191: Calibration and Standards in Flow Measurement

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1 GENERAL PRINCIPLES

Calibration is defined as follows: '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 realized by standards.'

It is important to recognize at the outset the definition of a 'calibration' and to note that the 'comparison' applies only to the conditions at the time of the calibration. The purpose of calibration is to increase the confidence in the reading obtained from the flowmeter in service.

Standards for flow measurement are based on a comparison of the quantity of fluid passed, or passing, through the flowmeter with the quantity measured by the standard. Standards can be based on the measurement of mass or volume. The required mass or volume quantity can be calculated from the measured quantity from a knowledge of the fluid density at the test flowmeter. Standards may be static or dynamic, and this choice is made on the basis of the output and end use of the flowmeter. Some flowmeters are used to measure quantity and have a fast response time; others are designed to measure flow rate and have a slow response time. Calibration of a flowmeter should cover a significant flow-rate range for the flowmeter and establish a performance across that range.

A 'standard' for flow calibration should replicate as closely as practicable the conditions under which the flowmeter will be used. Full replication is impossible, and the key to success is to be as close as practicable, and to recognize the nature and performance of the flowmeter type being tested. The factors that should be addressed are the fluid viscosity, the installation effects due to bends and fittings, temperature, and pressure. The standard should also have a defined traceability and uncertainty chosen to match the expectation of the final measurement.

The choice of standard must also recognize the dynamic performance of the flowmeter and the nature and resolution of the output. As a calibration is a comparison, the quantity measured by the standard must match the quantity measured by the flowmeter and this must take cognizance of the resolution of the flowmeter. A flowmeter used to measure very large quantities of fluid over a long period of time may not have a resolution suitable for measuring the smaller quantities measured by a standard.

The result of a flowmeter calibration will normally provide two related figures: one related to the flow rate and the other as a performance indicator. Flow rate will be expressed as mass per unit time, volume per unit time, Reynolds number, or some other flow rate–related measure. The performance indicator relates the expected performance of the meter to the measured performance. Examples of performance indicators are K-factor, error, and meter factor.

2 GRAVIMETRIC CALIBRATION OF LIQUID FLOWMETERS

A flowmeter can be calibrated gravimetrically by weighing the quantity of liquid collected in a vessel. The vessel is weighed and the weight (in air) of the fluid collected is noted.

As the quantity of fluid has to be expressed as mass, the weight has to be corrected for the effect of air buoyancy. As a weighing machine is calibrated using weights with a conventional density of 8000 kg m^{-3}, and the fluid collected will have a significantly different density, the upthrust of the air on the tank will have a significant effect. This amounts to around 0.1% for water. This correction is given in (1).

$$M = W \times \left\{1 + \rho_{\text{air}} \times \left[\frac{1}{\rho_{\text{f}}} - \frac{1}{\rho_{\text{w}}}\right]\right\} \qquad (1)$$

where M is the mass, W is the measured weight, ρ_{air} is the density of air, ρ_{f} is the density of the fluid, and ρ_{w} is the density of the calibration weights (by convention, 8000 kg m^{-3}).

To determine the volume, the mass is divided by the density determined at the flowmeter. Density can be measured using a densitometer but is more often calculated from a knowledge of the fluid properties and measurements of temperature and pressure at the test meter.

2.1 Standing-start-and-finish method

This method is generally preferred for flowmeters that are used for measuring the quantity of liquids, especially flowmeters for batch quantities (Figure 1).

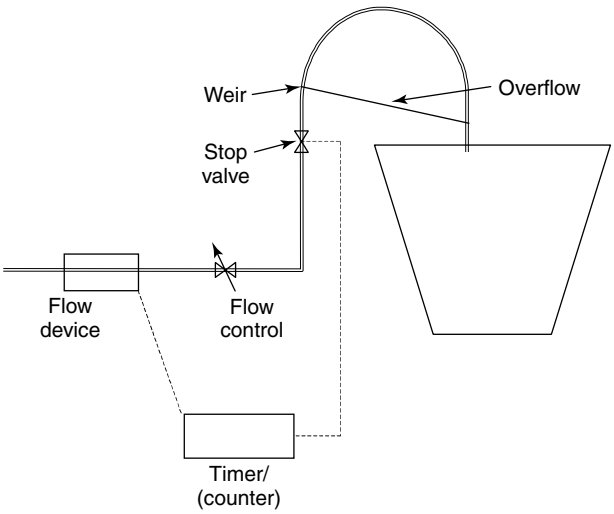

Figure 1. Standing-start-and-finish method for the gravimetric calibration of liquid flowmeters.

The required flow rate is established into the tank. The flow is then stopped using a fast-acting valve, the container drained, and the drain valve closed. The flow is restarted, the container filled, and the flow stopped. The weight of liquid is noted along with the time taken to fill the tank. The reading from the flowmeter is also noted. Temperature and pressure of the liquid at the flowmeter are also noted during the fill.

