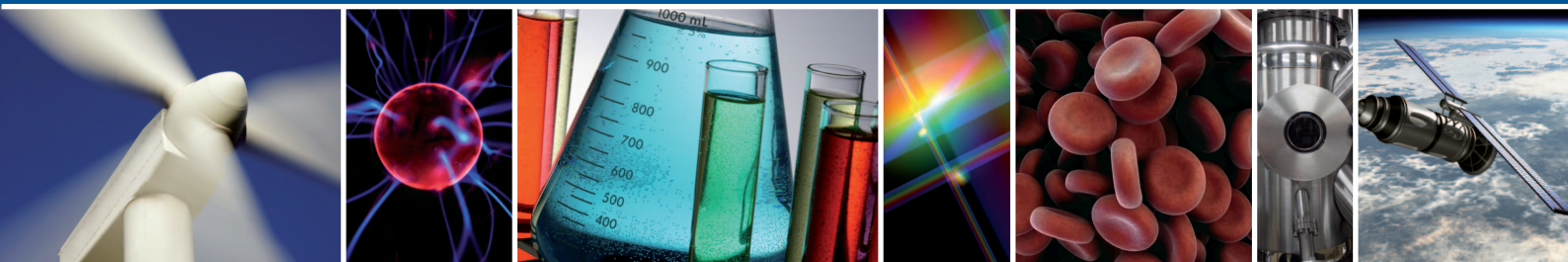


National Measurement System



GOOD PRACTICE GUIDE

THE CALIBRATION OF FLOW METERS

This good practice guide covers the general principles of calibration when applied to the flow meters or devices to measure flowing fluids, including gas. It provides an overview of methods used in a variety of situations from calibrations in standards laboratories to those in the field, including flow meter verification in a non-laboratory situation. The guide is aimed at operators of calibration facilities, users requesting calibrations and engineers having to establish a calibration method.

Contents

Summary		
1	Introduction	2
2	What is Calibration?	2
2.1	Calibration	2
2.2	Rate, quantity and time	4
2.3	Repeatability and reproducibility	5
2.4	Resolution	6
3	The Importance of Calibration Fluid and Conditions	6
3.1	Fluid properties	6
3.2	Flow profile	7
3.3	Traceability, accuracy and uncertainty	7
3.4	Accreditation	9
3.5	Reporting the result – performance indicators	9
3.6	Calibration frequency or how often should a flow meter be calibrated?	12
4	Calibration Methods for Liquids	12
4.1	Liquid collection methods	13
4.1.1	Standing start and stop method	13
4.1.2	Flying start and finish	14
4.1.3	Dynamic collection methods	15
4.2	Measurement methods	15
4.2.1	Gravimetric calibrators	15
4.2.2	Volumetric calibrators	16
4.3	Pipe provers	18
4.3.1	Uni-directional sphere prover	19
4.3.2	Bi-directional sphere prover	20
4.3.3	Piston provers	20
4.3.4	Small volume provers	20
4.3.5	Pulse interpolation	21
4.3.6	Operation and calibration of a prover	22
5	Calibration Methods for Gas Flow Meters	23
5.1	Displacement methods	23
5.1.1	Mercury seal prover	24
5.1.2	Soap film burette	24
5.1.3	Bell provers	24
5.2	Gravimetric / pressure, volume and temperature methods	25
5.3	Gas displacement method	26
5.4	Critical flow Venturi-nozzle (sonic nozzle)	26
6	Other Calibration and Verification Methods	27
6.1	Reference meters	27
6.2	On-site verification methods	28
6.2.1	Tracer methods	28
6.2.2	Insertion meters	29
6.2.3	Clamp-on ultrasonic meters	30
6.3	Unusual volume methods	30
7	Expectations for a Calibration	31
8	Bibliography	32
	Addendum – Client calibration check list	33



1 Introduction

This good practice guide has been prepared to give an overview of the general principles of calibration for flow measurement. It provides a summary of calibration methods available across a variety of locations and applications and is designed to outline all the basic principles which can be applied to high accuracy calibrations in laboratory and field applications. The guide also addresses less accurate calibrations or 'verifications' in difficult situations. This document has been produced to address the needs of calibration laboratories and institutes, users of flow meters, and engineers having to establish calibration and verification methods.

The guide first covers general principles of calibration when applied to devices for measuring flowing fluids (flow meters). It then addresses a variety of individual techniques and methods which may be employed as standards and methods of calibration.

Many of the principles of calibration apply equally across metrology and this guide re-iterates these principles and puts them in the context of flow calibrations. Vocabulary is important to the understanding of the principles and the key definitions of terms have been reproduced from the 'International Vocabulary of Metrology — Basic and general concepts and associated terms' (VIM) 2008, and this is freely available from the BIPM web site. (BIPM is the international body responsible for harmonisation of metrology and the SI). Where appropriate the older definitions from the previous version of VIM (1995) have been used in instances where the older version provides a clearer definition than the latest version. Establishing the correct terminology is important to provide a clear understanding of what is meant when various terms are used in defining a calibration.

2 What is Calibration?

Calibration embraces a number of operations, systems and concepts. This is best explained in a series of descriptions.

2.1 Calibration

The formal definition of 'calibration' taken from the VIM is given below. What has to be done now is to examine how this applies to flow measurement.

Calibration is a comparison between the reading of a device and that of a standard. The process which establishes this relationship is a set of interrelated measurements and operations which provide the comparison. Flow measurement does not rely on a single operation and so neither does a flow based calibration.

Measurement of the quantity of fluid depends on establishing the basic quantity and a number of influence factors. The quantity of fluid may be expressed as a volume or a mass. The measurand may be the quantity or the 'rate' i.e. the quantity per unit time.

Calibration:

operation that, under specified conditions establishes a relation between the quantity values (with measurement uncertainties) provided by measurement standards and corresponding indications (with associated measurement uncertainties)

uses this information to establish a relation for obtaining a measurement result from an indication. VIM 2008 - (2.39)

2.1 Calibration cont.

The quantity measured by the standard may be different from the quantity passed through the test device due to changes in volume or even mass between the meter and the standard. Changes are usually related to the influence factors such as temperature, pressure, viscosity and expansion. This combination of fluid, influence factors, the standard and the device come together to define a set of operations which to provide the calibration.

As the fluid and influence factors all affect the meter performance, the calibration is carried out 'under specified conditions' and these must be defined.

A calibration is not an absolute operation. It is a comparison between the measuring instrument, in this case the device under test or flow meter, and the standard. Through this comparison, a relationship between the quantity measured by the device under test and the measurement of the same quantity derived from the standard is established. This is expressed in some way which gives a meaningful expectation of how the device will perform in use.

Calibration:

the set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system and the corresponding values realised by standards. VIM 1995; (6.11)

The current definition in the VIM, although being more precise, seems to lack some of the clarity of the older definition, and so the older alternative has also been given for reference. Later in this guide the use of 'proving' and 'verification', terms used to describe particular types of calibration will be described.

The comparison during a calibration is against a standard.

The standard comprises the system of pumps, pipes, fluids, instrumentation, quantity reference measurement, calculations and operators. These all combined provide a measure of the quantity of fluid passing through the device or flow meter being calibrated.

Standard:

realization of the definition of a given quantity, with stated quantity value and associated measurement uncertainty, used as a reference. VIM 2008 (5.1)

Or

measuring instrument or measuring system intended to realise or reproduce a unit or one or more values of a quantity to serve as a reference. VIM 1995 (6.1)

The measurement of fluid flow is dynamic and all measurement devices are affected in some way by the conditions of use. It will be impossible to have a standard which fully reproduces the conditions under which the meter will be used in practice. Flow devices are affected by temperature, viscosity, flow profile, flow rate fluctuations and pulsations. They are also affected by the external environment, vibration, stress and temperature etc. Different devices are affected in different ways. Similarly the standard will also be susceptible to these same influences.

Since a calibration is a comparison between the measurement made by the device under test and that realised by the standard, the resultant relationship will be for the specified conditions; therefore a further assessment of the relevance to the final application must be carried out. Selecting the standard will be a compromise to best replicate the conditions of use while providing a suitable reference standard measurement. The standard must also be compatible with the performance and characteristics of the meter to be tested and the result desired.



2.1 Calibration cont.

The extent to which a flow measurement device is affected by the conditions of use is most often a function of the flowrate. It is therefore important that calibration takes place across a range of flowrates to establish this relationship.

2.2 Rate, quantity and time

The mechanism by which a flow measurement device gives a reading of flow is dynamic. The sensor reacts to the flow of fluid through it or past it to realise an output related to the flowrate or the quantity passing.

Measurement of flowrate and quantity are related through the time interval across which the quantity is measured. In practice the end user of the device has different expectations for the behaviour and hence the calibration. In establishing this relationship it is vital to relate the response time of the device to the calibration method. Again the current and older generic definitions of response times are given.

The interpretation of response time is reasonably straightforward for mechanical meters. The mechanical interface between the fluid and the indicator can be explained and defined in terms of momentum and drag affecting the meter when the flow changes. With the advent of electronics this has become more difficult to establish. For example, a positive displacement meter in liquid responds very quickly to changes in flowrate even very abrupt changes; the flow stops, the rotor stops and the register stops. If a pulse generator is fitted, the generated pulses stop when the flow stops. A frequency counter will not reflect this until it completes its measurement cycle which may be some seconds later. During that time, a totaliser or register will correctly indicate quantity, but the flowrate indicator will not be showing the correct (instantaneous) flowrate. If however the mechanism in the meter has play or is loose, stopping the rotor may allow the output register to 'run on' after the rotor stops hence generating additional quantity or pulses.

(Step) Response time:-

duration between the instant when an input quantity value of a measuring instrument or measuring system is subjected to an abrupt change between two specified constant quantity values and the instant when a corresponding indication settles within specified limits around its final steady value: VIM 2008 (4.23)

Or

time interval between the instant when a stimulus is subjected to a specific abrupt change and the instant when the response reaches and remains within specified limits around its steady value. VIM 1995 (5.17)

A different type of meter may of course not respond to an immediate change in flow. A turbine rotor will have significant momentum and, although speeding up quickly, may take time to slow down when subjected to a change in flow, particularly in gas measurement. Meters based on non-mechanical sensing techniques e.g. electro-magnetic, Coriolis or ultrasonic meters, have different response characteristics. For example, an electromagnetic meter may take some time to establish and measure a change in the generated voltage after a change in flow, while an ultrasonic meter output is the average of a number of measurement cycles and this averaging may take appreciable time to complete.

