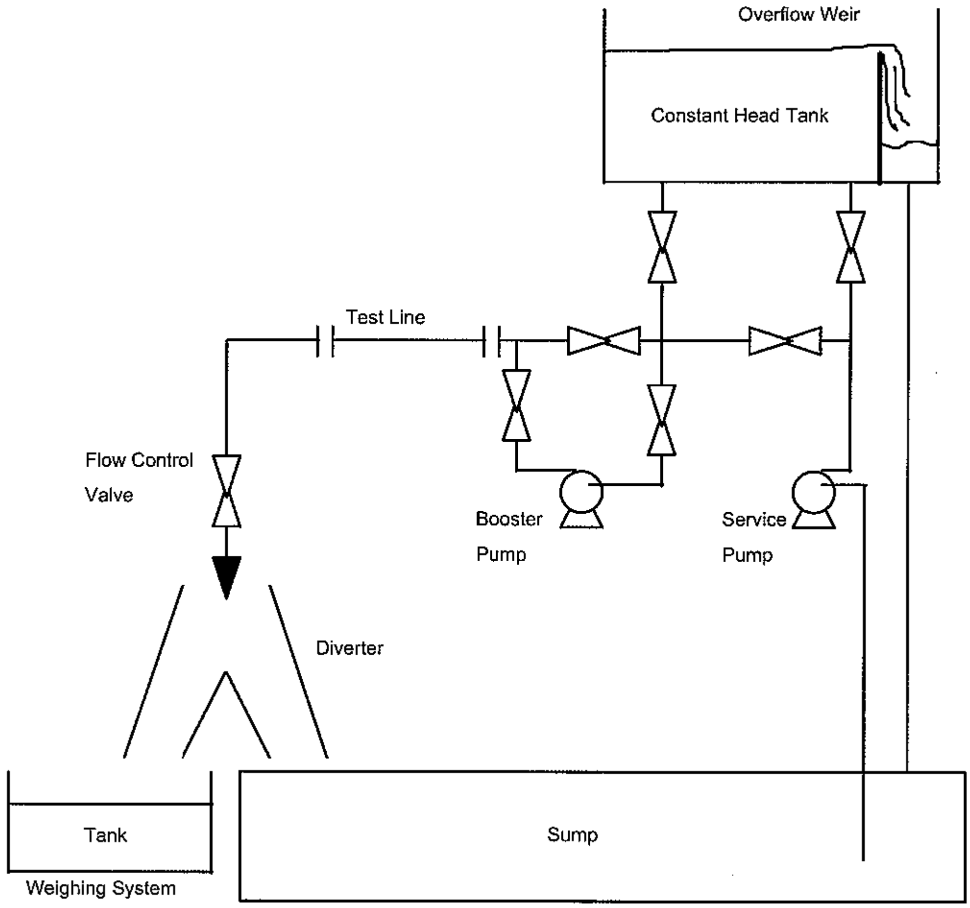
A flow measurement standard tends to be unique in that it is derived from and dependent on a combination of other more basic standards, namely, some synthesis of mass, length, time, pressure and temperature.

It may be either gravimetric or volumetric and the various forms are discussed in more detail in other lectures of this course; practical examples may be seen in water, oil or gas laboratory areas of NEL. It is not usually a device which can be easily transferred from one location to another nor, because of its size and complexity, is it something which can be kept in a glass case.

Generally speaking there are three basic elements of a gravimetric flow standard as shown diagrammatically in Figure 2.

The basic elements are:

- a flow source,
- a collecting device, and
- a measuring system.



Basic Elements of a Flow Standard

Figure 2

The procedures specific to the design, construction and performance proving of such a system are covered in the rest of the NEL Flow Course.

3.1 Transfer Standard Flowmeter Packages

Transfer standard flowmeter packages are the means used to compare the flow measurement accuracy of different calibration laboratories or to relate the performance of a meter in an industrial or commercial application to a recognised calibration standard. The word 'package' is used advisedly since the transfer device must consist of the flowmeter itself together with sufficient lengths of upstream and downstream pipework and perhaps a flow straightener, since it is made clear from other lectures of this course that the pipework adjacent to the meter can affect to a measurable extent the calibration factor of that meter. For the period of the transfer exercise the package should be maintained as a single construction, i.e. it should not be dismantled into its component parts since re-assembly could result in a different package through, for example, a 'rougher' section of pipe being placed adjacent to an orifice plate pressure tapping when compared with the first set-up.

