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Development of ISO Standards:

Uncertainties in Flow Measurement

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1 INTRODUCTION

Most people are aware of the national and international standards of mass and length since these are kept secure and safe in national laboratories. They may be a little unsure about where the international standard of time is kept but they will appreciate that there can only be one single measure of time. In fact time is now based upon the caesium 133 atom frequency and it can be transmitted from place to place quite easily without affecting the primary aspect of a standard. Copies have been made of mass and length standards and these are used in nationwide measurement services.

When it comes to flow measurement it is not possible to have a tangible standard in the way that the mass/length standard can be converted into a volume standard measure. The measurement is a dynamic one and the method used is to collect the flow for a measured time to obtain a mean value over that time. This mean value can be related to the flowrate measured by a transfer standard device. The calibration of this device then means that its indications have been checked against an accredited flow measurement test facility and it can be used to transfer this flowrate to a local site.

The modern industrial world depends upon accurate measurement whether the best that can be obtained is one part in a million or one in ten. What is of immense and vital importance is that the reality of the level of accuracy should be adequately estimated and accepted.

These notes describe the development of standards for the estimation of the uncertainties in flow measured - use of the word accuracy is to be discouraged for this purpose since it has come to have many different meanings.

2 STANDARDS ON FLOW MEASUREMENT

There are many different bodies which issue standards on flow measurement as such, or who include details about the way in which the flow measurements associated with the particular specification are to be carried out. The International Organization for Standardization, ISO, and the International Electrotechnical Commission, IEC, are the two world-wide bodies which have established the greatest acceptance since they are supported by the national standards bodies in all the key countries in the world. Examples of the second type of standard are the documents issued by the ISO Technical Committee dealing with pumps, ISO/TC115, which deal with the hydraulic testing of pumps, where flow measurement clearly plays a major role.

Though not all the standards attempt to explain in any detail about the estimation of the overall uncertainty of the measurement being made, most give a simple estimation of the 'accuracy'. The danger of neglecting to give such estimations entirely is obvious but it is a fact that there is a common tendency, even when the message is clearly stated in the standard, for the reader to jump over this section on the grounds that it is too difficult to understand and 'anyway it does not matter'.

The advent of the common calculator 20 years ago and now even more the recent introduction of the microchip and the video display can easily lead the user to accept the row of figures which he reads or sees being printed as being absolute.

Most of the equipment for making measurements sold today comes with its readout attractively digitised and displayed to four or more figures. It pays to stop and think what is behind such displays for while it need not be doubted that the calculations are accurate to the last figure given, it has to be realized that the electronics is subject to variations in its conversion to the microchip from the basic sensor, while that sensor itself could be in error by a significant amount.

The value of ±1-2 per cent which is usually given, for example, for the uncertainty associated with the measurement of flow requires 'experienced personnel with apparatus of high accuracy'. Turning this into practical terms so that its meaning can be appreciated, if the output of a large pump were stated as being: 2.763 m^3/s then it can be expected that with 95 per cent confidence limits (that is roughly 19 times out of 20) that the true flowrate will lie somewhere between 2.708 and 2.818 m^3/s. It will then be realized that this, in truth, brings the number of figures down to two or at most two and a half and not the four significant figures given.

Thus this flowrate should really be represented as lying between

$$2.7 \text{ and } 2.8 = 2.75 \pm 0.05 \text{ m}^3/\text{s}.$$

Think of how often you have seen a display with 27 653.08.

3 UNCERTAINTY OF MEASUREMENTS

Every physical measurement must have associated with it an uncertainty, however small. In this space age it may be claimed to measure time with unbelievable accuracy to one part in a million million, or better, but that statement still includes an uncertainty in the one part. By contrast the above example for the determination of the flowrate was only claiming one part in 50. The concept is the same, however, in that the absolute value is not known and can only be inferred from the measurements which have been made.

The degree of certainty in the precise value of any measurement can be found in fact only by a very careful examination of all the sources and contributory causes of error in the system being used, in the equipment and instrumentation available and in the fluctuations and variations of the phenomenon itself which is being measured.

If one thinks of measuring the velocity of the wind one realizes instantly that it is neither constant in space or in time and indeed that putting something in its path to measure its velocity itself changes it. So it is with the testing of pumps or compressors, though fortunately the degree of variation within the parameters of head, flow and speed is very much less than the fluctuations of wind velocity. Similarly on custody transfer the fluctuations in the flow can cause problems with the instrumentation attempting to read the total quantity passed.