2.2 Flying-start-and-finish method

This is sometimes called the *diverter method*. In this method, the flow through the flowmeter is not stopped but the flow is diverted between a return to the supply and the collection tank (Figure 2). A switch on the diverter mechanism starts and stops a timer to time the filling of the collection measure and counter to totalize pulses from the test device.

In this method, the key to accurate measurement is a clean separation between fluid entering the tank and fluid returning to the supply.

Flying-start-and-finish methods are used primarily for flowmeters with slow response times and where flow rate is the primary measurement rather than quantity passed. Flowmeters with visual displays cannot be calibrated by this method.

The main source of uncertainty for both gravimetric calibration methods lies in the timing error. In the case of the standing-start method, this is caused by the response time of the flowmeter and the changing flow at each end of the test. For the diverter methods, this is introduced by not triggering at the hydraulic center of the liquid jet.

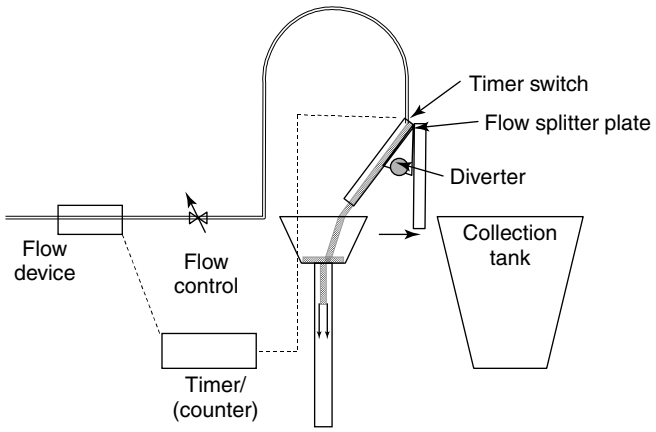

Figure 2. Flying-start-and-finish method for the gravimetric calibration of liquid flowmeters.

3 VOLUMETRIC CALIBRATION OF LIQUID FLOWMETERS

The measurement of the quantity of liquid collected may be carried out volumetrically, that is, by collecting a known volume of liquid in a container. In the volumetric method, the standard vessel takes the form of a container with calibrated volume. Normally, this would be a pipette with conical ends to facilitate drainage and to reduce the risk of air entrapment. The neck of the pipette is normally fitted with a sight glass and a scale marked in volumetric units. A typical volumetric tank is shown in Figure 3.

The tank volume must be determined by calibration against weighed water contained in the vessel, or by using smaller volumetric measures that are themselves traceable to national standards by weighing methods.

Volumetric systems are normally used with standing-start-and-finish methods owing to the difficulty of diverting flow into the tank and controlling the finish of the fill. Drainage time (after the tank is empty) is vitally important, as liquid clingage to the wall can be significant. Each tank has a calibrated drain time and this must be maintained.

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. For all volumetric methods, corrections due to the expansion and contraction of both the standard and the device being calibrated have to be accounted for along with the expansion and contraction of the fluid between the standard and the flowmeter. This applies to both thermal and pressure expansion.

Pipe provers provide a dynamic volumetric calibration standard method for calibration. They provide a sealed system providing high-accuracy calibrations in situ as well as in laboratories. 'Proving' is used extensively in the oil industry and is generally synonymous with calibration.

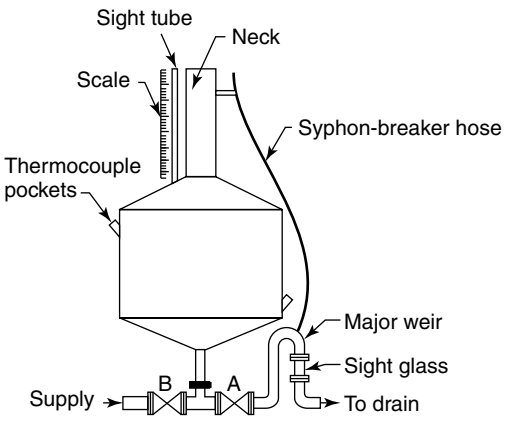

Figure 3. A volumetric tank.

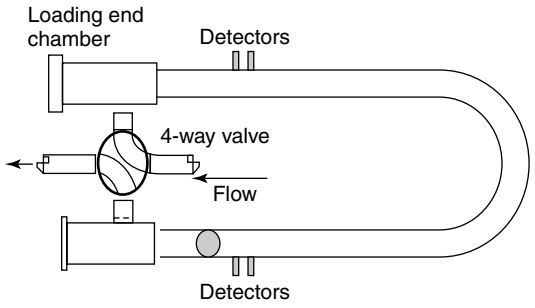

Figure 4. A bidirectional prover.