A commonly adopted procedure to further ensure the integrity of the device is to calibrate it against a nationally recognised flow standard both before and after it is used to calibrate the remote unit. In a series of round-robin tests spanning a period of many months and embracing several laboratories it may be advisable to bring in the master check of the transfer standard at intermediate intervals also.

A number of important requirements must be met in a satisfactory transfer standard flowmeter package. Among these are that it should:

- have a highly repeatable meter characteristic,
- have a wide flow range,
- be insensitive to installation conditions,
- be simple, robust and easily transportable,
- be capable of compact installation,
- have a low head loss,
- be suitable for use in a variety of fluids, and
- be available in a wide range of sizes.

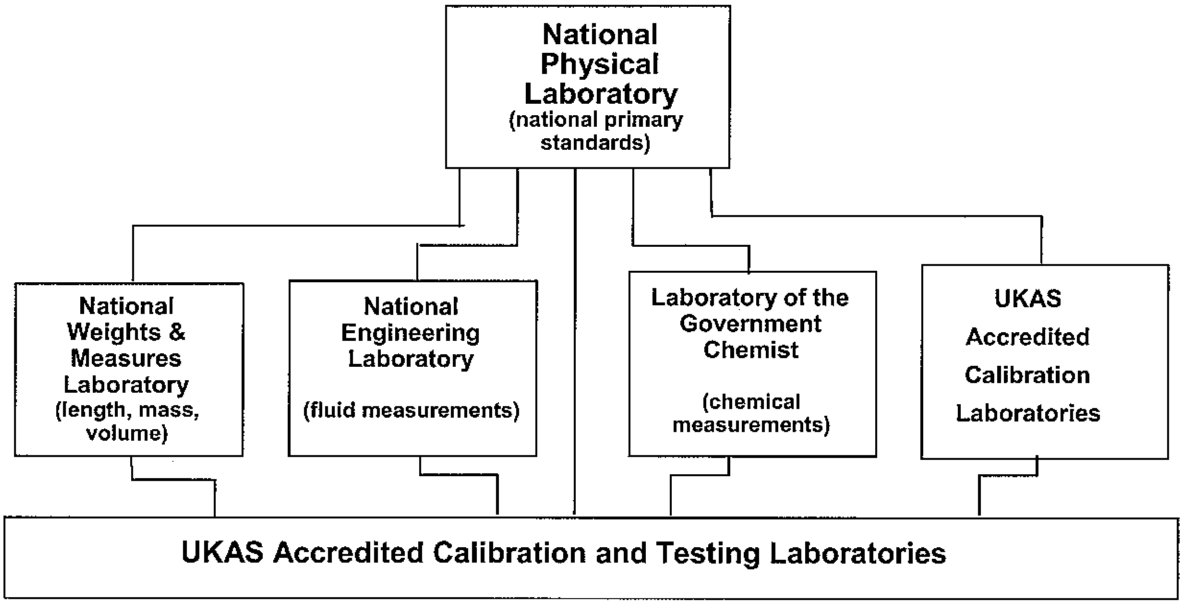
In the context of UKAS (United Kingdom Accreditation Service) especially, the term 'audit package' is often applied to the transfer unit. This is because it is being used to authenticate, by application under examination, the measurements or measurement capability of the equipment subject to inspection. In flow measurement the concept of dynamic testing of the transfer device is most important.

Studies of transfer standard flowmeters at NEL, and elsewhere, over the years have shown that no single flowmeter type would be suitable as the basis of a transfer standard package in all situations. The essential features of each case must be assessed in arriving at a decision on the method which the majority would regard as acceptable. On occasion, it may be shown that the intercomparison may best be achieved by using a combination of meters, e.g. a twin turbine meter package or an assembly comprising generically different meter types.

4 NATIONAL MEASUREMENT SYSTEM (NMS)

Within every modern state there exists a National Measurement System. Without such a system internal and external trade and manufacture could not function. It is function of the National Measurement system to establish the measurement standards to which reference and working standards within the country are traceable and ensure these standards can be recognized internationally. It is also the purpose of the NNS to encourage and impose good measurement practice as required and to provide the infrastructure to support this.

