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Introduction

1.1 Initial Considerations

Some years ago at Cranfield, where we had set up a flow rig for testing the effect of upstream pipe fittings on certain flowmeters, a group of senior Frenchmen was being shown around and visited this rig. The leader of the French party recalled a similar occasion in France when visiting such a rig. The story goes something like this.

A bucket at the end of a pipe seemed particularly out of keeping with the remaining high-tech rig. When someone questioned the bucket's function, it was explained that the bucket was used to measure the flow rate. Not to give the wrong impression in the future, the bucket was exchanged for a shiny, new, high-tech flowmeter. In due course, another party visited the rig and observed the flowmeter with approval. "And how do you calibrate the flowmeter?" one visitor asked. The engineer responsible for the rig then produced the old bucket!

This book sets out to guide those who need to make decisions about whether to use a shiny flowmeter, an old bucket, nothing at all or a combination of these! It also provides information for those whose business is the design, manufacture or marketing of flowmeters. I hope it will, therefore, be of value to a wide variety of people, both in industry and in the science base, who range across the whole spectrum from research and development through manufacturing and marketing. In my earlier book on flow measurement (Baker 1988a/1989, 2002b, 2003), I provided a brief statement on each flowmeter to help the uninitiated. This book attempts to give a much more thorough review of published literature and industrial practice.

This first chapter covers various general points that do not fit comfortably elsewhere. In particular, it reviews guidance on the accuracy of flowmeters (or calibration facilities).

The second chapter reviews briefly some essentials of fluid mechanics necessary for reading this book. The reader will find a fuller treatment in Baker (1996), which also has a list of books for further reading.

A discussion of how to select a flowmeter is attempted in Chapter 3, and some indication of the variety of calibration methods is given in Chapter 4, before going in detail in Chapters 5–20 into the various high- (and low-) tech meters available.

In this edition, I have introduced three additional chapters to cover new commercial meters and to allow a brief and superficial review of multiphase hydrocarbon flowmeters. Chapter 21 deals with probes. Chapter 22 covers general issues relating to verification and clamp-on meters. Chapter 23 provides a brief introduction to remote data handling and Chapter 24 provides final personal reflections relating to manufacture and future developments.

In this book, I have tried to give a balance between the laboratory ideal, manufacturers' claims, the realities of field experience and the theory behind the practice. I am very conscious that the development and calibration laboratories are sometimes misleading places, which omit the problems encountered in the field (Stobie 1993), and particularly so when that field happens to be the North Sea. This may be more serious for flowmeters than for some other instruments, and may require careful consideration of the increase in uncertainty which results. In the same North Sea Flow Measurement Workshop, there was an example of the unexpected problems encountered in precise flow measurement (Kleppe and Danielsen 1993), resulting, in this case, from a new well being brought into operation. It had significant amounts of barium and strontium ions, which reacted with sulphate ions from injection water and caused a deposit of sulphates from the barium sulphate and strontium sulphate that were formed.

With that salutary reminder of the real world, we ask an important – and perhaps unexpected – question.

1.2 Do We Need a Flowmeter?

Starting with this question is useful. It may seem obvious that anyone who looks to this book for advice on selection is in need of a flowmeter, but for the process engineer it is an essential question to ask. Many flowmeters and other instruments have been installed without careful consideration being given to this question and without the necessary actions being taken to ensure proper documentation, maintenance and calibration scheduling. They are now useless to the plant operator and may even be dangerous components in the plant. Thus, before a flowmeter is installed, it is important to ask whether the meter is needed, whether proper maintenance schedules are in place, whether the flowmeter will be regularly calibrated, and whether the company has allocated to such an installation the funds needed to achieve this ongoing care. Such care will need proper documentation.

The water industry in the United Kingdom has provided examples of the problems associated with unmaintained instruments. Most of us involved in the metering business will have sad stories of the incorrect installation or misuse of meters. Reliability-centred maintenance recognises that the inherent reliability depends on the design and manufacture of an item, and if necessary this will need improving (Dixey 1993). It also recognises that reliability is preferable in critical situations to extremely sophisticated designs, and it uses failure patterns to select preventive maintenance.

In some research into water consumption and loss in urban areas, Hopkins, Savage and Fox (1995) found that obstacles to accurate measurements were

- buried control valves,
- malfunctioning valves,
- valve gland leakage,
- hidden meters that could not be read and
- locked premises denying access to meters.