Most meters based on non mechanical sensing, and some mechanical meters, have a microprocessor which calculates the output quantity from the sensor signal. For some meter types this is an additional capability while others require this processing to convert the sensor signal and correct for influence factors before calculating and generating an output signal. The output signal can be a pulse frequency or a current (mA) output generated from this calculation process.

2.2 Rate, quantity and time cont.

A digital display may be added to show the required output value and many modern meters have digital outputs to transmit the chosen measurement(s) to a remote readout or computer. All these outputs will have a different response times delaying the raw sensor response by the signal processing and calculation time.

An example of a processed output signal comes from a vortex meter with a signal processor designed to smooth any pulses missed by the sensor and to increase the resolution of the output. Such a device may have output response times of many seconds even though the sensor itself has responded in under a second.

Modern flow meter types such as Coriolis, electromagnetic, or ultrasonic meters are totally dependent on microprocessor based output, and the variety of settings to average, damp or cut-off low flowrates must be understood and selected to ensure the response time matches the limitations of a calibration method. Matching the response time of a device to the chosen calibration method is a vital part of the process. If the device response time does not match the time within which a calibration test point is taken, poor repeatability or calibration offsets may be observed. This response time may however be perfectly adequate or even advantageous when the meter is in service.

2.3 Repeatability and reproducibility

To obtain confidence in a measurement it is expected that the measurement should be able to be repeated and give the same result. In practice measurements only repeat to within a certain band over a short time and a (probably) wider band over a long time period or under different circumstances. It is generally expected that a calibration should give some indication of the repeatability of an instrument; however it is not likely that one calibration will show the reproducibility. Repeated calibration may of course be carried out perhaps over many years to show this parameter.

Repeatability:

measurement precision under a set of repeatability conditions of measurement
VIM 2008 (2.21)

Reproducibility:

measurement precision under reproducibility conditions of measurement
VIM 2008 (2.25)

A measurement standard should have determined repeatability and reproducibility figures which will have been included in the uncertainty determination. The repeatability of a calibration will of course include the repeatability of the standard, but also the repeatability of the device under test. A large part of the repeatability will be the resolution of both the device and the standard.

It is interesting to note that a device or flow meter may be believed to have better repeatability than that of the standard. This belief is based on history, behaviour in other calibrations and service etc. The repeatability cannot however be proved to be better as it can only be demonstrated through repeated calibrations against the standard.

2.4 Resolution

Although it may seem obvious, the resolution of the device must be adequate to allow a calibration to match the uncertainty required. To achieve this, the standard must be able to measure enough fluid to match the resolution of the device. For example if a flow meter has a resolution of 1 litre, the standard must have a volume of significantly more than 1,000 litres to achieve an uncertainty of 0.1%. To meet oil industry norms, a volume of 10,000 litres would be expected to ensure an achievable uncertainty of 0.01%. The requirement for resolution

to be assessed applies equally to meters with pulsed analogue and digital outputs. For analogue meters the effect of sampling and averaging has to be considered along with the resolution of the instruments being used in the standard. For electronic pulsed or digital outputs it is possible to increase the resolution for calibration purposes. Care has to be taken however that an artificially high resolution is not applied, by mechanical or electronic increase, which is not representative of the sensor performance.

Resolution:

smallest change in a quantity being measured that causes a perceptible change in the corresponding indication.

VIM 2003 (4.14)

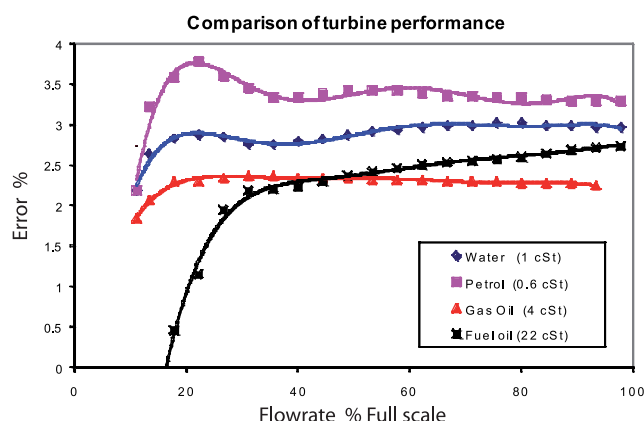
3 The Importance of Calibration Fluid and Conditions

3.1 Fluid properties

All flow meters interact in some way with the flowing fluid. The nature of this interaction is affected by the properties of the fluid or the velocity distribution of the fluid passing through the device. Changes in this interaction alter the ability of the device to give an accurate representation of the quantity. The magnitude of the error is different for different meter types and fluids.

For this reason it is desirable to calibrate using the same fluid and pipework configuration within which the meter will normally operate. This is clearly not often possible; the meter has to be installed in a test laboratory, or calibration standard has to be installed in the process application. In either case some degree of disturbance to the meter is inevitable. The best economic compromise must be established in choosing the calibration. This will be based on the final duty of the meter, the required uncertainty and knowledge of the meter performance. For some meters, for example orifice plates, the performance can be related to Reynolds number. This allows a calibration to be carried out in a fluid different to the meter's operating fluid. The relationship may even allow a liquid calibration to be applied to a meter for a gas duty by matching Reynolds numbers.

For other meter types, such as turbine meters, the choice of calibration fluid is particularly important. Turbine meters are viscosity sensitive, and the figure opposite shows some typical calibration results from a turbine meter using water and three petroleum products. Because of this sensitivity to viscosity it is important to calibrate these meters using a fluid as close to the viscosity of working fluid as is practicable. For this reason, among others, fiscal meters for oil are often calibrated on site using a dedicated pipe prover.



3.1 Fluid properties cont.

For gas meters, air is often used as the calibration fluid for safety reasons. When used with other gases the performance related to Reynolds number provides a good relationship for turbine and ultrasonic meters. Coriolis, and positive displacement meters do not follow this relationship. For variable area meters it is important to correct the gas density to a standard condition to match the scale. Gas pressure is probably the most important influence factor as this affects the density and hence many aspects of a meter performance.

Properties of the fluid such as density, temperature, conductivity, pressure may also have to be considered when replicating the use of the meter in a calibration.

3.2 Flow profile

When a fluid passes through a pipe, the distribution of velocity across the pipe alters to approach a 'fully developed' profile which is dependant on the pipe internal diameter, roughness and fluid Reynolds number. The presence of any change from a straight pipe will alter the profile drastically. Bends, double bends, valves etc. all introduce asymmetry to the velocity distribution and some introduce swirl or rotation. As the way the fluid interacts with the sensor can be highly dependant on the velocity profile, these effects must be considered in the calibration. Most calibration facilities allow adequate straight pipe lengths and the use of flow conditioners to establish predictable and reproducible flow profiles close to an ideal profile. It should be noted however that care has to be taken to ensure pipes upstream of the meter have the same internal diameter as the meter inlet and step changes or misalignment of joints and gaskets do not introduce irregular profiles.

3.3 Traceability, accuracy and uncertainty

Since a calibration is a comparison between the reading taken from a device under test and that of a standard, it is necessary to consider what properties are required from a standard. Firstly and most importantly, the standard should measure the same quantity as the device. There is little value in comparing a mass meter output with that of a volume tank without a measure of density to allow conversion between mass and volume. For flow measurement, the standard is a system comprising of a measure of quantity and the subsidiary measurements to determine the fluid conditions, properties and influence factors.

Another feature of the standard is that there must be confidence that the measurement taken by the standard is accurate. To achieve this all the measurements in the system have to show traceability to higher level measurements and ultimately to National and International standards.

The definition of traceability provided expresses the process by which a measurement can be related through an unbroken chain of comparisons to national/international standards. It must be noted that each step of the chain will have an uncertainty becoming smaller at each step. It must be noted that providing or claiming traceability alone makes no statement regarding the quality or uncertainty of the result; this requires an uncertainty value. Traceability must also be through comparisons to other/better calibrations and **NOT TO** an accreditation body.

Traceability:

property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty
VIM 2008 (2.41)



3.3 Traceability, accuracy and uncertainty cont.

It is contentious to use the term 'accuracy' in relation to calibration work. Accuracy has not the rigour or precision required to describe a scientific process. In practice however 'accuracy', when used correctly, is the term to which users relate and can usefully be used to express expectation and general specification. Accuracy is a qualitative term and therefore the number associated with it should be used for indicative purposes.

Accuracy:

Closeness of the agreement between the result of a measurement and a true value of the measurand
VIM 1995 (3.5)

To correctly express the 'accuracy' of a standard or a calibration the 'uncertainty' must be determined and quoted. Uncertainty provides confidence that the determination of the value lies within the stated value. For flow measurement the confidence in the result lying within the uncertainty is normally quoted with a 'coverage factor' of $k=2$, which is approximately 95% confidence level. A full explanation is given in the Guide to Measurement of Uncertainty (GUM) or ISO 5168.

Uncertainty:-

non-negative parameter characterizing the dispersion of the **quantity values** being attributed to a **measurand**, based on the information used
VIM 2008 (2.26)

Every standard must be assessed for the uncertainty in the determination of its measured quantity, as indeed must the result of a calibration.

Note this is slightly different wording from both VIM 1995 and the GUM

The uncertainty quoted for a calibration or a standard will be estimated from a detailed examination of all the components within the system, the use of the system and its history. It will specifically state for what parameter the uncertainty applies to. This parameter may be the quantity measured by the standard or the quantity passed through the device under test. The latter is the uncertainty which is needed initially. It is stressed this is not the uncertainty of the calibration result. The resolution of the meter, the influence factors and finally the repeatability and linearity of the calibration results must all be included to provide the uncertainty of the calibration.

The purpose of a calibration is to estimate the uncertainty associated with measurements from the meter in its final application. It is clear that the calibration will only provide a component of this final measurement uncertainty. A responsibility remains with the end user to use the calibration uncertainty along with an understanding of the use of the meter compared with the calibration conditions to provide this final result.

All calibration results should have a stated uncertainty and this should be stated clearly on the calibration report or certificate. The uncertainty statement should be clear and unambiguous as to what is included and which quantity it refers to. Uncertainty can be expressed on the certificate as being the uncertainty of the measured quantity (flow, volume or mass), or uncertainty of the device under test during calibration.