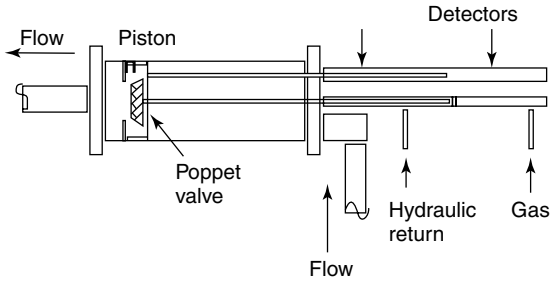

Figure 5. A small volume prover.

A length of pipe is fitted with switches such that the volume between the switches is known. If a displacer, or 'pig', is introduced to the flow, the time it takes to travel between the switches will give a measure of the flow rate. If the switches are used to gate a pulse counter, totalizing pulses from a flowmeter, a measure of the flowmeter factor (pulse per liter) can be found.

A variety of designs are available, and one of the most common, the bidirectional prover, is illustrated in Figure 4.

A four-way valve, of very high integrity, changes the flow path without breaking the flow. The sphere is held in special end chambers. These are designed to launch the sphere and absorb the shock of capture. One chamber also provides a means of removing the sphere. Note from Figure 4 that two switches are provided at each end. This provides better integrity of the measurement by giving redundancy and a means of checking results by developing four separate volumes.

A small volume prover is a pipe prover where the length, diameter, or volume is smaller than that required to obtain 10 000 pulses from the flowmeter. A proprietary device is illustrated in Figure 5, where a precision pipe and a piston along with optical detectors are used. Flowmeter resolution is effectively increased using pulse interpolation.

4 CALIBRATION OF GAS FLOWMETERS

In general, all the methods for the calibration of gas flowmeters have analogies with liquid methods. The main

difference between the calibration of a gas and a liquid flowmeter is the compressibility of the gas and the fact that the gas has to be contained in a closed container. As gas is compressible, the volume measured at the standard and the volume measured at the test device have to be corrected to a common or to a 'standard' condition.

Volume standards generally take the form of displacement devices much akin to flowmeter provers. Three common examples are discussed.

A common standard used extensively for lower pressure calibrations is the 'bell prover' (see Figure 6). In this device, air is displaced into a calibrated bell, which rises or lowers as the bell is filled. A bath of oil or water acts as the seal.

Piston provers for gas are based on a very light and low-friction piston displacing gas from a smooth cylinder. The piston may be driven by the gas or from a mechanical mechanism. The example of the mercury-seal piston prover is illustrated in Figure 7.

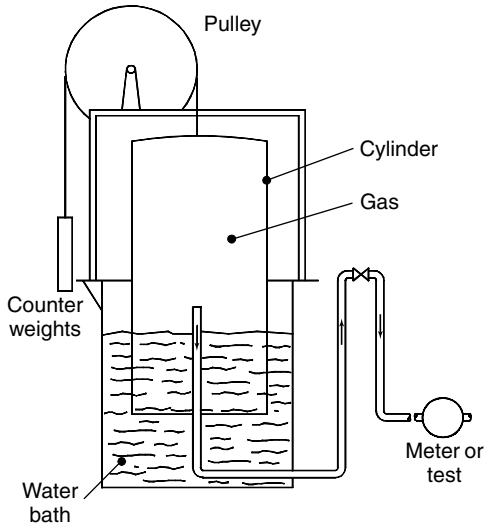

Figure 6. A bell prover.

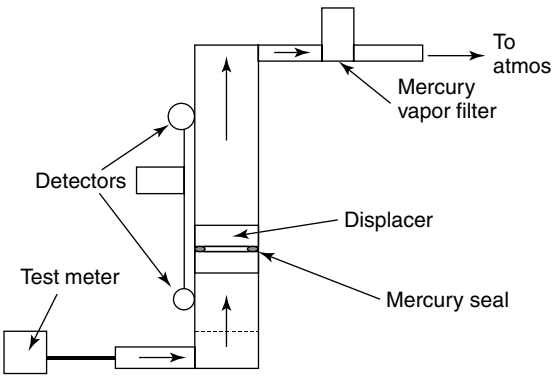

Figure 7. A mercury-seal piston prover.

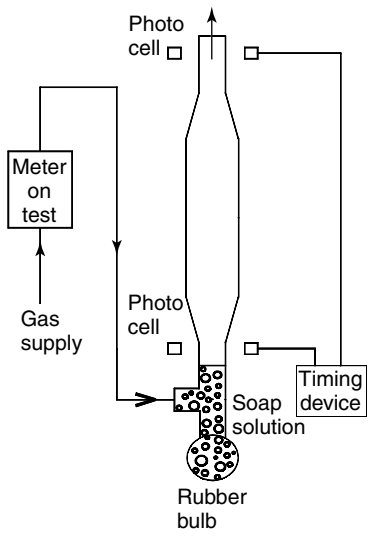

Figure 8. A soap-film burette.