They commented that "water supply systems are dynamic functions having to be constantly expanded or amended. Consequently continuous monitoring, revisions and amendments of networks records is imperative. Furthermore, a proper programme of inspection, maintenance and subsequent recording must be operative in respect of inter alia:

- networks,
- meters,
- control valves,
- air valves,
- pressure reducing valves,
- non-return valves."

They also commented on the poor upstream pipework at the installation of many domestic meters.

So I make no apology for emphasising the need to assess whether a flowmeter is actually needed in any specific application.

If the answer is yes, then there is a need to consider the type of flowmeter and whether the meter should be measuring volume or mass. In most cases, the most logical measure is mass. However, by tradition, availability and industrial usage, volume measurement may be the norm in some places, and as a result, the regulations have been written for volume measurement. This results in a Catch-22 situation. The industry and the regulations may, reasonably, resist change to mass flow measurement until there is sufficient industrial experience, but industrial experience is not possible until the industry and the regulations allow. The way forward is for one or more forward-looking companies to try out the new technology and obtain field experience, confidence in the technology and approval.

In this book, I have made no attempt to alert the reader to the industry-specific regulations and legal requirements, although some are mentioned. The various authors touch on some regulations, and Miller (1996) is a source of information on many documents. An objective of the Organisation Internationale de Métrologie Légale (OIML) is to prevent any technical barriers to international trade resulting from conflicting regulations for measuring instruments. With regard to flow measurement, it appears to have been particularly concerned with the measurement of domestic supplies and industrial supplies of water and gas (Athane 1994). This is because two parties, the supplier and the consumer, are involved, and the consumer is unlikely to be able to ascertain the correct operation of the meter. In addition, the supplier does not continually monitor these measurements, the meters may fail without anyone knowing, the usage is irregular and widely varying in rate, the measurements are not repeatable, and the commodities have increased in value considerably in recent years.

In order to reduce discussions and interpretation problems between manufacturers and authorised certifying institutes, the European Commission was mandating the European standardisation bodies (CEN and CENELEC) to develop harmonised standards that would give the technical details and implementation of the requirements based on OIML recommendations. These would be such that a measuring instrument complied with essential requirements, assuming that the manufacturer had complied with them (Nederlof 1994).

The manufacturer will also be fully aware of the electromagnetic compatibility (EMC), which relates to electromagnetic interference. In particular, the EMC characteristics of a product are that

- the level of electromagnetic disturbance the instrument generates will not interfere with other apparatuses, and
- the operation of the instrument will not be adversely affected by electromagnetic interference from its environment.

In order to facilitate free movement within the European area, the CE mark was designed to identify products that conformed to the European essential requirements. For further details relating to the European Community (EC), the reader is referred to the Measuring Instrument Directive (MID 2004, DTI 1993, Chambers 1994).

First, we consider the knotty problem of how accurate the meter should be.

1.3 How Accurate?

Inconsistency remains about the use of terms that relate to accuracy and precision. This stems from a slight mismatch between the commonly used terms and those that the purists and the standards use. Thus we commonly refer to an accurate measurement, when strictly we should refer to one with a small value of uncertainty. We should reserve the use of the word *accurate* to refer to the instrument. A high-quality flowmeter, carefully produced with a design and construction to tight tolerances and with high-quality materials as well as low wear and fatigue characteristics, is a precise meter with a quantifiable value of repeatability. Also, it will, with calibration on an accredited facility, be an accurate meter with a small and quantifiable value of measurement uncertainty. In the context of flowmeters, the word *repeatability* is preferred to *reproducibility*. The meanings are elaborated on later, and I regret the limited meaning now given to *precision*, which I have used more generally in the past and shall slip back into in this book from time to time! In the following chapters, I have attempted to be consistent in the use of these words. However, many claims for accuracy may not have been backed by an accredited facility, but I have tended to use the phrase “measurement uncertainty” for the claims made.

Hayward (1977a) used the story of William Tell to illustrate precision. William Tell had to use his crossbow to fire an arrow into an apple on his little son's head. This was a punishment for failing to pay symbolic homage to an oppressive Austrian ruler. Tell succeeded because he was an archer of great skill and high accuracy.

An archer's ability to shoot arrows into a target provides a useful illustration of some of the words related to precision. So Figure 1.1(a) shows a target with all the shots in the bull's-eye. Let us take the bull's-eye to represent ±1%, within the first ring ±3%, and within the second ring ±5%. Ten shots out of ten are on target, but how many will the archer fire before one goes outside the bull's-eye? If the archer, on average, achieves 19 out of 20 shots within the bull's-eye [Figure 1.1(b)], we say that the archer has an uncertainty of ±1% (the bull's-eye) with a 95% confidence level (19 out of 20 on the bull's-eye: $19 \div 20 = 0.95 = 95 \div 100 = 95\%$).