An equation fitted to the data, if provided, should also have a stated uncertainty estimated. The uncertainty will not include 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.

It is also worth noting that uncertainty may vary across the flow range of the meter. The quantity of fluid collected by the standard may contribute to different uncertainties, or the meter performance may vary.

3.3 Traceability, accuracy and uncertainty cont.

In specifying the required uncertainty of a standard relative to that of a meter, it is good practice that the standard should have an uncertainty 10 times smaller than that of the requirement of device to be calibrated. Although this is a good principle, in flow measurement it is often not possible to achieve due to the high expectations of flow meters and the applications for them. A standard with an uncertainty of a factor of three lower than the requirement of the application is often all that can be achieved.

In some situations, especially in field testing, the uncertainty of the standard may be higher than the expected uncertainty of the meter. This applies when some methods of in-situ calibrations are called for. When this occurs the achieved uncertainty of the 'calibration' must be larger than that of the standard, hence increasing the uncertainty of the final measurement.

When this situation is encountered, 'verification' rather than a calibration is often specified. The result is used to provide increased confidence that the meter is operating correctly but not used to make corrections to the meter or as the primary assessment of its uncertainty.

Verification:

provision of objective evidence that a given item fulfils specified requirements.

VIM 2008 (2.44)

It is to be noted that uncertainty should not be confused with error.

Error expresses how far away from the 'true' value the reading is; however, this value may be known to have a much smaller uncertainty. Knowing the error may allow a correction to be made to the reading.

3.4 Accreditation

Accreditation is the process that a calibration laboratory or service provider undergoes to give confidence that the result provided to a client meets the expectation stated in the scope of the work. It is a process by which the equipment, technical methods, contractual arrangements, and quality of the results are examined to give confidence to the client in the delivery of the service. A third party, or indeed the client, accredits and organisation hence giving confidence in future works without individual inspection. This process ensures that traceability has been established, an uncertainty budget produced, and procedures are sound.

To avoid multiple client accreditations, and to provide commonality, accreditation is provided by a National accreditation body and subject to meeting international agreement on the standards for inspection. Most developed countries have their own accreditation body and it is now recommended that only one body should be appointed in each country. In UK the body is the United Kingdom Accreditation Service (UKAS).

3.5 Reporting the result – performance indicators

To display the result of a calibration, the nature of the meter output has to be understood. Flow meters may indicate flowrate or quantity in a number of different ways. There may be a mechanical or electronic display indicating quantity or flowrate, or an electronic output based on pulses, frequency or current (mA). The output may be in the form of a differential pressure.



3.5 Reporting the result – performance indicators cont.

Where the output or display is based on the 'rate' measurement (i.e. frequency, flowrate, differential pressure or mA), readings normally vary a little during a calibration test point. It is normal to average the readings taken at a controlled sample rate across each calibration determination.

If the output is based on quantity passed (i.e. total pulses or display of quantity) the reading of the display has to be compared with a quantity of fluid measured by the standard. If the display is a visual one, clearly the flow has to be stopped to read the display unless some form of photographic reading triggered from the calibration process is used. If the output is electrical, electronic gating can coincide with a trigger signal from the standard.

Where electronic digital outputs such as serial or 'field bus' data transfer is used, rate measurements can be sampled or quantity can be read at the end of the calibration period. This type of output cannot normally be triggered electronically to synchronise with a calibration standard, therefore extreme care must be taken to recognise update and processing times if a 'dynamic' calibration method is used.

The result of a calibration is normally given in tabular form listing the measurements from the standard and the device. Information on the influence factors and the amount of raw data given will vary depending on the calibration specification.

The presentation of meter and standard readings is not the most helpful to interpret the result of the calibration. It is therefore normal to calculate a performance indicator. A performance indicator can be used to display the result in a way which best displays the performance of the meter across the flow range. It will also allow the determination of a quantity when the meter is used in practice.

A number of different performance indicators are commonly used.

K-factor Used for meters with pulsed outputs proportional to quantity passed. K-factor is expressed as pulses per unit quantity (e.g. pulses per m³ or pulses per kg)

Meter factor The generic definition is 'correction factor' in the VIM but in the flow meter industry the term 'meter factor' is used. The meter factor is normally dimensionless and is calculated as the ratio of the meter output to value determined by the standard. This can be computed from rate measurements or quantity measurements. Units should be the same.

Correction Factor:

numerical factor by which the uncorrected result of a measurement is multiplied to compensate for (systematic) error
VIM1995 (3.16)

$$\text{e.g. } F = \frac{Q_s}{Q_i} \quad \text{or} \quad F = \frac{V_s}{V_i}$$

Where F is the meter factor; Q is flowrate; V is volume; i is indicated by the device and s is the measured value from the standard.

As with the K-factor, this is the number which the output is multiplied to give the 'true' reading.

3.5 Reporting the result – performance indicators cont.

Error : Error is the difference between the indicated value and the value determined by the standard. **Relative error** is the error divided by the value determined by the standard and is normally expressed as a percentage.

$$E = \frac{Q_i - Q_s}{Q_s} \times 100 \text{ percent}$$

It is important to always define this equation in a calibration report as some industries use a different convention. This is best described as the inverse or negative error and this is based on the standard minus the indicated value.

Error can also be defined for meters with electrical outputs of pulses, frequency, volts or mA. In this case the indicated value is calculated from the output reading and the predetermined relationship (normally linear) between the output value and the equivalent quantity or flowrate.

Error:

measured quantity value minus a reference quantity value.

VIM 2008 (2.16)

Relative error:

error divided by a true value of the measurand

VIM 1995 (3.12)

An example is if a meter is configured to provide 20 mA = 10 l/s and 4 mA = 0 l/s. The value of Q_{ind} would be the flowrate calculated from the measured current and the linear relationship derived from the maximum and minimum settings.

Discharge coefficient: For differential-pressure meters, such as orifice plates and nozzles, the performance indicator used is the discharge coefficient (C). This is effectively an expression of the ratio of the actual flow to the theoretical flow. The theoretical flow is however, defined in terms of the diameter of the throat of the device. C is given by the formula:

$$C = \frac{q_m \sqrt{1 - \beta^4}}{\frac{\pi}{4} d^2 \epsilon \sqrt{2 \Delta p \rho_1}}$$

Where:

d is throat diameter (m)

β is ratio of throat diameter to pipe diameter - d/D
(D being the internal pipe diameter)

Δp is measured differential pressure (bar)

ρ is density (kg/m³)

q_m is the mass flow rate (kg/s)

ϵ is the expansibility [expansion] factor.

The coefficient ϵ is used to take into account the compressibility of the fluid. For incompressible fluids (liquids) $\epsilon = 1$; for compressible fluids (gas) the value for ϵ is calculated from formulae based on the properties of the fluids.

The numerical value of C will commonly vary depending on the device. Typical orifice plates have a C value of around 0.6 and nozzles between 0.9 and 1. Discharge coefficient is relatively constant for any particular device, only varying slightly over the working flow range of that device. For these devices the flow range is most usefully expressed in terms of Reynolds number. Values of C derived from a liquid calibration may be used in gas applications with appropriate application of ϵ .



3.5 Reporting the result – performance indicators cont.

It is to be noted that when calibrating a device, the values chosen for the diameters must be recorded and quoted in the calibration certificate. If these values are subsequently used to determine flowrate from the derived C , any inaccuracy or uncertainty in the diameter values does not contribute to the uncertainty of flowrate. Changes in the diameter due to wear, fouling or indeed temperature will of course make a difference. Accurate dimensions are only required where the value of C is derived from theoretical equations rather than by calibration.

Flowrate: To express the overall performance of a device, its performance across its flow range has to be determined. The flowrate is normally expressed in terms of quantity per unit time with the units chosen to suit the application. 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.

3.6 Calibration frequency or how often should a flow meter be calibrated?

There is no correct answer to the question. In some applications an answer is apparently easy. An industry standard or third party (regulator or trading partner) dictates the calibration frequency. In this case the meter is calibrated whether it requires it or not and is often assumed accurate between calibrations. For most applications however, it is the user who must define the calibration interval and the policy to determine when to calibrate. The calibration interval should be chosen to minimise the risk of an incorrect meter reading making a significant impact on the process.

For example, high flowrates of oil attract huge tax liabilities. The product value is high, the risk of meter damage is high and so perhaps weekly in-situ calibrations of the meter, in the actual product, will be specified. Alternatively metering waste water with a Venturi may only require annual inspections, irregular verification, and no flow calibration. The differential pressure measurement device will however be calibrated regularly. The risk of the pressure transducer being in error is reasonably high, the risk of the Venturi changing is low, and the product value is low.

Other factors affecting the decision are the history of the meter, when the process is closed for maintenance, or what checking and diagnostics are monitoring the meter.

It is always good practice to keep calibration graphs, and control charts of the meter performance. This will assist in selecting intervals and also show changes in performance indicating degradation of meter performance.

4 Calibration Methods for Liquids

A number of quite specific methods and systems are recognised for the calibration of flow devices. Methods for both gas and liquid follow the same principles although major differences in implementation exist between the two fluids.

There are two main differences between gas and liquid flow methods. The first is that liquids will remain in an open container while gasses need to be contained. Also gasses are highly compressible while liquids, for most practical purposes, may be assumed incompressible (except for some small corrections); resulting in fundamental differences in approach. This is of course a generalisation as volatile liquids may require to be contained and many liquids e.g. Liquid Petroleum Gas (LPG), have a high compressibility in addition to being gas at ambient conditions. Liquid methods are discussed in this section, gas is covered in Section 5.

