Field evaluation of large in-line flow meters#

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Abstract

The combined application of a portable insertion flow meter, a velocity-area method of flow determination together with the use of a velocity profile function provides a cost-effective method for the *in situ* evaluation of the accuracy of large in-line flow meters within the water supply and distribution network.

The calibration of large in-line flow meters in the field is required because of differing site conditions which affect a flow meter's performance, the expense of testing on off-site facilities and the practical problems associated with the removal and testing of some types of flow meters.

Research has indicated the relative accuracy of velocity-area methods for both axisymmetric and asymmetric flow profiles. The log-linear method appears to be relatively more accurate and cost-effective in its application than other velocity-area methods of flow determination.

The modified Pao equation is a function which is independent of the friction factor and which describes the velocity profile within a pipe. It is dependent, however, on the actual positions where the mean axial velocity occurs and the value of the centre-line velocity. These characteristics facilitate the practical application of the function in establishing a flow reference standard.

The position of the mean axial velocity in a pipeline varies and this position has to be determined for each situation and application.

Practical guidelines given in this paper ensure the cost-effective application of a portable insertion flow meter, the log-linear method and the modified Pao equation for providing a flow reference standard.

Research is required to establish the accuracy of this flow reference standard with respect to the national flow standard.

Introduction

As flow data collected from potable water supply and distribution systems are used for various forecasting and revenue purposes, it is important to know the degree of accuracy of the data obtained. Generally, the less the error in the data, the greater the accuracy of the forecast and possibly the reduction in lost revenue.

Flow meters can be evaluated on test facilities where the meter under test is compared against a standard. This standard could either be another flow meter of better accuracy or a technique utilising weighing methods or volumetric methods. Ideally, this standard should be traceable to an appropriate national standard.

In South Africa, the National Calibration Services (NCS) of the CSIR facilitates a national system for the calibration of instruments which then have an accuracy traceable to national measuring standards as required by law. The NCS therefore verifies a test facility's stated accuracy, the values of which have been determined by SABS, British or International Standards. The NCS specifies requirements such as which documentation should be kept, the competence of the staff undertaking the tests, the intervals with which the test facility itself should be recalibrated (i.e. reference meters), etc. On compliance with these requirements, the test facility is certified by the NCS as an approved laboratory.

The two better known NCS-approved flow laboratories are those of Eskom and the Johannesburg Municipality which can test flow meters up to 1 000 mm and 400 mm dia. respectively.

These test facilities have reference accuracies of 0.1% which is not a necessary requirement for all flow-meter calibrations.

On these types of test facilities the evaluation of in-line flow meters obviously requires their removal from site which can be expensive considering the labour, transport and testing costs.

On installation, a calibrated flow meter's performance will differ from its performance as evaluated on a test facility. This difference cannot be verified unless the meter is calibrated *in situ* (Furness, 1991).

There is, therefore, also a need to determine the flow rate to a known degree of accuracy within large pipelines by means of a portable flow meter so that those in-line meters which cannot be easily removed for testing can be evaluated or, previously calibrated flow meters can be calibrated *in situ* to take into account particular site conditions.

Guidelines for the reduction and control of unaccounted-for water give high priority to the *in situ* testing of source (production) and district meters in an unaccounted-for water investigation (Jeffcoate and Saravanapavan, 1987). These guidelines were designed for use by managers of water authorities in developing countries.

By using a portable insertion meter to measure the velocity at various points in the pipe, and the velocity-area method to determine the flow, a suitable reference standard can be established for calibrating flow meters *in situ* (Johnson, 1987).

The basic assumption in deriving most of the velocity-area methods for velocity profile integration is that the velocity curve assumed approaches the real velocity profile in the line of traverse. This is reasonable for axisymmetric flow profiles (Salami, 1971).

This paper provides a brief review of previous studies on the subject of velocity-area methods for flow determination, and suggests some practical guidelines as to the application of insertion meters to ensure that a suitable *in situ* reference standard can be established for the calibration of large in-line flow meters within a water supply and distribution network.

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#Revised paper; originally presented as a slide presentation at an SAIMC and SAICE Seminar on Water Management at Richards Bay on 9 July 1992 and to Eskom and DWAF representatives at Witbank on 9 June 1993.

Received 9 May 1994; accepted in revised form 15 February 1995.