Suppose that another archer clusters all the arrows, but not in the bull's-eye, Figure 1.1(c). This second archer is very consistent (all the shots are within the same size circle as the bull's-eye), but this archer needs to adjust his aim to correct the offset. We could say that the second archer has achieved high repeatability of ±1%, but with a bias of 4%. We might even find that 19 out of 20 shots fell within the top left circle so that we could say that this archer achieved a repeatability within that circle of ±1% with a 95% confidence. Suppose this archer had fired one shot a day, and they had all fallen onto a small area [Figure 1.1(c)], despite slight changes in wind, sunshine and archer's mood; we term this good day-to-day repeatability. But how well can we depend on the archer's bias? Is there an uncertainty related to it?

Finally, a third archer shoots 20 shots and achieves the distribution in Figure 1.1(d). One has missed entirely, but 19 out of 20 have hit the target somewhere. The archer has poor accuracy, and the uncertainty in this archer's shots is about five times greater than for the first, even though the confidence level at which this archer performs is still about 95%.

If the third archer has some skill, then the bunching of the arrows will be greater in the bull's-eye than in the next circle out, and the distribution by ring will be as shown in Figure 1.1(e).

We shall find that the distribution of readings of a flowmeter results in a curve approximating a normal distribution with a shape similar to that for the shots. Figure 1.1(f) shows such a distribution where 95% of the results lie within the shaded area and the width of that area can be calculated to give the uncertainty, ±1% say, of the readings with a 95% confidence level. In other words, 19 of every 20 readings fall within the shaded area.

With this simplistic explanation, we turn to the words that relate to precision.

Accuracy

It is generally accepted that *accuracy* refers to the truthfulness of the instrument. An instrument of high accuracy more nearly gives a true reading than an instrument of low accuracy. Accuracy, then, is the quality of the instrument. It is common to refer to a measurement as accurate or not, and we understand what is meant. However,

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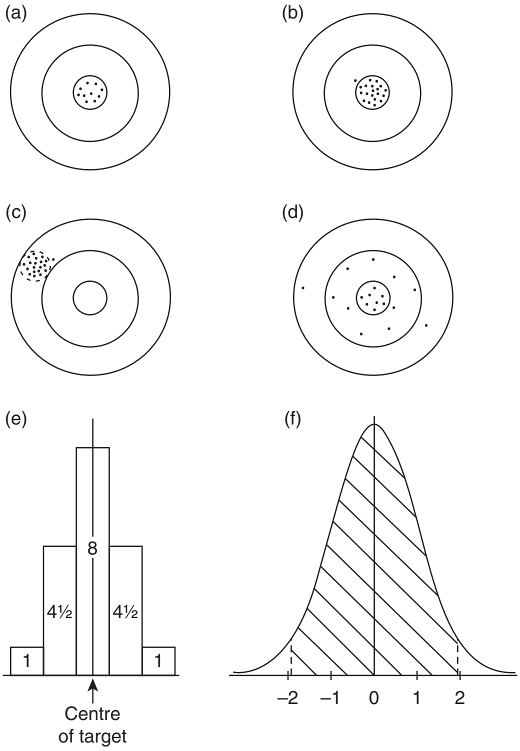

Figure 1.1. Precision related to the case of an archery target. **(a)** Good shooting – 10 out of 10 arrows have hit the bull's-eye. An accurate archer? **(b)** Good shooting? – 19 out of 20 arrows have hit the bull's-eye. An accurate archer and a low value of uncertainty (±1%) with a 95% confidence level. (**c**) Shots all fall in a small region but not the bull's-eye. Good repeatability (±1%) but a persistent bias of 4%. (**d**) Shots, all but one, fall on the target – 19 out of 20 have hit the target. A ±5% uncertainty with 95% confidence level. **(e)** Distribution of shots in (d) on a linear plot, assuming that we can collapse the shots in a ring semicircle onto the axis. **(f)** The normal distribution, which is a good approximation for the distribution of flowmeter readings.

the current position is that accuracy should be used as a qualitative term and that no numerical value should be attached to it. It is, therefore, incorrect to refer to a measurement's accuracy of, say, 1%, when, presumably, this is the instrument's measurement uncertainty, as is explained later.