4.1 Liquid collection methods

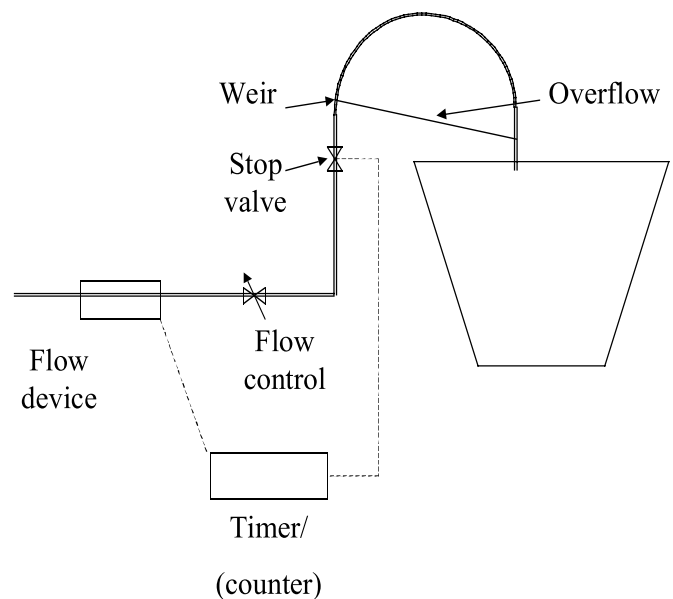
Unless a liquid is volatile or hazardous it can usually be contained in an open vessel. As a result, calibration standards are usually classified as being 'bucket and stopwatch' systems. The 'bucket' is a container which is weighed or has a known volume. The 'stopwatch' is a method of measuring the time to fill the bucket. Static methods of calibration are based on collecting fluid in the bucket and determining its quantity by a static measurement. Although dynamic methods are available, they are generally less accurate.

4.1.1 Standing start and stop method

This method is generally preferred for meters measuring exact quantities of liquid, especially meters for batch measurement.

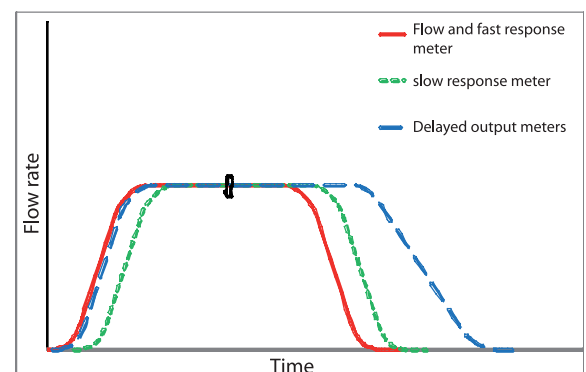
'Standing start and stop' is the simplest method available and can be used for both high and low accuracy calibrations.

The flow system is filled, all air purged and the required flowrate established. The flow is then stopped using a fast acting valve. When the container is empty, the drain valve is closed, the flow started and the container filled and when the container is full the flow is stopped. The quantity collected is measured and compared with the meter reading; the time to fill gives the flowrate.



In order to have an effective standing start and stop calibration system, a number of criteria have to be met. Firstly, the pump and circuit supplying the flow has to be designed and arranged to allow the flow through the meter to be stopped without damage to the pump or pipework; a pump bypass is usually fitted. Secondly no air should be left trapped in dead ends or T pieces as this will provide a spring effect causing the flow to oscillate when stopped suddenly, resulting in incorrect meter readings. The flow has to be started and stopped as quickly as practical to minimise the rise and fall time errors. Too fast a stop will create pressure fluctuations and 'water hammer' and must be reduced by slowing down the valve until an acceptable performance is found. The stop valve should have an equal opening and closing time.

The meter being calibrated has to have a fast response time to match the start and stop of the flow. The test time has to be sufficiently long in comparison with the acceleration and deceleration periods as to give insignificant error. This is illustrated diagrammatically for different meters. A slow response meter is one where the response time means the output starts after the flow, is started and continues for a short time after the flow stops; this may result in error. A delayed output meter shows the effect of microprocessor or electronically enhanced meter where the sensor responds quickly. The internal totalising of quantity, and indeed the output, starts quickly, but is slow to provide the final result. Many meters of course respond quickly and closely follow the flow curve.



4.1.1 Standing start and stop method cont.

The level established in the vertical pipe leading to the weighing vessel has an indeterminate level when the flow is stopped quickly. This would be worse if the pipe was not vertical and the pipe allowed the draining back of the test fluid to the meter. A vertical pipe allows the system to remain full. The weir and overflow allows liquid above the weir at the end of a test to drain back to a precise level, hence minimising the variability of the system. This point corresponding to the weir is the 'transfer point' and this is the point at which fluid transfers from the meter to the standard. It is unlikely to achieve high accuracy with test times less than 60 seconds. With a slow operating valve, longer times may be required. Switches on the stop valve may be used to time the tank filling and start and stop pulse counter gates taking care all pulses are collected, even if delayed.

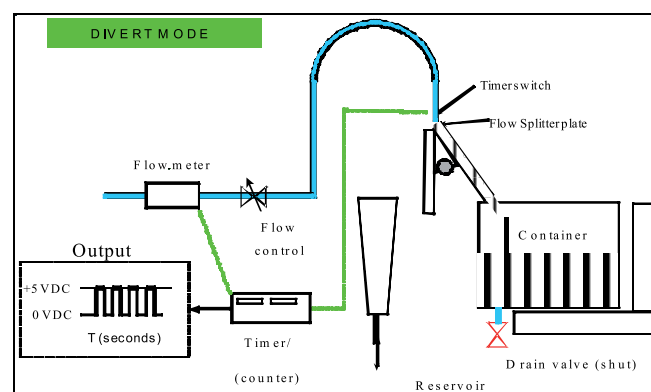
What is discussed above is a standing start and finish method based on a gravimetric (weighing) method. If a volume tank is used, filling is usually from the bottom, and the valve closing time is slow or stepped at the last stages to ensure the level stops within the measuring neck. The 'transfer point', (the level at which the volume starts and finishes) will be established in the lower neck of the tank.

4.1.2 Flying start and finish

This is sometimes called the diverter method where the flow through the meter is not stopped but continues uninterrupted.

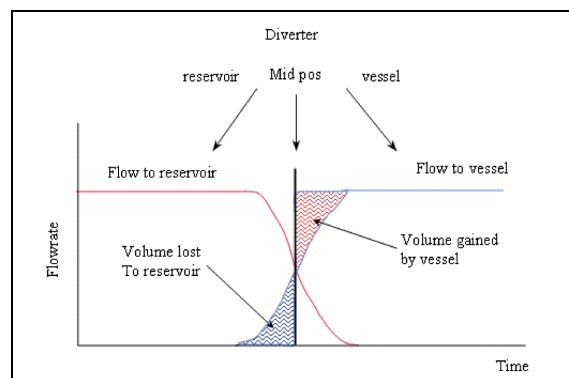
The flow is physically diverted between a return path to the liquid supply tank and the collection container. A switch on the diverter mechanism starts and stops a timer and a pulse totaliser

The key to accurate measurement is a clean separation between fluid entering the container and fluid returning to the supply. This should be accomplished without any change of flowrate through the device. For this reason the flow into the diverter is normally conditioned by creating a long thin jet impinging on a splitter plate. This will be open to atmosphere ensuring no change of pressure occurs when diverting and hence removing the potential for a change in flowrate during a test. The diverter mechanism is operated as quickly as possible to reduce 'timing errors' to a minimum. With a well designed diverter, test filling times down to 30 seconds can be achieved.



The main source of uncertainty lies in the timing error, shown diagrammatically. The 'hydraulic centre' of the diverter is found by calibrating a high quality reference meter at a constant flowrate. The calibration is repeated using alternatively long and short diversion times. The difference between them defines the timing error.

The diverter sensor is moved until the difference between calibrations is minimised. This is repeated at different flowrates and a best compromise position found. The residual scatter and difference between long and short diversion calibrations gives the uncertainty due to timing error.



4.1.2 Flying start and finish cont.

Flying start and finish methods are used primarily for meters with slow response times and where flowrate is the primary measurement rather than quantity passed. Meters with visual displays cannot be calibrated by this method.

A three port valve can be used as the diverter. Most valves, even those designed to maintain flow during changeover, will not have equal port area sizes during the change. The pipe resistance may well be different for the two paths resulting in different flowrates being produced. These differences can result in pressure/flow surge during changeover and different flowrates in the two conditions. It is also difficult to find valves which operate quickly enough to provide a fast changeover.

4.1.3 Dynamic collection methods

Dynamic methods are techniques where not only is the flow continuous through the device under test but also through the standard while it is measuring.

The static methods outlined above can be modified to utilise a dynamic measurement technique. The changing weight (dynamic weighing) or volume (dynamic level gauging or switching) can be detected and used to trigger the test point measurements of time and meter output. Flow is established into a tank with the drain open. To initiate a test, the drain is closed and the rising level, or increasing weight is detected and used to initiate a test point by starting a timer and reading the meter. When the tank is full, and after a signal has been sent to stop collection of data, the tank drain opened and the tank emptied. The drain has to be large enough to allow the full flow to pass through when open.

The techniques are generally only used for low accuracy calibrations. Repeatability is normally poor (0.5 to 1 per cent) is especially on larger systems. There is lack of resolution and response time (on the level instruments and dynamic weighing systems) while being filled which limit the operation. Some carefully designed and engineered systems can achieve much better performance than is suggested here. The method is sometimes employed using very large tanks in the field where long test times can give reasonable accuracy for in-situ calibration or verification of a meter.

4.2 Measurement methods

Two principles are used to measure the quantity of liquid in the container, mass or volume.

4.2.1 Gravimetric calibrators

A flow meter can be calibrated gravimetrically by weighing the quantity of liquid collected in a vessel. The vessel is weighed empty, then full and the difference calculated. This gives the weight of the fluid collected.

Since the quantity has to be mass (and probably converted to volume) the weight collected needs to be corrected for the effect of air buoyancy. A weighing machine is calibrated using weights with a conventional density of 8,000 kg/m³. The fluid collected will have a significantly different density from the weights and hence will be subject to significantly different up-thrust from the air. This difference is significant and amounts to around 0.1 per cent for water. The formula to calculate the mass is given below.

$$M = W \times \left\{ (1 + \rho_{air} \times (\frac{1}{\rho_f} - \frac{1}{\rho_w})) \right\}$$



4.2.1 Gravimetric calibrators cont.

Where M is the mass (kg),
 W is the measured weight (kg)
 ρ_{air} is density of air (kg/m³),
 ρ_f is the density of the fluid (kg/m³),
 ρ_w is the density of the calibration weights (8,000 kg/m³)

The term in the large brackets is called the 'buoyancy correction factor' which, In some applications, can be pre-determined and applied as a constant.

To determine the volume, the mass collected is divided by density at the flow meter. This allows the calculation of the volume from the mass measured by the standard assuming conservation of mass through the system. Density can be measured using a densitometer on-line or sampled at a different location. The density at the meter is then calculated from the density measurement, the expansion factor of the fluid and the temperature and pressure at the meter.