Flow-meter accuracy

As the accuracy of a flow meter can be interpreted in various ways, "accuracy" has been briefly defined here to ensure conformity in its meaning and use. Accuracy is defined as the closeness of the actual reading to the true value and it includes the effect of both precision and bias error.

Precision is the ability of a measuring device to repeat the same readings for the same input. Because variations in readings are random, statistical theory can be used to calculate a precision value from the variance of the readings (Miller, 1989). Precision is calculated from the standard deviation for the data points multiplied by a correction factor derived from the student's t-distribution for the 95% confidence level. Bias error is the difference between the average and the true value, as established by a reference standard. The respective formulae are detailed in the **Appendix**.

"Uncertainty" is often used as a synonym for "accuracy". However, uncertainty is the property of a measurement rather than the instrument used to make the measurement (Hayward, 1979).

International Standard ISO 5168 (1978) defines the uncertainty of measurement as the interval within which the true value of the measured quantity can be expected to lie with a suitably high probability. This uncertainty of measurement and the confidence level associated with the uncertainty indicates the probability that the interval quoted will include the true value of the quantity being measured.

The International Organisation for Legal Metrology (Organisation Internationale de Métrologie Légale, 1971) describes accuracy as an overall quality of a measuring instrument from the point of view of errors. Accuracy is greater when the indications are closer to the true value. Therefore, an accuracy of 99% is an inaccuracy of 1%. However, inaccuracy is also sometimes referred to as "accuracy" (Miller, 1989).

Flow meters and auxiliary instruments are usually assigned a reference condition accuracy which is a laboratory-determined accuracy envelope for the range of the instrument's operation. If however, the instrument is used outside its reference range, it can be specified in terms of a limit of error.

Velocity-area method of flow determination

The determination of velocities at various points across one plane in a pipe flowing full and under pressure usually finds the maximum velocity positioned at the centre of the pipe with the velocity reducing as measurements are taken closer to the pipe wall.

The velocity-area method requires that the flow sensor should be inserted at predetermined points across the plane for the measurement of the local velocity. The mean of these local velocities is the average velocity of the water flow in the pipe.

Evaluation studies (Winternitz and Fischl, 1957; Salami, 1971) have indicated the merits of the various velocity-area methods of flow determination in pipes. The tangential method seems to be the one which is most commonly adopted while the log-linear method appears to be the most accurate.

According to Winternitz and Fischl (1957), the objective of these methods is to determine the flow rate through the pipe. This is given by:

$$Q = 2\pi \int_{o}^{R} r \, dr \, v \ldots.$$

where:

Q = flow rate
R = pipe radius
r = local radius at which point velocity is measured
v = point velocity.

Tangential method

This method consists basically of dividing the cross-section of the pipe into concentric rings of equal area, the innermost being a circle. The position at which the velocity reading is taken is at points which bisect each ring into two equal areas. The arithmetic average of these velocities is assumed to be the mean velocity of the flow through the cross-section.

The radii of these concentric rings of equal area can be determined by:

$$r = R\sqrt{\frac{2i - 1}{2N}} \qquad \text{(Salami, 1971)}$$

where:

r = local radius at which point velocity is measured
R = pipe radius
N = *number of gauging points per pipe radius*
i = 1, 2, 3, ... N

Log-linear method

The positions for measuring the velocities in each annulus are selected at the points where the mean velocity for a particular cross-section would occur. The proviso here is that a function must adequately describe the velocity profile and include these points.

The logarithmic functions used to describe the profile in the log-linear method can be expressed in general form as:

$$V = A^* + B^* \operatorname{Log}\left(\frac{y}{D}\right) \qquad \text{(Winternitz and Fischl, 1957)}$$

and for flow not fully developed:

$$V = A^* + B^* \operatorname{Log}\left(\frac{y}{D}\right) + C^*\left(\frac{y}{D}\right) \qquad \text{(Winternitz and Fischl, 1957)}$$

where:

A*, B* are constant with the dimension of velocity
C* = constant for a given velocity distribution and has the dimension of velocity
D = diameter
y = distance from pipe wall velocity is measured.