Another device for the measurement of very low-pressure gas is the soap-film burette where the piston is replaced by a soap film (Figure 8).

Gas flowmeters can also be calibrated using mass as the reference quantity. This can be done gravimetrically by weighing high-pressure gas collected from, or delivered to, a test meter. Alternatively, the mass can be calculated using PVT (pressure/volume/temperature) calculations if a fixed volume is used.

Critical flow nozzles provide an extremely stable calibration device. In this device, when the velocity of gas reaches the speed of sound in the throat of the nozzle, the mass flow will be a function of the upstream pressure and the properties of the gas only. This allows measurement of mass flow to 0.3% using a standard nozzle and down to 0.1% if the nozzle has been calibrated. The equation is given by (2).

$$\frac{\mathrm{d}m}{\mathrm{d}t} = C_\mathrm{d} C^* A_\mathrm{t} P_\mathrm{o} \frac{1}{\sqrt{RT_\mathrm{o}}} \tag{2}$$

where C_d is the discharge coefficient, C^* is the critical flow factor, A_t is area of the nozzle throat. P_o and T_o are the upstream pressure and temperature.

5 MIXED OR MULTIPHASE FLOWMETERS

Multiphase flowmeter applications are commonly used for two main applications.

The first application is for mixtures of oil, gas, and water, particularly in the offshore production of hydrocarbons. Meters can be calibrated at a dedicated laboratory such

as NEL in the United Kingdom. Flows of oil, water, and gas are separately metered and combined upstream of the meter. They are then separated and recirculated. The multiphase flowmeter reading is compared with the single-phase measurements. In the field, flowmeters are 'calibrated' or assessed against a 'test separator'. The metered multiphase flow is introduced to a separator and the single-phase measurements from the separator are measured over long time periods.

The second application of multiphase meter is to meter 'wet' gas. This type of meter can also be calibrated in a specialist laboratory, such as NEL, by injecting measured quantities of liquid to a measured gas flow. In the field, dilution tracer techniques can be used to estimate the flow rate of the liquid phase, hence giving a measure of the correction to be applied to the primary gas meter previously calibrated in dry gas.

6 IN SITU OR FIELD CALIBRATION

In an ideal world, all flowmeters would be calibrated in situ, hence avoiding differences in fluid and installation changing the calibration of the flowmeter. In practice, this cannot be done with low uncertainty as the field installations and the possible standards are not suitable.

In the oil industry and for fiscal installations, it is common to have flowmeter provers permanently installed and valve arrangements in place to allow calibration of a bank of flowmeters to be carried out at any time. In other applications, mobile flowmeter provers or even volume tanks can be taken to the installation. This concept is used for high-accuracy systems and for lower-uncertainty systems such as petrol dispensers.

Where a portable volume standard is impractical, reference flowmeters can be installed in series. The various effects of installation and fluid conditions have to be recognized. This applies also to differences between the in situ use and the laboratory calibration of the meter. A different type of reference flowmeter that can be used is the clamp-on ultrasonic meter. In this type, the sensors are strapped to the outside of the pipe wall and the flowmeter measures the velocity of the fluid. If the pipe diameter is known, the flow rate is calculated. Although improved greatly in recent years, uncertainties of better than 1% cannot be expected and 5 to 10% is not uncommon.

Insertion meters can be used to 'verify' the calibration of in situ meters. An insertion meter can be a pitot tube, an electromagnetic sensor, a turbine type sensor, or a thermal sensor fitted to the end of a probe, which can be inserted into the pipe through a fitting on the wall. The point velocity of the fluid is measured, and hence the bulk flow rate calculated. 1 to 10% uncertainties can be expected.

A final technique is to use tracer fluids injected into the fluid to measure the flow. Two methods are used. In the first, a radioactive tracer with a very short half-life is injected as a pulse into the flow. The tracer is injected some distance upstream of a detector strapped to the pipe wall. A second detector is located a measured distance downstream. The time taken for the tracer to travel between the detectors gives a measure of the flow. In the second technique, a chemical tracer is continuously injected at a measured rate into the flow. A sample is withdrawn from the flow some distance downstream and the concentration of the chemical is analyzed. The concentration gives a measure of the flow.

Further information on the calibration of flowmeters can be found in Baker (2000) and Spitzer (2001).

REFERENCES

Baker, R.C. (2000) *Flow Measurement Handbook: Industrial Designs, Operating Principles, Performance and Applications*, Cambridge University Press, Cambridge.

Spitzer, D.W. (ed.) (2001) *Flow Measurement: Practical Guides for Measurement and Control*, 2nd edn, ISA International, Research Triangle Park, NC.