The weighing machines must be calibrated using recognised standards of mass. Normal platform machines fitted with steelyards provide measurements of weight to high accuracy providing they are carefully maintained. Electronic 'force balance' or load cell machines provide a better performance and the added addition of electronic output. Simple strain gauge load cell weighing techniques may be used, but generally will not provide the uncertainty capability much better than 0.1%. Modern shear force and compensated strain gauge cells are however now available to rival or even exceed the capability of the force balance cell. Gyroscopic weighing gives the ultimate resolution but probably exceeds the requirements of flow measurement.

Combined with the other uncertainties (density etc.) uncertainties of 0.05% or better in some facilities, can be achieved for volume passed through the test device.

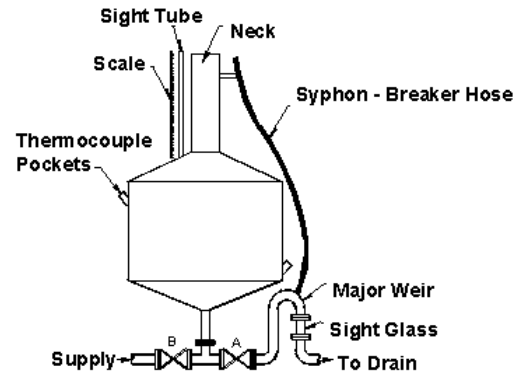
4.2.2 Volumetric calibrators

The measurement of the quantity of liquid collected may be carried out volumetrically by collecting a known volume of liquid in a container. In the volumetric method the standard vessel takes the form of a container with a calibrated volume. Normally this will be a vessel with conical ends to facilitate drainage and to reduce the risk of air entrapment. The neck of the vessel is normally fitted with a sight glass and a scale marked in volumetric units. A typical volumetric tank is shown below. Various shapes of vessel are used. Inclined cylindrical vessels with the necks at opposite ends are one design, as are simple 'cans' with no bottom drain and the level being established at the top 'brim'. This latter type is used for the calibration of fuel dispensers.

The tank volume must be determined by calibration of the vessel. 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. Calibration is usually by filling the vessel with a measured weight of water, or by emptying the vessel into a weighing tank.

4.2.2 Volumetric calibrators cont.

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. Drainage time (after the tank is empty) is vitally important. Liquid clingage to the wall can account for a significant part of the volume and takes appreciable time to drain down. It is normal practice therefore to calibrate the tank (including drainage pipework) and establish a consistent drainage time for the calibration. Each tank has this drain time defined and marked on the calibration plate and certificate. For this reason higher 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.



For all volumetric methods, a number of corrections and conventions have to be observed due to the expansion and contraction of both the standard, and the device being calibrated. The expansion and contraction of the fluid between the standard and the flow meter has to be recognised. Expansion due to temperature is the most important, but expansion in a pressurised system must also be accounted for.

Reference volume tanks, and pipe provers, have their volume defined at a stated reference temperature (and pressure). Normal reference temperatures are 15 °C or 20 °C. Other references can be defined for special purposes to minimise the size of corrections. Similarly reference pressure is normally atmospheric pressure (1.01325 bar(a)).

The volume contained in the standard during use is the base volume corrected for the expansion, or contraction of the vessel if the temperature is different from the base temperature. As the container makes up a volume, it is the cubical expansion of the material used (three times the linear expansion of the material is assumed). The equation is

$$V_s = V_b \times (1 + 3\alpha_s(t_s - t_R))$$

Where V_s is the volume contained, α_s is the linear expansion of the material of construction of the standard (prover or tank), t_s is the temperature of the standard and t_R is the defined reference (base) temperature.

To define the volume of fluid which has passed through the flow meter into the standard, the expansion of the fluid due to the temperature difference has to be calculated.

$$V = V_s \times (1 + \alpha(t_M - t_s))$$

Where V = volume passed through the meter, α is the cubical expansion of the fluid, t_s is the temperature of the standard and t_M is the temperature of the meter.





4.2.2 Volumetric calibrators cont.

Similar corrections have to be applied due to pressure (compressibility of the fluid) if it changes from meter to the vessel.

It is sometimes found more practical to reduce all volumes to base conditions rather than correcting to actual conditions and then calculating the error or K-factor. Both approaches should give the same answer.

In the oil industry these corrections are calculated individually in a formulaic manner and are given 'Correction factor' nomenclature:

Ctsp = temperature expansion correction for the steel of the prover

Cpsp = pressure expansion correction for the steel of the prover

Ctlp = temperature expansion correction of the liquid for the prover to standard conditions.

Cplp = pressure expansion correction of the liquid for the prover to standard conditions.

Corrections may be calculated by referring everything to a reference condition rather than the difference in conditions. Tables and algorithms are available to provide these corrections for hydrocarbon liquids.

The correction of the flow meter to a reference condition is contentious. The difficulty is defining the expansion coefficients (temperature and pressure) for a flow meter. Flow meters are complex devices and as such a simple volume correction factor will not be accurate. For this reason it is not normally advised to apply corrections to the flow meter during calibration, but quote the result at actual conditions. Some industry practice does however demand these corrections are made in which case the assumptions must be stated on the certificate.

Note: Different conventions are used as the base or reference conditions of temperature and pressure, e.g. for temperature, 20 °C, 15 °C, 60 °F are all commonly used.

The reference conditions used must be stated on any report or certificate.

4.3 Pipe provers

Pipe provers provide probably the best calibration devices for truly dynamic calibration. They are used in a sealed system and provide high accuracy. Provers, can be used in-situ as travelling standards, be part of a metering system or be used as the reference in calibration laboratories.

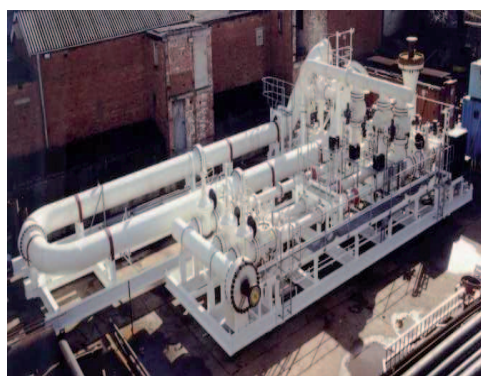
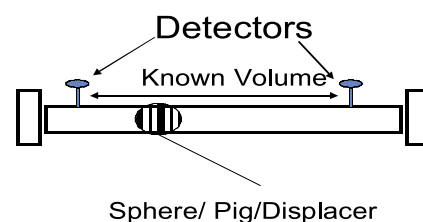
The pipe prover principle is illustrated diagrammatically. A length of pipe is fitted with switches and the volume between the switches is known. If a displacer is introduced to the flow, the time it takes to travel between the switches will give a measure of the flowrate. If the switches are used to gate a pulse counter, totalising pulses from a flow meter, a measure of the meter factor (pulse per litre) can be found.

Proving:

The term 'proving' is used extensively in the oil industry for a **calibration** which has the additional operation of demonstrating (or proving) the accuracy and fitness for purpose of a device, normally to comply with standard acceptance criteria.

4.3 Pipe provers cont.

The technique illustrates the ingenuity brought to bear on a calibration problem. The first prover was a mile long pipe linking two oil refineries in dispute over the accuracy of the transfer flow meters. With no ability to independently calibrate the meters, the length and diameter of the pipe were estimated and the time for a cleaning 'pig' to travel the distance provided an adequate measurement of volume to verify the transfer meters.



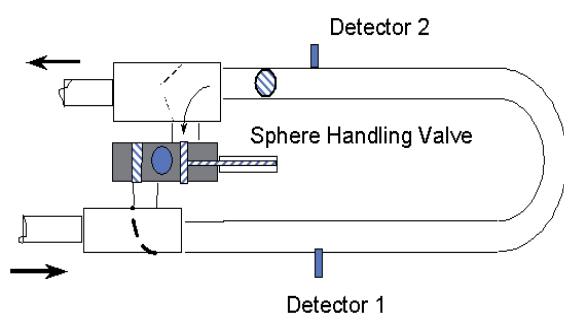
This concept has been refined to allow the design and manufacture of standardised measuring devices called 'pipe provers'. These devices are used extensively to measure all types of high value fluid from LPG to high viscosity crude oil. They are produced in all sizes from 50 mm to 1250 mm (2-48 inches).

With a pipe prover, the fluid remains contained and sealed in the system. The calibration fluid can be a clean reference fluid or the actual product. A calibration can take place without interrupting the process and if the product is used the conditions of use can be maintained. Pipe provers are often installed as an integral part of high value custody transfer and fiscal metering

stations where they are dedicated to a particular set of flow meters and duty. Pipe provers can also be mobile and taken to different metering stations.

Four main classifications of liquid pipe provers are recognised in documentary standards.

4.3.1 Uni-directional sphere prover



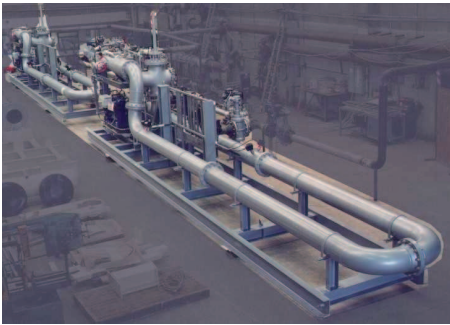
As the name implies, a unidirectional prover has a displacer which only travels in one direction along the pipe. The displacer consists of an elastomer (neoprene, viton, polyurethane, etc) sphere which is hollow. The centre is filled with liquid and pressurised to inflate the sphere until it is larger than the pipe bore. A typical inflation is around 2 per cent larger than the pipe bore. When the sphere is inserted into the pipe it takes up an elliptical shape and makes a good seal to the pipe wall.

The pipe itself is a long length of steel pipe with a smooth bore. 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 triggering a switch when the sphere passes under it.



4.3.1 Uni-directional sphere prover cont.



Located at the end of the prover is the sphere handling valve arrangement, designed to hold the sphere. At the start of a test the sphere is launched into the flow and carried round the loop captured and returned to the launch position ready for another run. The design of the valve is critical, and must not only be leak-tight but must have mechanisms to prove it is leak-tight. The valve also normally allows a means to remove the sphere for inspection.