Add to this that in a single measurement the evidence and data which can be collected are inevitably limited both by cost and time, then it is clear that it is quite impracticable to make all the exhaustive analyses of all sources etc which are described in textbooks on statistics. In consequence it is not possible to deduce explicit and exact values and confidence levels for the uncertainties in these measurements. What has to be remembered however is that it is important to collect as much evidence from calibrations, other data, the standard and the measurements themselves as possible in the time available, and to use this. In addition, in their absence, it is equally important that reasoned estimates should be made of all possible sources of uncertainty based on observation and previous experience.

4 ACCURACY AND REPEATABILITY

To illustrate the importance of agreement on standarized ways of reporting, the words accuracy and repeatability can be cited. There has been, and still is, immense confusion for the reader on what is meant by these terms. They will be seen in instrument catalogues and in reports and books, often without any qualification or accompanying definition.

Apart from the difficulty in understanding what is meant by someone saying that 'the accuracy of this measurement was higher than that one' which could be greater or less in absolute value, the word used on its own is dangerous. Hence it is that over the past 20 years the word 'uncertainty' with a specific meaning has come to be adopted to replace the vague word 'accuracy'.

In the flow measurement field the responsible ISO Technical Committee, ISO/TC30, created a subcommittee, TC30/SC9, to prepare standards on the assessment of uncertainties. In fact the principles given in the first of these ISO 5168$^{(1)}$ have been very well received and are being applied to many other measurements.

Suppose, as shown in Fig. 1, that ten readings of a parameter have been taken. The mean value of these ten readings can be determined. What then is the uncertainty of this mean value or in the old terminology, what is its accuracy? Statistically the standard deviation of the individual test points can be calculated and the standard error of the mean found from:

$$S_{\bar{a}} = \pm \left\{ \frac{\sum_{i=1}^{i=n} (a_i - \bar{a})^2}{n(n-1)} \right\}^{\frac{1}{2}} .$$

This must be multiplied by a factor called Student's t to obtain a statistical value which then has confidence limits. The 95 per cent confidence limits referred to earlier are the preferred and internationally recognized confidence levels used by mechanical engineers. They are equal to $tS_{\bar{a}}$ where t approaches 1.96 as the number n approaches infinity. For a set of test points numbering 15 or more the value of 2 for t is a reasonable approximation. Student's t can be estimated with adequate confidence from the equation

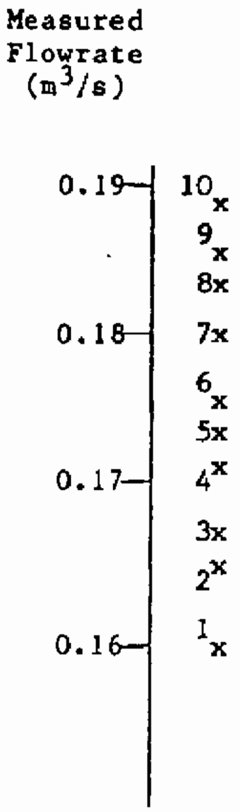
$$t = 1.96 + 2.36/v + 3.2/v^2 + 5.2/v^{3.84}$$

where v is the number of degrees of freedom, and is usually one less than the number of test points.

From Fig. 1 it can be seen how an uncertainty value might be quoted which would be valid say for 50 per cent confidence limits, instead of the 95 per cent level. Unless the value is stated as being associated with that level of confidence, however, a very false impression could be given.

Turning to the term 'repeatability', confusion over its definition has still not been fully resolved. The table overleaf illustrates the problem.

ILLUSTRATING DIFFERENT WAYS OF DEFINING 'REPEATABILITY'



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

*Repeatability values vary from 1.5 to 14.1 per cent

Eight different definitions are given in this table of the repeatability indicated by the set of points. The first five are associated with the statistical determination of the standard deviation; the last three are definitions which have been put forward at various times to simplify the procedure of estimating the repeatability value. Of course it could be that the person responsible for assessing the repeatability of the measurement did not bother to collect a sample of ten readings as instanced here, but only took two and said that his repeatability was ±½ the interval (number 9 in the list). This may be thought absurd and it might be assumed that such a procedure would never be used by qualified people but examples of this approach can be found and are present even in some international standards.