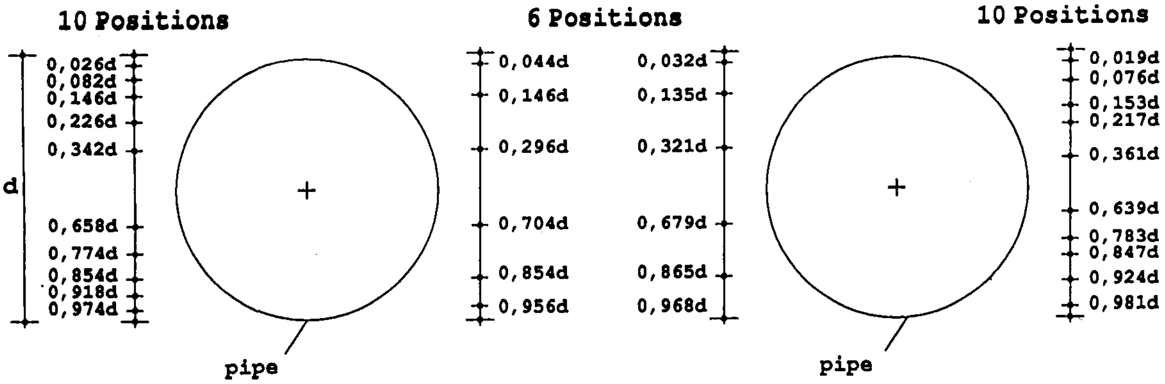
The **Appendix** to the article by Winternitz and Fischl (1957) provides the details of calculations and formulae for the determination of the gauging positions.

The gauging positions for both methods are indicated in Fig. 1.

Method-accuracy comparison

Salami (1971) measured ten asymmetric profiles of various shapes using four velocity-area methods of flow determination. As these profiles were asymmetric, the velocity measurements at the respective points along a number of traversing lines across the pipe are required to ensure that the true flow is determined. Salami's results concur with previous research (Winternitz and Fischl, 1957), that when measuring irregular velocity profiles, the log-linear method is more accurate for flow determination than the tangential method.

A comparison of the various integration methods for a single traverse line with volumetric measurements for 36 velocity profiles



(a) TANGENTIAL METHOD (b) LOG-LINEAR METHOD

Figure 1
Gauging positions for velocity-area methods (Winternitz and Fischl, 1957)

in fully developed turbulent pipe flow, indicated that the log-linear method was relatively more accurate than the tangential method (Winternitz and Fischl, 1957).

A general observation of these results is that for any method adopted, the greater the number of measuring points per traverse the more accurate is the flow determination for that method. The log-linear method is, however, more efficient in its application as it requires fewer measuring points to achieve accuracies better than that of the tangential method with a greater number of measuring points. This method is therefore cost-effective as it reduces the time required to determine the flow.

Pitot tubes were used in both the research projects detailed above and the assumption made was that the device was error-free with emphasis on the relative accuracy of the velocity-area methods rather than the overall accuracy of the measurement.

Velocity profile function

It is not always possible to place the measuring point of an insertion meter in the position stipulated by the particular velocity-area method being used. This may be due to the fact that the measuring position is related to the particular pipe dia., and therefore, the device is unable to measure near the pipe wall in cases of small dia. pipes because of the device's physical size. Alternatively the probe's length may be insufficient to traverse the length of an isolation valve, access tee and the full dia. of the pipe in the case of large dia. pipes.

Defining a function that best describes the velocity profile being measured in the field therefore becomes important when the restrictions mentioned above prevent the actual velocity measurement of some of the prescribed positions.

Prandtl derived a formula for the velocity distribution across a pipe operating within the constraints of the smooth pipe law (Webber, 1979). This theory assumes that the turbulent flow is separated from the pipe wall by a thin layer which serves the function of transmitting frictional drag, induced by turbulent flow, to the boundary by the mechanism of viscous shear. This implies that the laminar boundary layer acts as a smooth lining preventing the flow from being influenced by any excrescences on the pipe walls and consequently no eddies are formed.

The measuring section of a pipe would generally be selected smooth enough so that excrescences would not project through the laminar boundary layer and cause a disturbance and the resultant formation of a train of eddies that is characteristic of the rough pipe law (Johnson, 1987).

The velocities nearest the pipe wall that cannot be measured by the insertion meter can be calculated by fitting a parabolic curve to those velocities that can be measured and determining these missing values by extrapolation. The velocity distribution is, however, only parabolic in the laminar zone and extrapolation of the parabolic curve outside this laminar layer can result in an inadequate approximation of the velocity distribution (Winternitz and Fischl, 1957).