4.3.2 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 unidirectional type, the main difference is that flow can circulate around the loop in both directions. A four-way valve of 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. One chamber also provides a means of removing the sphere. Note that two switches are

provided at each end. This provides better integrity of the measurement by giving redundancy and allowing four separate volumes to be defined.

4.3.3 Piston provers

For difficult fluids which may damage a lining material, or leak past the conventional sphere displacer, a piston displacer may be used. Since a piston is unable to pass round bends a piston prover is straight and hence these devices tend to be quite long. The pipe is normally a smooth honed bore pipe of stainless or plated carbon steel. The displacer is a piston with multiple seals. Switches can be conventional plungers or high integrity, non-contacting types. By their nature, they must be bi-directional and the four-way changeover valve is normally located midway along the pipe length to equalise the inlet and outlet pipework. This type of prover is not so common however finds a particular application with LPG, Liquified Natural Gas (LNG) and other difficult high value products.

4.3.4 Small volume provers

A 'conventional' prover is defined in this guide as one which counts 10,000, or more, pulses from the meter being calibrated during one pass of the displacer. A 'small volume' prover is defined as one where less than 10,000 pulses are counted. As this definition is strongly dependant on the characteristics of the meter being calibrated, the term 'small volume prover' can be applied to two concept designs. Note, 10,000 pulses are chosen in the oil industry to ensure the uncertainty introduced by pulse resolution is less than 0.01 % and is hence insignificant.

Concept 1: This is any prover following the general design characteristics specified in standards and generally designed to allow the collection of 10,000 pulses from a multi-bladed turbine flow meter. In other respects it will be of the same design as a 'conventional' prover but 'pulse interpolation' will be employed to improve meter resolution when required for a particular application.

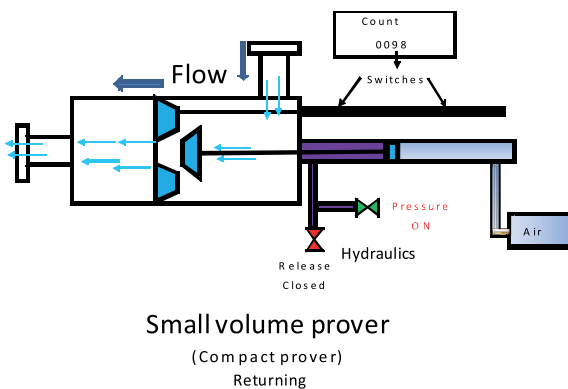
4.3.4 Small volume provers cont.

The prover will be designed to the normal standards but the use with low resolution meters, e.g. twin bladed turbines, will require the use of pulse interpolation.

Concept 2: A custom designed or commercially available pipe prover with a volume about one-tenth of a conventional design for the same duty. They are normally piston provers with trade names such as 'compact prover' and one company has adopted the generic term 'small volume prover'.

The design below shows one commercially available small volume prover which best illustrates the design criteria required. Other commercial designs are available with specific design features. Chain or mechanically constrained pistons, free pistons and even ball type displacers are available. The internal valve described is proprietary and external by-pass valves are used in other designs. Other forms of high resolution switches or continuous linear position indicators are also part of different designs.

For this illustrative design, a piston has been chosen as the displacer operating in honed bore cylinder to minimise leakage and pressure loss. To allow a short length, and retain accuracy, optical detectors are mounted external to the pipe which can resolve to fractions of a millimetre. A rod fixed to the piston extends out of the end of the cylinder and carries 'flags' which pass through optical detectors. These detectors give very precise control and start and stop signals across the measured volume.



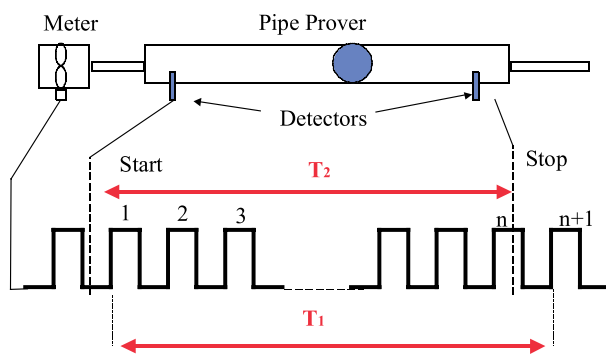
For this device the flow is maintained at a constant rate through the use of an internal valve located in the piston and operated through hydraulic control. The piston has an integral 'poppet' valve which allows the flow to pass through it when held open. An external rod allows the piston to be pulled, using hydraulic pressure to the upstream end of the cylinder while holding the valve open. Releasing the hydraulic pressure allows the valve to be shut by a combination of a spring, gas pressure on the end of the external rod and the force of the flow. The flow then carries the piston down the pipe. When the piston reaches the downstream end, the hydraulic pressure is restored, the valve opens and the piston is returned to the start position.

A small volume will not correspond to a large enough number of pulses from the flow meter to give adequate resolution, therefore a technique called pulse interpolation is used to increase the resolution of the pulse counting.

4.3.5 Pulse interpolation

This technique effectively increases the resolution of a pulsed output by estimating the fraction of a pulse missed at the beginning and the end of a test. This can be achieved electronically using frequency multipliers working from the input signal, or by pulse timing using one of three available techniques. By far the most common timing method is double chronometry.

4.3.5 Pulse interpolation cont.



To estimate the fraction of a pulse lost or gained at the start and finish of a pass, the whole number of pulses are first counted. This total is multiplied by the interpolation factor. This is the ratio of the time between the switches, and the time between the first pulse after the start switch and the first pulse after the stop switch.

The 'interpolated' pulse count is therefore no longer an integer number and is expressed as a decimal number of pulses.

$$n' = n \times \frac{T_2}{T_1}$$

The technique works well when the pulses have a constant frequency or period. If the period of the individual pulses varies by more than 5-10% lack of repeatability is found. Guidance is given in ISO 7278 Part 3.

As a technique this is provided as a standard option in many prover calculators and flow computers, particularly those designed to accept small volume provers. This allows low resolution meters to be calibrated against large provers in addition to controlling small volume provers. The technique can be applied elsewhere for gas provers and for other dynamic calibration methods.

4.3.6 Operation and calibration of a prover

When using pipe provers the process conditions need to remain stable throughout the calibration and even more care has to be taken to ensure stability when calibrating the prover itself.

To use a prover, the flow is directed through the prover and the meter with no leakage paths between the two devices. The prover may be located up or downstream of the meter. When the system has been filled, all gas removed and the flow established, conditions are allowed to stabilise for flowrate and temperature. The displacer is launched into the flow and 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, volumetric flow rate and K-factor are derived. This process is repeated a number of times and at the required number of flowrates.

Earlier oil industry standards stated that a successful 'prove' was achieved if a fixed number (3 or 5) successive results were within a specified range (0.04 % or 0.05 % being common). The current standard from the American Petroleum Industry (API) specifies that tests should be repeated an indeterminate number of times until the standard deviation of the results falls with a specified criteria based on standard deviation times the 'students t' statistic. Both methods rely on an experienced operator knowing that there is a problem with the calibration and not continuing until 'chance' provides a acceptable result.

4.3.6 Operation and calibration of a prover cont.

The volume of the prover between the switches is determined by calibration. This is called the 'base volume' and is quoted as being the volume at a specified reference temperature and pressure (15 °C or 60 °F and 1.01325 bar are the common conventions). The volume is determined by displacing water into a volume (or mass) standard. This may be achieved by filling the reference vessel repeatedly as the displacer passes through the calibrated volume. A solenoid valve connected to the prover switches ensures the flow is stopped at the correct point. For larger provers this is impractical and a reference meter is used to measure the volume. The reference meter is itself calibrated, as part of the same operation, against a volume or mass standard which may be a volume measure, small pipe prover or small volume prover. This is carried out immediately prior and subsequent to use.

A prover is a volumetric calibrator and the calculations have to take into account the corrections for temperature and pressure of the prover and liquid. Codes of Practice governing the design, calibration and use of pipe provers, including the small volume versions are available from ISO, The Energy Institute (EI) and the API.

5 Calibration Methods for Gas Flow Meters

The choice of calibration method for any particular flow meter is governed by the meter type, the ranges of flow and flow conditions, pressure, temperature and the accuracy of calibration required. In general all the methods have analogies with the liquid methods. The main difference between the calibration of a gas flow meter and a liquid device is the compressibility of the fluid. When calibrating a gas flow meter the temperature, pressure and hence volume of gas measured by the standard will be different from that at the device under test; corrections to common conditions must therefore be made. It is often best to convert to mass flow at the calibrator then back to volume using the conditions at the device under test or, if this is the requirement, at 'standard' conditions. The use of 'standard' conditions is common when considering specifications for gas meter calibrations. Note these conditions may be defined as 'standard', 'normal', or 'reference' conditions and have to be defined.

It is vital that the reference conditions are defined and never assumed.

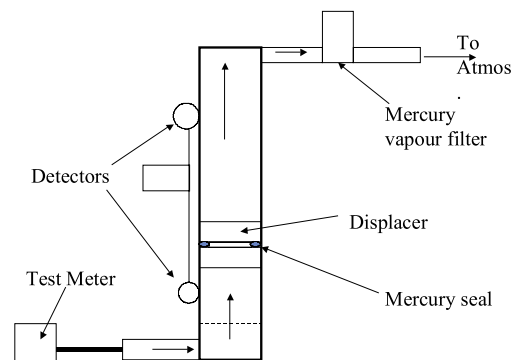
5.1 Displacement methods

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 for gas is the friction generated by the displacer seal. This friction will require the gas to compress until the pressure difference overcomes the friction. Variations in the friction can prevent the displacer moving smoothly, causing sticky or juddering movement hence giving poor results.

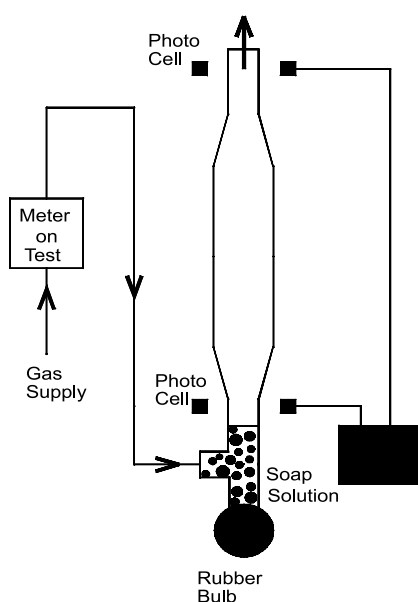
Some piston pipe provers have been produced for gas service and are in operation in standards institutes. These are generally specialised devices and used for higher pressures where the gas density is high or the piston is driven (or assisted in some manner). One commercially available device is available for small meters operating at low pressures and works through a piston driven externally rather than by the flow.