The logical approach to what is intended by the word 'repeatability' is to think of it as defining how well two successive measurements will agree in general. This is different from taking only two measurements in order to determine the value to be used, for what is required is a statistical probability that this level of agreement will occur.

The term which it is hoped will become universally adopted is that published in ISO 5725(2). It is the fifth term in the table, that is:

$$\text{repeatability} = 2t_{95}S$$

5 RANDOM AND SYSTEMATIC UNCERTAINTIES

The uncertainty of a measurement depends partly on the residual uncertainty in the instruments and the measuring system when the test is carried out and partly on the non-repeatability of the measurements.

Repetition of a set of measurements using the same equipment will reduce the uncertainty introduced by the second of these causes. Fluctuations will occur arising either because the quantity itself is changing or because the characteristics of the measuring equipment are not stable or for both reasons. Such fluctuations are shown up in the form of scatter, seen in Figs 1 and 2, and are termed random uncertainty.

The greater the number of repeated measurements taken the better is the estimate of the true value. Thus the mean of a large number of test points is better than the mean of a smaller number provided there is no systematic change occurring in the measuring system over the time taken for the measurements or in the quantity being measured. It is important to have control measurements to check on this.

There is another source of error which is hidden and all too often forgotten. All known errors in the measuring systems should have been removed by calibration, proper installation, checking etc, prior to the tests. But there will still be a residual source of uncertainty in each one of these measurements which cannot be determined from the measurements themselves. This is termed systematic uncertainty and is illustrated in Fig. 2.

In flow measurement or the other measurements associated with equipment/ tests the systematic uncertainty is often as large or significantly larger than the random uncertainty. It will therefore be realized that its reasonable estimation is vitally important. Repetition of the measurements any number of times does not reduce the systematic uncertainty at all. It can only be reduced if equipment of a higher standard of 'accuracy' is used or if the same equipment can be calibrated to a higher standard. But even then it must be realized that this will not eliminate or reduce all the sources of systematic uncertainty. If the quantity being measured is not the true quantity required (because say there is a leak somewhere) then however good the measuring equipment has been made it will still he reading wrongly. Hence the systematic uncertainties in each of the measured or derived values must be estimated on the basis of separate intercomparisons with data considered to be of higher absolute accuracy.

There is no universally accepted method of combining random and systematic uncertainties. It has been recommended by some authorities that after the calculated value being determined is presented there should follow a list of all the sources of uncertainty and their estimated values. Such a listing really just begs the issue, for the reader will be unable to appreciate the combined effect, if the writer himself cannot do this.

The solution must be to adopt a single method which then becomes so well known that its implications are generally known and accepted. It is believed that the method recommended in ISO 5168(1) is already the most popular and contains a balance which for most engineering purposes is reasonable. The least squares method of propagation is adopted, giving for each quantity the following statement:

Quantity = ...

Combined uncertainty $(e_R)^2_{95} + e_s^2$ = ...

Random uncertainty $(e_R)^2_{95}$ = ...

where uncertainties are calculated in accordance with ISO 5168.

The result given by this estimate of the overall uncertainty, which should always be quoted alongside the value of the measurement, is a balanced one. It assumes that there is an equal likelihood (as in the determination of a standard deviation) that the statistical laws for the propagation of error-based on the assumption that the individual contributions are small, independent, numerous and of Gaussian distribution will hold equally for systematic as for random uncertainties.

ACKNOWLEDGEMENTS

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2 Precision of test methods - determination of repeatability and reproducibility. Geneva: International Organization for Standardization, ISO 5725, 1981.