The Reynolds number is a correlating parameter that combines the effect of viscosity, density and pipeline velocity. The dimensionless number is calculated with the following formula:

$$\text{Reynolds number} \quad (\mathrm{Re}) = \frac{DV}{\nu}$$

where:

D = dia. of the pipe (m)
V = average velocity of the water (m/s)
ν = kinematic viscosity for water (m^2/s)

As the dimensionless Reynolds number and the pipe's relative roughness are useful criteria for distinguishing between laminar and turbulent flows, it can therefore be deduced that since the water mains in the network operate at a Reynolds number in the approximate region of 10^5 to 10^6 (which is well within the turbulent flow zone) and have an approximate relative roughness of 5×10^{-5}, the parabola equation cannot be applied outside the laminar boundary sublayer to any great extent (Johnson, 1987).

Since the objective of measuring the velocity profile within the pipe is to determine the mean velocity and its positions, other factors influencing the velocity distribution, such as the friction factor, are not directly relevant. The function describing the measured velocity distribution should therefore be independent of the friction factor, but dependent on the actual positions at which the average velocities (Y_{ave}) occur and the value of the centre-line velocity (V_{max}).

The Pao equation which relates the friction factor to average velocity has been used to describe the velocity profile in turbulent flow (Miller, 1989) and is modified here by the author to fulfil the above stated objective.

The Pao equation expressed in the general form is:

$$\frac{V}{\bar{V}_p} = 1 + (A + B \log \frac{y}{r_p}) \sqrt{f} \qquad \text{(Miller, 1989, Eq. 5.19)}$$

where:

V = Point velocity at distance y from pipe wall

r_p = Radius of pipe

y = Distance from pipe wall to point velocity (i.e. point velocity depth)

$\bar{v}_p$ = Average velocity in the pipe

f = Darcy-Weisbach friction factor derived from the Colebrook White formula (Webber, 1979)

$$A = \frac{1}{\sqrt{f}} \left[\frac{V_{max}}{\bar{V}_p} - 1 \right]$$

i.e. at the centre of the pipe the velocity is at a maximum and the point velocity depth is equal to the pipe radius.

$$B = \frac{-A}{\log \frac{Y_{ave}}{r_p}}$$

i.e at the depth of average velocity the point velocity equals average velocity.

therefore:

$$\frac{V}{\bar{V}_p} = 1 + \left[\left(\frac{\frac{V_{max}}{\bar{V}_p} - 1}{\sqrt{f}} \right) - \left(\frac{\frac{V_{max}}{\bar{V}_p} - 1}{\sqrt{f} \log \frac{Y_{ave}}{r_p}} \right) \log \frac{y}{r_p} \right] \sqrt{f}$$

simplifying:

$$\frac{V}{\bar{V}_p} = 1 + \left[\left(\frac{V_{max}}{\bar{V}_p} - 1 \right) - \left(\frac{\frac{V_{max}}{\bar{V}_p} - 1}{\log \frac{Y_{ave}}{r_p}} \right) \log \frac{y}{r_p} \right]$$

which shall be described as the modified Pao equation for the purposes of this paper.

The velocity profile calculated for both theories has been compared with the actual velocity profile measured within a 667 mm dia. cement mortar-lined pipeline and indicated that results from the modified Pao equation gave values closer to those measured than those determined by the smooth pipe law. The smooth pipe law is influenced by a change in temperature while the modified Pao equation is independent of temperature changes (Johnson, 1987).

Position of average velocity

Measuring the mean axial velocity within a pipe by single point measurement requires the positioning of the sensor at the position where this velocity will actually occur or within the known ratio of the insertion position to mean axial velocity depth. The latter method would appear, however, to be less accurate (Bossy et al., 1980).

A summary of 23 velocity profiles measured in pipelines ranging from 210 to 800 mm dia. has been detailed in Fig. 2 (Johnson, 1987). A portable turbine insertion meter was used to measure the point velocities at the ten positions defined by the tangential method. The position at which the mean axial velocity occurs is not constant for these profiles as indicated by standard deviations of 7.5 and 6.0% for the top and bottom positions respectively, which illustrates the degree with which these positions vary about the mean.