Repeatability

In a process plant, or other control loop, we may not need to know the accuracy of a flowmeter as we would if we were buying and selling liquid or gas, but we may require repeatability within bounds defined by the process. *Repeatability* is the value below which the difference between any two test results, taken under constant conditions with the same observer and with a short elapsed time, are expected to lie with 95% confidence.

Precision

Precision is the qualitative expression for repeatability. It should not take a value and should not be used as a synonym for accuracy.

Uncertainty

Properly used, *uncertainty* refers to the quality of the measurement, and we can correctly refer to an instrument reading having an uncertainty of ±1%. By this we mean that the readings will lie within an envelope ±1% of the true value. Each reading will, of course, have an individual error that we cannot know in practice, but we are interested in the relationship of the readings to the true value. Because *uncertainty* is referred to the true value, by implication it must be obtained using a national standard document or facility. However, because it is a statistical quantity, we need also to define how frequently the reading does, in fact, lie within the envelope; hence the confidence level.

Confidence Level

The *confidence level*, which is a statement of probability, gives this frequency, and it is not satisfactory to state an uncertainty without it. Usually, for flow measurement, this is 95%. We shall assume this level in this book. A confidence level of 95% means that we should expect on average that 19 times out of 20 (19/20 = 95/100 = 95%) the reading of the meter will fall within the bracket specified (e.g. ±1% of actual calibrated value).

Linearity

Linearity may be used for instruments that give a reading approximately proportional to the true flow rate over their specified range. It is a special case of *conformity* to a curve. Note that both terms really imply the opposite. *Linearity* refers to the closeness within which the meter achieves a truly linear or proportional response. It is usually defined by stating the maximum deviation (or nonconformity e.g. ±1% of flow rate) within which the response lies over a stated range. With modern signal processing, linearity is probably less important than conformity to a general curve. *Linearity* is most commonly used with such meters as the turbine meter.

Range and Rangeability

An instrument should have a specified range over which its performance can be trusted. Therefore, there will be upper- and lower-range values. This reflects the fact that probably no instrument can be used to measure a variable when there are no limitations on the variable. Without such a statement, the values for uncertainty, linearity etc. are inadequate. The ratio of upper-range value and lower-range value may be called the *rangeability*, but it has also been known as the *turndown ratio.* The difference between upper- and lower- or negative-range values is known as *span.* It is important to note whether the values of uncertainty, linearity etc. are a percentage of the actual flow rate or of the full-scale flow [sometimes referred to as full-scale deflection (FSD), full-scale reading (FSR), maximum-scale value, or upper-range value (URV)].

1.4 A Brief Review of the Evaluation of Standard Uncertainty

Kinghorn (1982) points out the problem with terminology in matters concerning statistics and flow measurement. To the engineer and the statistician, words such as *error* and *tolerance* may have different meanings. The word *tolerance* was used for what is now known as uncertainty.

In providing an introduction to the terminology of uncertainty in measurement, I shall aim to follow the guidance in BIPM et al. (2008), which is usually known as the *Guide* or GUM, and also in a document consistent with the *Guide*, which provides the basis for uncertainty estimates in laboratories accredited in the United Kingdom (UKAS 2012). The reader should note that the *Guide* may also be available as ISO/IEC 98-3: 2008 and that a further valuable document is a guide on the vocabulary of metrology, ISO/IEC 99: 2007. The reader is strongly advised to consult this document, which is full of clear explanations and useful examples. Those wishing to pursue background arguments are referred to Van der Grinten's (1994, 1997) papers.

Random error, the random part of the experimental error, causes scatter, as the name suggests, and reflects the quality of the instrument design and construction. It is the part that cannot be calibrated out, and the smaller it is, the more precise the instrument is. It may be calculated by taking a series of repeat readings resulting in the value of the standard deviation of a limited sample n, and sometimes called the experimental standard deviation:

$$s\left(q_{\mathrm{j}}\right)=\left\{\frac{1}{n-1}\sum_{j=1}^{n}\left(q_{\mathrm{j}}-\bar{q}\right)^{2}\right\}^{1/2} \tag{1.1}$$

where $\bar{q}$ is the mean of n measurements q_{j}. The experimental standard deviation of the mean of this group of readings is given by

$$s\left(\bar{q}\right)=\frac{s\left(q_{\mathrm{j}}\right)}{\sqrt{n}} \tag{1.2}$$

Where too few readings have been taken to obtain a reliable value of $s(q_{\mathrm{j}})$, an earlier calculation of $s(q_{\mathrm{j}})$ from previous data may be substituted in Equation (1.2). In obtaining the overall uncertainty of a flowmeter or a calibration facility, there will be values of group mean experimental standard deviation for various quantities, and so UKAS (2012) defines a standard uncertainty for the *i*th quantity as

$$u(x_i) = s(\bar{q}) \tag{1.3}$$

where x_i is one of the input quantities. For those with access to UKAS (2012), this is, essentially, dealt with there as a Type A evaluation of standard uncertainty.