In UK the NMS is the responsibility of DTI and is delivered through a network of National laboratories, academic institutes and industrial establishments. The structure is shown below.



Within UK support is given to some 20 programmes of work. This covers length, temperature, pressure, radiation chemical, trade standards etc. Flow is one of these programmes. NEL provides the recognized National Standard for Flow measurement through the provision of the widest range of standards and expertise in flow. Although also providing a number of the best metrological standards this is by no means true for all flow conditions. Across limited ranges, specialist applications and single fluids, metrologically superior standards can and are in existence, these can not be supported by the NMS directly as they fill a specialist niche.

4.1 International

Two organizations exist to allow co-ordination of metrology. CIPM/BIPM are subtle differences in the international organisation set up to maintain the best practice and definition of international metrological standards. Primarily geared up to work with the base measurements and units, they are slowly expanding to bring in some other measures such as pressure. Flow will have a working committee perhaps next year but clearly this is reaching the periphery of the remit as flow standards are quite removed from base standards.

EUROMET however is a different organisation. Within Europe, but wider than the EU, EUROMET is an agreement between Standards laboratories on cooperation through sharing of facilities, knowledge and research to improve the acceptability of standards and to improve efficiency by reducing individual state provision of very expensive and underused standards. It also provides links to similar groupings in America and the far east. The flow group has co-operated particularly through intercomparisons, exchange of best practice methodology, and identification of measurement problems.

5 ACCREDITATION

Accreditation is the process in which a third party inspects and approves a calibration or test laboratory to ensure it meets its stated capability for the measurements it offers. UK has led in the provision of a National accreditation service for calibration and testing. The body responsible for granting this accreditation was originally BCS for calibration laboratories and NATLAS for testing the testing laboratories. These merged to form NAMAS (National Accreditation for Measurement and Sampling) and now have undergone a further merger with NACCB, (Accreditation of companies providing accreditation and certification services) to form UKAS.

UKAS (United Kingdom Accreditation Service) is a private sector company limited by guarantee and is licensed by the UK Government to use and the already familiar NACCB and NAMAS logos subject to strict compliance with DTI rules.

The process of providing accreditation of calibration laboratories has rapidly been adopted by most countries in the world. UKAS provides for the inspection and accreditation of organisations carrying out calibration or test work and it ensures that the technical competence, facilities, traceability and quality control comply with acceptable standards. Presently the standards are UKAS guides which are equivalent to ISO/IEC guide 25 and EN45001 with the introduction of ISO 17025 UKAS accreditation will now be granted against compliance with this new standard.

Accreditation by UKAS is voluntary and is open to any organisation performing objective calibrations and tests and which meets the specific assessment criteria. Its remit includes not only independent commercial calibration laboratories and test houses, but also laboratories which form part of a larger organisation such as a manufacturing company, an educational establishment or a government department. Equipment manufacturers enrolled in the scheme may provide services to all comers or only to their parent company.

UKAS assesses, accredits and monitors organisations, which, subject to stringent requirements are authorised to issue formal certificates and reports for specific types of measurements and tests. The key aim of accreditation is in providing a means of improving the quality and competitiveness of industry.

It should be noted that UKAS is a quality assurance accreditation which demonstrates that the provider has been inspected to ensure the service complies with the relevant specifications and conditions. Traceability to UKAS is impossible: UKAS holds no standards. UKAS accreditation ensures that traceability to National Standards has been proved, within the accreditation process.

In this way UKAS accreditation is additional to ISO 9000. UKAS (calibration or testing) accreditation adds strict compliance to technical requirements.

The international impact of UKAS is ever widening. Mutual recognition agreements on either the calibration or testing roles, or both, are in existence with the equivalent certification bodies in many other countries including - Australia, Finland, Germany, Italy, Sweden, Singapore and The Netherlands. This is co-ordinated by EAL for greater Europe with links to similar groupings in America and the Far East. To allow access to European markets UKAS has accredited numbers of laboratories outwith Europe where mutual recognition is not yet in place.