The slight asymmetry of the velocity profile could be ascribed to the access tee having an influence on the shape of the top portion of the profile as there is no pipe wall providing frictional drag, only a "plug" of water within the tee. The access tee could also cause a disturbance and therefore have an effect on the profile. The lower portion of the profile lies within established theories.

Profiles measured by means of Pitot tubes (Gebhardt, 1979) and electromagnetic insertion meters (Elmart Instruments, 1992) have also indicated that the location of the mean axial velocity within a pipe is not constant.

Codes, theories and research also differ as illustrated in Fig. 3 and are detailed as follows:

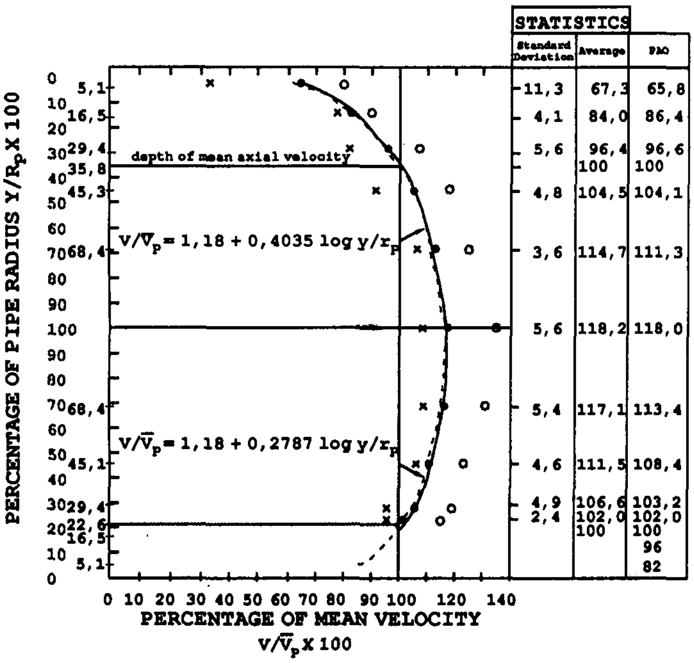


Figure 2

Summary of measured velocity profiles (Johnson, 1987)

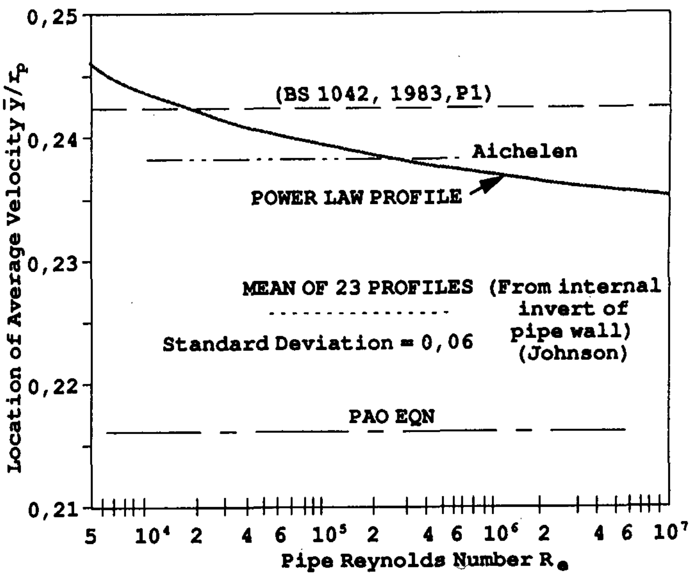


Figure 3
Location of average velocity from pipe wall (Miller, 1989)

NOTE: $\bar{y}$ = position of average velocity
r_p = pipe radius

Researcher/ Standard	Position of mean axial velocity	Reference
Aichelen	0.238 r	(Winternitz and Fischl, 1957)
Winternitz	0.224 r	(Winternitz and Fischl, 1957)
BS1042:1983	0.242 r	(BS1042 : Section 2.2 : 1983)
Pao	0.216 r	(Miller, 1989)
Johnson	0.226 r	(Johnson, 1987)

The British Standard (BS1042, Section 2.2, 1983) also provides a depth range of 0.229r to 0.255r at which the mean axial velocity can be measured in order to attain the specified flow accuracy of ± 3%. Aichelen (Bernard, 1988) found that the measured velocity at 0.238r was equal to the mean velocity within ± 0.7% for Reynolds numbers between 4 x 10^3 and 3 x 10^6.