Systematic error, according to flowmeter usage, is that which is unchanging within the period of a short test with constant conditions. This is, essentially, dealt with in UKAS (2012) under the heading Type B evaluation of standard uncertainty. It is also called *bias.* However, in modern flowmeters and in calibration facilities, it is likely that this bias or systematic error will result in a meter adjustment, or a rig correction. The resulting uncertainty in that adjustment or correction will contribute to the overall uncertainty. The systematic uncertainty, therefore, may derive from various factors such as

a. uncertainty in the reference and any drift,
b. the equipment used to measure or calibrate,
c. the equipment being calibrated in terms of resolution and stability,
d. the operational procedure, and
e. environmental factors.

From these we deduce further values of $u(x_i)$.

There has been debate about the correct way to combine the random and systematic uncertainties. We can combine random and systematic uncertainties conservatively by arithmetic addition. This results in a conservative estimate. UKAS (2012) has followed the *Guide* in taking the square root of the sum of the squares of the standard uncertainties in consistent units. Thus the combined standard uncertainty is

$$u_c(y) = \sqrt{\sum [c_i\, u(x_i)]^2} \tag{1.4}$$

where y is the output quantity. To ensure consistent units, a sensitivity coefficient, c_i, will be required for each input x_i, although in practice this may be unity in most cases (as in Figure 4.3).

The final step (and we have glossed over many important details in UKAS 2012) is to deduce from u_c the bracket within which the reading of, say, the meter lies.

In the past, bearing in mind that u_c or its components have been derived from standard deviations, we have used Student's t value, which for a number of readings n is given by

n	t
10	2.26
20	2.09
>30	2.0

for a 95% confidence level. The *Guide* replaces this, in general, with a coverage factor, k, to obtain the expanded uncertainty

$$U = ku_{\mathrm{c}}(y) \tag{1.5}$$

The recommended value is $k = 2$, which gives a confidence level of 95.45% taken as 95%, assuming a normal distribution. If this assumption is not adequate, then we need to revert to Student's t.

The net result is that the assumption of a factor of 2 has now been given a systematic basis. The reader who is interested in more details about the basis of normal and t distributions is referred to Appendix 1.A.

1.5 Note on Monte Carlo Methods

An alternative approach, which is an outcome of the speed and accessibility of personal computers, is based on the use of random number generators to model instrument errors, and on running many tests to obtain the overall uncertainty of the system, say, a flow calibration rig. This is known as the Monte Carlo method for assessing uncertainty.

Not being a statistician, my perception of these methods is that, essentially, a numerical model of the measurement system is set up on a computer, instrument and system errors are modelled using values obtained from a random number generator and the measurement procedure is, thereby, modelled. The program is then run very many times, to obtain the likely uncertainty by averaging all the results. The procedure may be less conservative in its assessment than the standard GUM (BIPM et al. 1993) approach.

Monte Carlo computer programs are available, some as freeware. One or more such programs may be specifically modelled on the latest GUM approach (e.g. GUM-Workbench may be available) (private communication from Peter Lau).

Some explanation of the procedure can be found in Coleman and Steele (1999).

1.6 Sensitivity Coefficients

Suppose that output quantity, a flow rate, has the relationship

$$y = x_1^p x_2^q x_3^r x_4^s \tag{1.6}$$

then if x_2, x_3 and x_4 are held constant, we can differentiate y with respect to x_1 and obtain the partial derivative. This is the slope of the curve of y against x_1 when the other variables are kept constant. It also allows us to find the effect of a small change in x_1 on y. This slope (or partial derivative) is the sensitivity coefficient c_1 for x_1 and may be found by calculation. It will have the value $c_1 = px_1^{(p-1)} x_2^q x_3^r x_4^s$, where the values of x_1, x_2, x_3 and x_4 will be at the calibration point and may be dimensional. In some cases, it may be a known coefficient (e.g. a temperature coefficient of