LIST OF FIGURES

1 Illustrating the link between uncertainty and confidence level

2 Illustrating error and uncertainty.

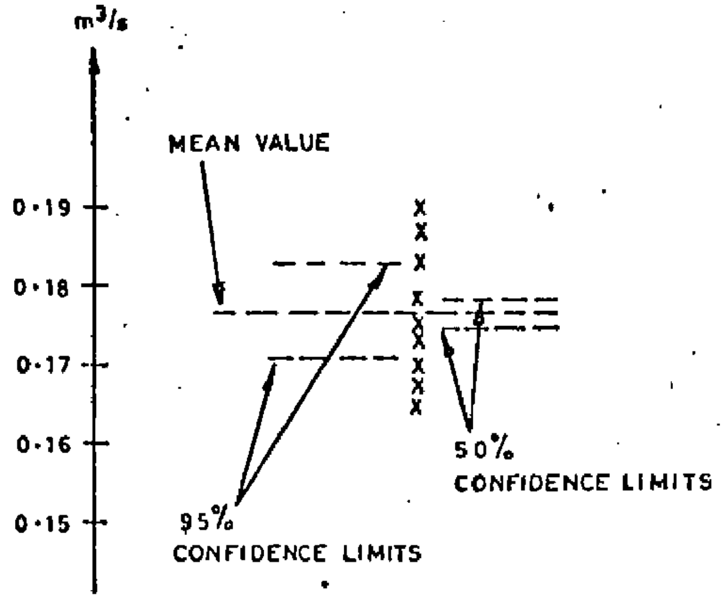

FIG 1. ILLUSTRATING THE LINK BETWEEN UNCERTAINTY AND CONFIDENCE LEVEL

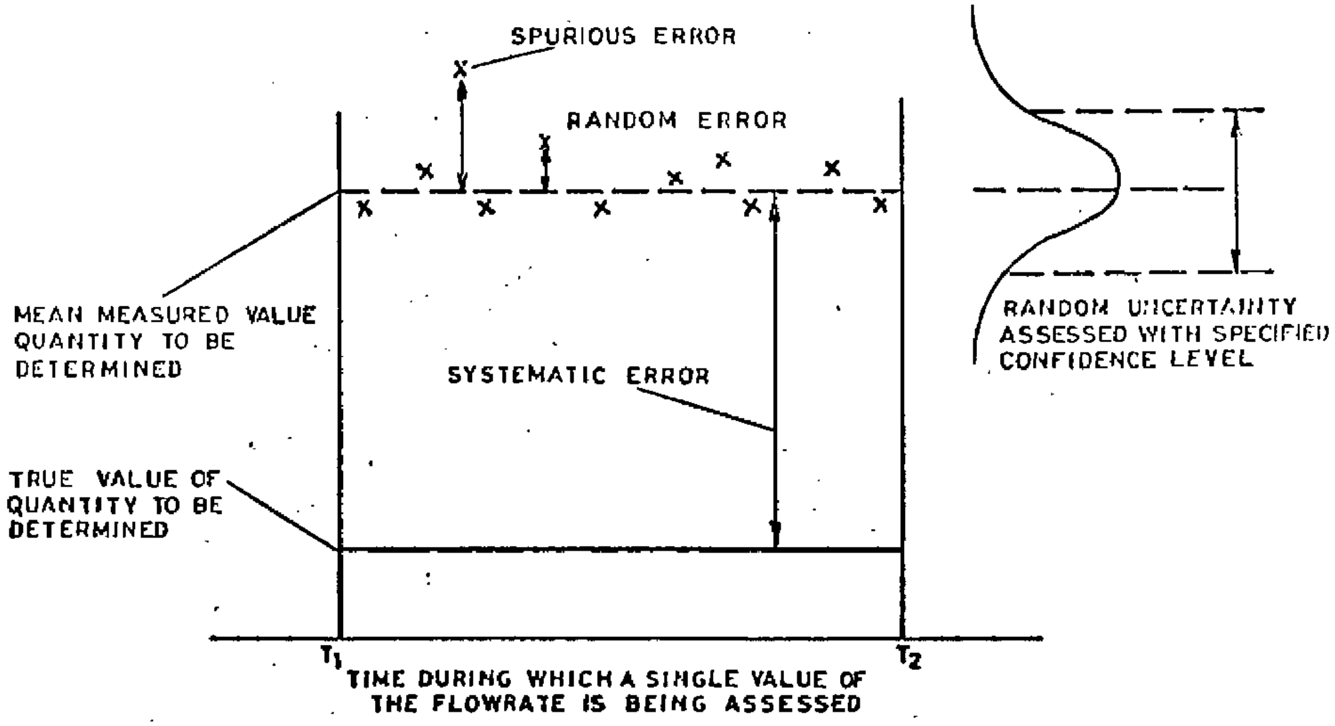

FIG 2. ILLUSTRATING ERROR AND UNCERTAINTY