In practice, the varying position of the mean axial velocity confirms the need to utilise a velocity profile function which is based on the actual positions for a particular installation. These positions are therefore determined each time the velocity profile is measured to allow for any change in upstream conditions.

Field application

Turbine-type current meters are accurate instruments (<0.2%) and are used for the calibration of differential pressure devices (Staubi, 1988). Although this type of insertion meter has been used by the author, other types could also be used (See **Reference Standard**).

The turbine insertion meter consists of a small diameter turbine and a magnetic pick-up on the end of a retractable probe.

The meter is inserted into the pipeline via an isolation valve (Fig. 4).

The passage of the water through the device causes the rotor to revolve at a rate proportional to the velocity of the fluid at that particular point. The magnetic pick-up at the end of the probe senses the movement of each rotor blade as it passes the pick-up. The frequency of the output pulses is directly proportional to the fluid flow rate.

In the field each point velocity is determined by measuring the frequency of the turbine's blade with the aid of the electronic instrumentation supplied with the flow meter.

This frequency is divided by the manufacturer's calibration constant for that particular flow meter. This constant has been determined by the evaluation of the flow meter's accuracy on a test facility which has a standard traceable to an appropriate national standard (local or overseas).

The measured point velocity is therefore calculated as follows:

$$\text{Measured point velocity} = \frac{\text{measured frequency}}{\text{manufacturer's calibration constant}}$$

Other factors affecting the overall accuracy of the turbine insertion

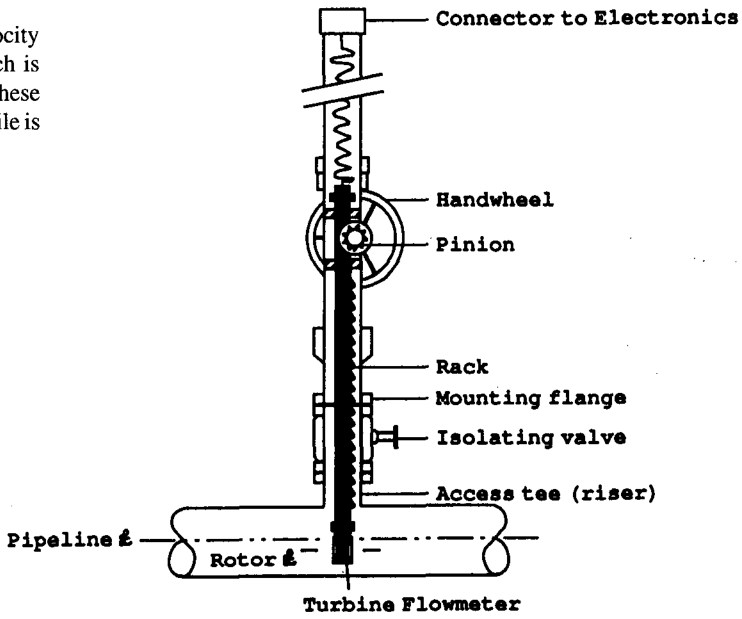


Figure 4
Insertion meter installation

meter include the blockage factor and the orientation of the insertion meter. The further the probe is inserted into the pipe the greater the area of pipeline which is blocked and, therefore, the greater the velocity of the water passing through the remaining unrestricted area. A blockage factor is determined for each insertion depth via a ratio of areas which corrects the local velocity measured.

The following relevant calculations are made:

$$\text{Blockage factor} = \frac{\text{calculated blockage} \times 100}{\text{area of pipe}}$$

$$\text{Velocity factor} = \frac{100}{100 - \text{blockage factor}}$$

$$\text{Actual point velocity} = \frac{\text{measured point velocity}}{\text{velocity factor}}$$

Application of the portable turbine insertion meter in the field requires the assistance of a hand-held computer for the determination of flow rates.

A program based on the modified Pao equation and which makes use of the log-linear method has been written for hand-held computers (Johnson, 1987).

The program developed uses empirically based constants for a first approximation of velocity measurement of the inaccessible measurement positions. The positions where the actual mean axial velocities occur are then calculated taking into account the point velocities which have been measured and new constants determined. This is an iterative process incorporating the modified Pao equation, the log-linear method and measured point velocities that determine the missing point velocities ensuring that the overall average velocity converges to within acceptable limits.