6 CERTIFICATION

This is another term badly used. Certification is the process by which a company, product or instrument is certified as complying with, or calibrated to, a specified standard by a third party. This implies that the process or product has been inspected and deemed to meet the requirements of the relevant standard or specification. It is sometimes difficult to tell if certification has been carried out. Items carrying the TÜV mark will have had the process of production certified. Items CE marked will not necessarily have been certified as not always is third party involvement required. CE mark indicates that the supplier confirms the item complies with the relevant directive(s). Some directives do require third party certification but many do not.

A flowmeter may carry a certificate of calibration. This states that the flowmeter has been calibrated to the stated method and given result. This may be provided by an accredited laboratory or not. An instrument calibration refers to the results at the time of calibration and the conditions of calibration only!

7 'SOFT' STANDARDS

Where the previous section covered the instruments and artifacts which carry out high quality measurements and are therefore called standards, this section examines the paper specifications or instructions which comprise 'soft' standards.

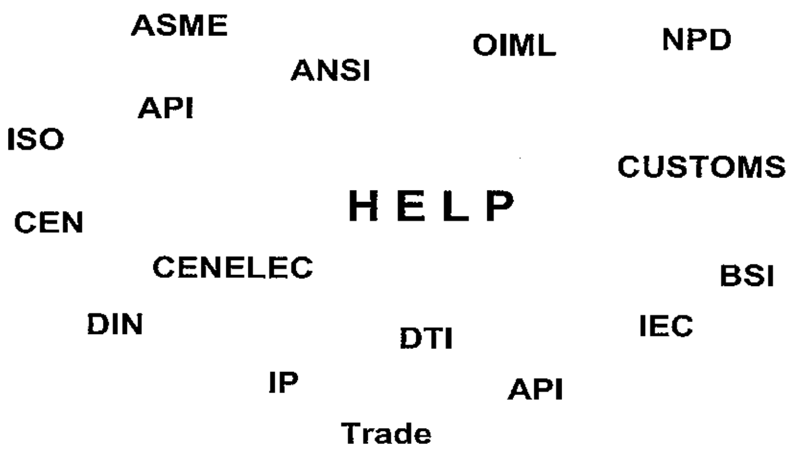


Figure 3

What is a standard? For this we assume a standard will cover regulations, standards, recommendations and a variety of other documents which may apply in the use of measurements.

Every advanced country has established a standards body tasked with producing written standards which ensure the quality of goods or activities, the minimum acceptable standard and advice or instruction on how to obtain this state. British Standards Institute (BSI) in UK, DIN in Germany and ANSI in US are examples of standards bodies. All produce standards for use in their own country which can give guidance, instruction or specification for a measuring systems. To harmonise this activity, the International Standards Organisation (ISO)' was formed to produce Internationally agreed standards of a similar nature. Commonly now BSI will adopt an ISO standard as a British Standard (BS) ensuring speed of implementation and international agreement. If the ISO standard is not accepted within UK practice, a BS forward can be added outlining changes, or a separate BS produced.

ISO standards can be in many forms. In the petroleum industry (TC28) the standards are strict, with performance and acceptability criteria applied. In the more general flow field under TC30 they are more guidance documents to best practice, design and expectation.

To ensure European harmonisation CEN standards are produced and these mirror the ISO/BSI situation with some being dual or even triple accepted while others remain purely CEN alone. CEN standards do however hold a particular status as they can be held up as the only acceptable standard to be met when a European directive is involved.

Legal metrology holds its own set of standards. For trade use each country establishes legal provisions for measurement. These provisions are governed by legislation and associated specifications. To harmonise legislation throughout the world, OIML was formed to provide the best practice internationally. OIML recommendations are not standards, but specifications which have to be met and adopted within National legislation to comply with the legal requirements of each specific country. In some cases these national laws are being superceded by EU directives. Some OIML recommendations also exceed their remit and include much standards content rather than just legal requirements.

Particular industries, usually Nationally based, also produce standards for use and produced by recognised professional institutes. For the petroleum industry the IP in UK and the API in the US produce standards for measurement which are frequently better focussed than their ISO equivalents and have equal merit and reputation but do tend to reflect local practice. Often these documents are used to produce an equivalent ISO. Other bodies such as ASME also produce standards which are applicable in their own field. All this leads to a minefield of documents on specific topics which can give rise to confusion.