5.1.1 Mercury seal prover

For low flows, mercury seal provers use a very light displacer in a vertical glass tube. The piston travels upwards in the tube and the seal is a mercury ring formed in a recess in the piston. The use of a vertical piston and mercury seal reduces friction to a minimum. The weight of the piston has to be counterbalanced by an external weight (not shown on the schematic drawing).



5.1.2 Soap film burette

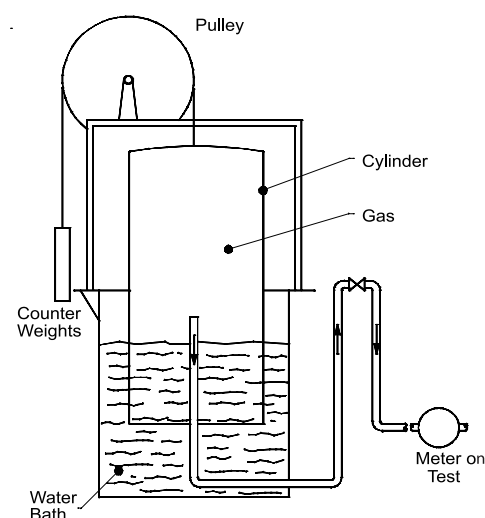


Soap film burettes are again a form of pipe prover used for both calibration and measurement. In this case a glass tube is vertically mounted with a reservoir of soap dissolved in water below the gas inlet. As the gas enters the burette a soap film is generated and travels up the tube at the same velocity 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.

What is created is a pipe prover with the displacer formed by the soap film. This method is usually used to measure gas flows within the range 10^{-7} to 10^{-4} m³/s at close to ambient conditions. Under very carefully controlled conditions reference flows can be determined to within ± 0.25 per cent using soap film burettes.

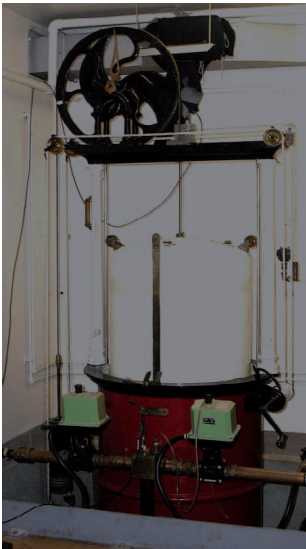
5.1.3 Bell provers

The 'Bell prover' is the standard for calibrating low flow gas meters such as domestic meters. A cylinder (or bell), open at the bottom and closed at the top, is lowered into a liquid bath. The weight of the cylinder is supported by a wire, string or chain and counter balanced by weights. A smaller counterbalance on a shaped cam arrangement (not shown) is added to compensate for the changing buoyancy as the cylinder is submerged. All pulleys are fitted with low friction bearings. By altering the counterbalance weight a pressure can be generated in the cylinder. A pipe passing through the liquid is open to the trapped volume and, as the cylinder is lowered, gas is displaced from the cylinder 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.



5.1.3 Bell provers cont.

By closing a valve leading to the meter and opening a valve (not shown) from a gas supply, the cylinder can be returned to the start position. Originally the liquid used would be water. As the water evaporates, the humidity changes, and hence the density of the air and this has to be corrected for. The water has to be topped up when the bell is in use. Most bell provers are now filled low vapour pressure/low viscosity oil.



In order to minimise expansion or contraction of the gas the liquid, gas and external air temperatures should not differ by more than 1 °C. Errors can also arise due to incorrect compensation for change in buoyancy of the bell as it is immersed and the gas is not fully saturated. At present, for flows up to some 10⁻² m³/s, bell provers can be used to measure flows to within ±0.2 per cent if strict precautions are taken to minimise the errors. Bell provers from 500 mm to 3 m diameter are available.

If required, the bell prover can be used in reverse where gas from the meter under test is used to raise the bell during a calibration with gas venting to return to the start position.

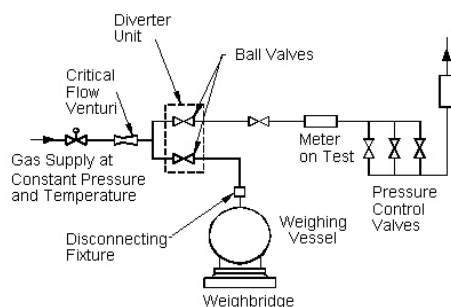
5.2 Gravimetric and volumetric approaches

For gravimetric systems the vessel is weighed before and after filling. Generally, the vessel has to be disconnected to prevent the connection pipes interfering with the weighing and gas vented during disconnection has to be accounted for. For small systems dynamic weighing has been employed both as a collection system and also by a delivery system. The vessel is pressurised and then discharged through the device under test and the effect of filling hoses accounted for in the weighing.

For volumetric systems the vessel must be very stable and of known volume. The pressure and temperature in the vessel is measured before and after the fill which allows the mass of gas to be calculated. Filling and emptying the vessel will create significant temperature effects due to the changes in pressure. In the most accurate systems the vessel is submerged in a water bath to maintain the wall temperature as stable as possible hence minimising temperature corrections to the vessel.

For both methods, as gas enters the vessel the pressure rises the flowrate will reduce as equalisation of pressure takes place between the test line and the tank. To get round this, these systems are usually used in conjunction with a sonic or critical flow device to 'de-couple' the pressure. As will be explained in Section 5.4, the mass flow through a critical nozzle is dependent on the upstream pressure and independent on the downstream (vessel) pressure. This allows the mass flow through an upstream device to remain constant while the tank fills, as long as the sonic device is 'choked'. The calibration of devices such as mass meters upstream of the choke point can be calibrated at a constant mass flow. Alternatively if an accurate sonic nozzle is used, the nozzle can be used as a transfer device to calibrate a lower pressure meter downstream with the nozzle itself being calibrated against the vessel. Any restrictive device (e.g. a valve) may be used to de-couple the system however using a nozzle allows superior control and the simultaneous calibration of the nozzle as a secondary device.

5.2 Gravimetric and volumetric approaches cont.



Due to gas compressibility effects, it is more difficult to maintain a closely controlled flowrate than it is for liquid flow systems. As pressure changes, potentially large changes in temperature can occur making it difficult to obtain stable conditions.

5.3 Gas displacement method

For low pressure systems, gas can be displaced from a closed vessel by filling a transfer vessel with liquid. This can be likened to filling the bath of a bell prover rather than allowing the bell to move. The liquid transferred can be weighed or measured in some other way, and the volume calculated. The volume of liquid can be equated to the volume of gas displaced, with suitable pressure and temperature corrections. In one design the liquid is allowed to flow from a weighing vessel which is located on a rising platform which maintains a constant pressure on the system as the liquid runs out.

5.4 Critical flow Venturi-nozzle (sonic nozzle)

Sonic nozzles are effectively reference flow meters which can be used to calibrate other devices. As explained previously they can also be a more fundamental part of a primary standard. They are mentioned specifically due to their extensive use as the calibration reference standard in many applications and laboratories. Although not a primary method of calibration, sonic nozzles can form part of a system when combined with primary methods. Sonic nozzles provide the reference system for many calibration facilities where their stability requires infrequent calibration of the nozzle or simply reliance on the performance outlined in documentary standards.

If the pressure drop between the inlet and the throat of a nozzle or restriction is increased, the flowrate rises until sonic velocity is reached at the throat. At this point the nozzle is 'choked' and from this point, the mass flowrate through the nozzle will be constant for any given upstream pressure. The expression for the mass flowrate of the gas is:

$$\frac{dm}{dt} = C_d C^* A_t P \frac{1}{\sqrt{RT}}$$

Where

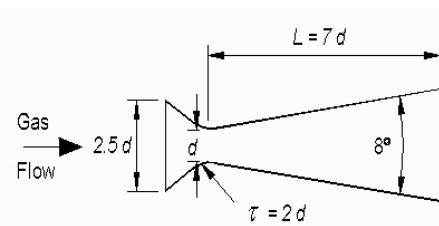
C_d is discharge coefficient,

C^* is critical flow factor,

A_o is area of the nozzle throat.

P_o and T_o are the absolute values of upstream pressure and temperature.

5.4 Critical flow Venturi-nozzle (sonic nozzle) cont.



At this condition the mass flowrate is dependent on the geometry of the nozzle, the properties of the gas, and the upstream pressure and temperature. This makes the device particularly suitable for calibrating meters which can introduce pressure pulsations into the flow. A standard toroidal throat sonic Venturi as specified in the ISO standard is shown. Other designs based on conical entries, or parallel throat orifice plates can be used but these provide a larger pressure loss and hence a narrower operating range.

One disadvantage of the critical flow Venturi-nozzle is the large pressure loss which is normally much greater than that for subsonic nozzles or other flow metering devices. Moreover, an accurate knowledge of the thermodynamic properties of the gas is required. 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 flow meters in high pressure gas flows at flowrates where the throat Reynolds number exceeds 10^5 and uncertainties of 0.2 per cent may be required. The large pressure drop can in some situations lead to extended test times to establish stable temperature conditions at the test meter. Nozzles are frequently installed as parallel arrays, with the nozzles sized to provide a set range of mass flowrates by using different combinations of nozzles in parallel. Sonic nozzles in this way are often used to calibrate low pressure meters where the meter is working at ambient pressure upstream and a vacuum is created downstream of the nozzle to allow one unique mass flow for each nozzle.

By establishing a 'choked' flow where the gas velocity is at the speed of sound at the nozzle throat, variations of pressure downstream cannot be reflected to conditions upstream and hence the mass flow becomes independent of downstream variations. The nozzle therefore effectively de-couples the reference mass flow from variations in downstream pressure when a calibration is being carried out. This condition also allows a downstream vessel to be filled and the mass flow maintained when otherwise the flow would reduce as the pressure equalise.