The positions of the mean axial velocity are therefore determined from actual velocity measurements during each traverse irrespective of the device's ability or inability to measure near the pipe wall and/ or over the full pipe dia. The reference accuracy would, however, generally be restricted to the accuracies of the log-linear method and those of the complete device if the whole profile could be measured.

After determination of these positions of mean axial velocity, the portable turbine insertion meter can then be set at either of these positions for the monitoring of various flow rates or for volumetric determination over a time period.

Reference standard

As it is uneconomical to calibrate a flow meter to a greater accuracy than that which is required (BS7405, 1991), it is essential when undertaking the evaluation of large "in-line" flow meters, to decide at the outset what accuracy is required from the calibration system.

From experience large in-line flow meters that are installed in the potable water supply and distribution network should have the accuracies for their respective functions as follows:

Revenue	± 2%
Control	± 3 to 5%
Planning/management	± 3 to 5%

The flow rate within the large (≥300 mm dia.) pipes in the water supply and distribution network is usually restricted to an equivalent maximum velocity of 3 to 4 m/s. This smaller range ensures greater accuracy in the calibration of the reference meter itself. Extrapolation outside this range of calibration is not recommended (BS7405, 1991).

The general accepted accuracy of the reference standard for production testing is four times better than that of the meter whose accuracy is being determined. Miller (1989) considers that it should be five times better. However, the overall accuracy as determined by the root-sum-square of the reference standard plus the in-line meter complete, should be within the required accuracy limits for which the flow data are required.

Some of the various types of insertion probes that could be utilised for the measurement of velocity profiles within pressure pipes are:

- Turbine (BS7405, 1991)
- Electromagnetic (BS7405, 1991)
- Vortex Shedding (Perrin, 1977)
- Pitot static tubes (BS1042, Section 2.1, 1983)
- Ultrasonic (Spitzer, 1990)
- Target (Spitzer, 1990)

A particular insertion flow meter's suitability as part of a reference standard would be determined by the following:

- It should be portable
- It should be uncomplicated to use (easy to operate)
- The particular device's measurement of point velocities must be within the required accuracies of the reference standard
- Access by the probe into the pipe under pressure must be possible
- The probe's length should be sufficient to traverse the length of an access tee, isolation valve and full dia. of the pipe
- The probe and velocity sensor should provide minimum restriction to the flow but be rigid enough not to vibrate at full extension
- Sampling of velocities at each point of measurement defined by the method should be possible
- An external micrometer or similar device should be included in the design of the insertion meter so that the exact position of the measuring point can be determined within the pipe.

Furness (1992) considers that long lengths of pipe upstream of the meter are required before the performance is unaffected by the actual installation.

To ensure that the flow is fully developed so that the best possible velocity profile is available at the measuring cross-section, the straight length of pipe before the measuring section should, where possible, equal a hundred times the pipe dia. (Miller, 1989). The BS1042 standard considers that a straight length of pipe equal to thirty to fifty times the pipe dia. is sufficient depending on the type of turbulence-causing device upstream (BS1042, 1983). The latter standard is related to the single predetermined point measurement of the mean axial velocity and therefore is considered acceptable for the measurement of the complete velocity profile especially as subsequent flows could be measured at the derived depth of mean axial velocity.

Some of the limitations and considerations in the use of the combination of a portable turbine insertion flow meter, with log-linear method and modified Pao equation as a flow reference standard for large in-line flow meters within the potable water supply and distribution network are:

- The minimum pipe dia. within which the velocity profile can be measured is 300 mm (BS1042, Section 2.2, 1983).

- At least the top half of the velocity profile must be measured (if used in conjunction with the previously mentioned computer program), but for greater accuracies the whole profile should be measured.
- It is important to ensure that there is a fully developed turbulent velocity profile that is non-swirling and axisymmetric by allowing a straight unobstructed length of pipe at least 30 to 50 times the pipe dia. upstream of the measuring point, dependent on the type of disturbance upstream. Downstream from the measurement point, the straight length should be at least equal to five pipe dia. irrespective of the type of disturbance (BS1042, Section 2.2, 1983).
- The flow must be steady at reference conditions and in order to comply with this requirement, it must not vary by more than ±3% for linear flow meters and more than ±6% for differential pressure flow meters (Miller, 1989). A factor to consider when complying with this requirement would be to restrict the time taken to measure the velocity profile to a minimum or to sample the velocity at the derived position of mean axial velocity.
- The insertion flow meter and associated instrumentation should be calibrated by the respective approved laboratories.
- The access tee dia. should be restricted to the minimum practically feasible for the insertion of the meter probe.
- The relative roughness of the internal pipe wall should be 1.0×10^{-4} or better.

It should be noted that establishing an overall reference standard by means of a complete accuracy (uncertainty) audit including all the sources of error is not practically feasible for every application. It is therefore incumbent on the user to establish from experience or otherwise, which factors to incorporate and which factors not to incorporate into the accuracy audit for each evaluation. It is, however, still important to identify all sources of possible error even if some of the values determined are small enough to be ignored in the final audit.

The objective of establishing this reference standard is to provide a cost-effective practical method for the field evaluation of large in-line flow meters and not necessarily to attempt to duplicate the high accuracies obtained by permanent test facilities.

Conclusion

The positions at which the mean axial velocity occurs in a pipeline are not fixed. The lack of conformity about these positions in the various codes and theories confirms this finding. These positions need to be determined for each situation and application especially if the measuring device is to measure the mean axial velocity by a single point velocity measurement for various rates.

A cost-effective method for the field accuracy evaluation of large in-line flow meters is required to ensure the subsequent flow data obtained are within the required accuracy for the purpose for which it is required. The application of a portable insertion flow meter, the log-linear method and modified Pao equation can be used for this purpose, which could be considered superior to the method whereby only a single velocity measurement is taken at a predetermined position.

Previous research has generally placed emphasis on the relative accuracy of the velocity-area methods rather than the overall accuracy of the measurement as related to a national flow standard.

Recommendations

It is recommended that research is undertaken to determine the combined accuracy of insertion meter measurements and velocity-area methods as compared to the national flow standard. Knowledge as to this combined accuracy can then be used as a reference standard for the *in situ* calibration of flow meters. It is further recommended that in establishing this reference standard cognizance is taken of relevant local and overseas standards.

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Appendix

Accuracy formulae

Precision at the 95% confidence level is:

$$\sigma_p = t\sigma \qquad \text{(Miller, 1989, Eq 4.4)}$$

where:

σ_p = precision (ISO 5168 (1978) defines this as uncertainty)
t = students t-value at 95% confidence level
σ = standard deviation

Bias error (B) is the difference between the average and the true value, as established by a reference standard.

$$B = \frac{\bar{I} - I}{I} \times 100 \qquad \text{(Miller, 1989, Eq 4.5)}$$

where:

B = Bias error (directional)
$\bar{I}$ = average
I = reference standard value

However, bias-error calculations have a degree of confidence associated with the average value. When the 95% confidence level is taken into account for the determination of precision a bias error range centred on the average can be established.

$$\pm B = \sigma_p / \sqrt{n} \qquad \text{(Miller, 1989, Eq. 4.8)}$$

where:

σ_p = precision
n = number of values

With the bias error known and with each reading corrected the accuracy calculation is

$$\text{Accuracy} = \pm \sqrt{\left(1 + \frac{1}{n}\right)\sigma_p^2} \qquad \text{(Miller, 1989, Eq. 4.10)}$$

Flow meters with good precision and for a reasonable number of data values, the accuracy can be approximated from:

$$\text{Accuracy} = \pm \sigma_p \qquad \text{(Miller, 1989, Eq. 4.11)}$$

Most instruments have a reference accuracy envelope that incorporates precision, directional bias and bias-error range over a specified range of the measured variable. The limits of the envelope are expressed as a percentage of the upper range value (URV) or as a percentage of the reading. Accuracy envelopes are specified for reference conditions and apply within the stated limits.

Operating condition accuracy is used to relate other independent influence quantities by the root-sum-square method.

$$\text{Accuracy} = \pm (\text{Acc})_{\text{ref}} \pm \left(B_1^2 + B_2^2 + B_3^2 \ldots\right)^{1/2}$$

(Miller, 1989, Eq. 4.12)

where:

ref = reference condition accuracy
1, 2, 3 = influence quantities.