6 Other Calibration and Verification Methods

6.1 Reference meters

Any reliable, stable and predictable flow meter type can be used, either in a laboratory or in the field, as a calibration reference. Reference meters are used when a 'primary' method is restricted due to lack of resolution, capacity or inadequate response time. A single meter may be used as the reference in series with the meter to be calibrated. Equally, multiple meters in parallel can be assembled to achieve a flowrate range in excess of what may be economically managed through a primary system. In this way calibration facilities have been designed to double their flowrate capacity by using two meters in parallel. Manifolds of six, eight or more reference meters in parallel can be assembled to test and calibrate very large flow meters. The use of reference meters will add uncertainty to the quantity measured when compared with that of a primary system. However there is no significant reduction in uncertainty using multiple meters as against a single meter or a primary system.

Improvement in the uncertainty of the calibration of a test meter may be lower when using a reference meter as compared with a primary system calibration of the same device; through reduction of uncertainties due to longer test times, reduced resolution uncertainty and removal of response time issues.

6.1 Reference meters cont.

The correct selection and installation of a reference meter is vital. Predictable behaviour with changes of fluid properties must be assured and the installation effects on both the reference meter and the device under test should be understood. The installation must ensure that the reference meter does not interfere with the test device by generating pulsations, electronic, vibration or acoustic interference, or flow disturbance.

6.2 On-site verification methods

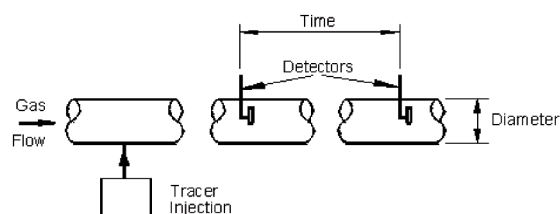
Meters can be calibrated on-site using any of the methods previously described such as mobile pipe provers, volume tanks and reference flow meters. Care has to be taken during installation to ensure the influence factors such as weather and temperature etc. does not add uncertainty. Establishing a steady flowrate is also recommended.

Three methods, suitable for verifying (rather than calibrating) flow meters on site, are described. Generally these methods are used to calibrate meters where standard laboratory methods or portable calibration standards are not suitable for installation in the field. This may be due to access, the product in use, the meter size, or an inability to stop the process. Generally they are methods which do not give the best uncertainty, and may be in some cases poorer than the expected uncertainty of the meter. If doubt exists however these may be the methods which can be employed to verify meter performance.

6.2.1 Tracer methods

Tracer methods are used in situations where a flow meter or calibration device cannot be inserted in a process flow and the installed meter cannot be removed and calibrated elsewhere. This may be due to size, availability of time to withdraw the meter, or the meter is operating in a 'difficult' fluid. Tracer methods would normally be used to verify that a meter is operating within an acceptable tolerance rather than providing a traditional calibration. These methods involve the injection of a fluid which can be detected in the flow stream and using this to measure the flowrate within the pipe.

Two recognised techniques are available.



Transit time (velocity) methods: For this method pulses of tracer fluid are 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 can be determined. At present, tracers used are usually radioactive isotopes, which can be generated on site, with very short half lives. This reduces any potential contamination risk to well below safety limits.

The tracer is injected into the flow and the 'pulse' of tracer is detected by external sensors on the pipe wall. The distance between the detectors is known as the pipe diameter and when combined with the time between pulses the volumetric flowrate can be calculated. The main source of error is the determination of the internal area of the pipe due to inaccuracy in the pipe wall measurement or internal corrosion/deposition. Also the time is measured from the 'peak' of the pulse passing the detectors. The flow should have a reasonable profile and avoid swirl etc which would cause the 'pulse' to be ill defined.

6.2.1 Tracer methods cont.

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; however 1 per cent is probably the lowest uncertainty which can be assumed achievable.

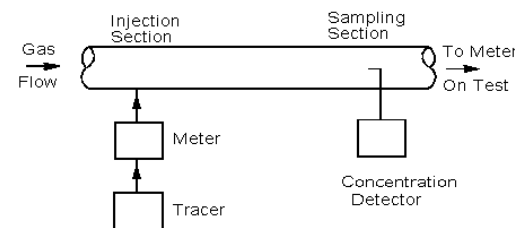
The second technique is the **dilution method**; where a tracer fluid which can be detected in low concentrations, is injected into the flow at a known rate. If this injected flowrate is known accurately and a sample of the mainstream flow is taken downstream, the flowrate of the main flow can be deduced from the concentration of dilutant. A sample of the main flow is taken, as single samples or continuously, and the concentration of dilutant is measured. The main line flowrate can be derived from:

$$Q = \frac{q}{Conc}$$

Conc, is the concentration of the dilutant

q is the flowrate of the dilutant.

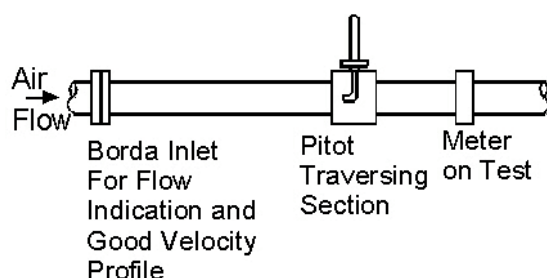
The dilutant has to be sampled after mixing and therefore the flow is sampled at a distance downstream of the injection point, to allow homogeneous mixing to take place. The method is used for both gas and liquid flows.



In dilution methods the main source of error occurs in obtaining accurate determination of the tracer concentration particularly if on-line determination is being used.

6.2.2 Insertion meters

Using an insertion flow meter, the flowrate is estimated by measuring the velocity at a single point location in the duct and from that estimating the volumetric flow. The device used to measure the point velocities may be a pitot tube, insertion turbine or an insertion electromagnetic meter and other types are available.



To use this method, the installation and the positioning of the sensor has to be carried out accurately. The cross sectional area of the duct has to be known, and an ideal flow profile present to allow the calculation of volume flow from point velocity. Insertion meters can be used by inserting them into an existing duct or pipe and this can be done without stopping the process. This will allow an installed meter to be verified in-situ.

The main disadvantage of these methods is finding a location to install the meter where there is a good undisturbed flow profile which approximates an ideal profile. The determination of the area of the pipe at the measurement location also has to be known. Calculation standards allow the mean velocity and therefore the volumetric flowrate to be derived from the point velocity measurement. Corrections for 'blockage factor' have to be applied. The technique is also highly dependent on correct installation, depth and alignment and therefore a skilled operator is required.



6.2.2 Insertion meters cont.

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. Measurement in the accuracy range 1 to 5 per cent can be anticipated in liquids.

The technique is used extensively to characterise flow calibration test facilities. For this purpose the probe is traversed across the pipe and across different diameters to ensure the facility has an acceptable flow profile.

6.2.3 Clamp-on ultrasonic meters

Clamp-on ultrasonic meters operate by measuring the mean velocity of the flow across the diameter of a pipe. These devices usually use 'time of flight' ultrasonic measurement methods. The transducers are clamped on to the outside wall of a pipe, diametrically opposite each other. The area of the pipe is known, and therefore from the velocity and area the flowrate computed. The pipe has to be of suitable construction and the transducers 'coupled' to the wall to allow the signal to penetrate. As a mean velocity is measured across a diameter, the flow profile has to be known (or assumed); uncertainties between 2 and 5 per cent the norm when there is a good installation.

A clamp on ultrasonic flow meter is however an efficient way to verify in-situ meters when there is no method of installing a reference and as an alternative to breaking into the pipe to install a insertion probe. Liquid meters have been available for many years and gas clamp on meters have now entered the market.

6.3 Unusual volume methods

Volumetric methods can be used for calibration and verification for specific and difficult situations. If a reference volume is available and a means to transfer the fluid to the meter under test established a calibration method is in place.

One method in use employs a very large diameter and very tall tower. The tower is filled with water and then discharged through the device under test. The volume of the tower can be determined with a reasonable degree of accuracy and the level detected as it falls during a calibration. Passage of the water surface (level) across the detectors defines the start and finish of the calibration test with the detectors used to start and stop readings from the test meter. Volume and the time can then be used to define the reference values.

The engineering of such a system is quite challenging. Level switches have to be fast and accurate enough to detect the falling level. Flow profile has to be assured as the water turns from the vertical tower to the horizontal test section. It is also extremely challenging to maintain a constant flowrate as the head reduces as the level drops. The example device known uses a tower some 40 m high and 4 m diameter and is used to calibrate large water meters.

Based on this example device other designs and concepts can be considered, however a very careful uncertainty budget has to be created to account for all sources on uncertainty.

7 Expectations for a Calibration

The calibration and 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. Systematic uncertainties can only be estimated from knowledge of the calibration system and its method of traceability and transfer through to the final duty with the addition of influence factors and historical performance being added.

Liquid flow meter calibration facilities should be able to measure flowrates to uncertainty levels between 0.05 to 0.5 per cent depending upon the complexity of the system and its design. It is noted that volumetric and gravimetric systems have similar uncertainty however volumetric systems appear to be able to deliver lower repeatability figures.

Calibration systems for gas flow meters should be able to measure flowrate to uncertainty levels of between 0.2 and 0.5 per cent.



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- ASTM D 1250 Petroleum measurement tables; 2004.
(These are also available as API petroleum measurement manual; Chapter 11.
The 2004 version is based on the 1980 tables however the standards is now a computer implementation rather than the older paper tables.)

Addendum

Client calibration check list

1. Type of meter Turbine/DP/Coriolis/Ultrasonic/etc	
2. Make/Model	
3. Size of meter (Length, diameter,) (weight) (other sizes)	
4. Type Fluid to be Calibrated Water/Oil/Gas (air?) / Multiphase (get details ie what is the viscosity of the oil etc)	
5. Flowrate/Flowrange (remember to note Units!)	
6. Operating Pressure (especially for gas)	
7. Operating Temperature	
8. Signal Output: Pulsed/mAmps Pulsed = max frequency Resolution: is it a scale, pulses/unit What's the electrical characteristics (volts etc)	
9. K-factor (Check pulses required for calibration)	
10. Is pipework included. Are all electronics included	
11. What uncertainty is required	
12. What Flanges: screw etc Are the flanges raised or RTJ Some standard fittings are ANSI 150 PN 10 BSP ANSI 600 PN 16 BSP(T) ANSI 300 NPT	
13. Measured Points required e.g. (3 @ 5 flowrates) (1 at 10 flows) etc.	
14. Timescale required	
15. Have you had the meter calibrated before	
Contact Name:	
Company:	
Address:	
Tel:	
E mail:	

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