ELECTROMAGNETIC INSERTION PROBE CALIBRATION.

ADVANCES TOWARDS A STANDARD.

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Abstract   The aim of this paper is to illustrate the methods and equipment which have been developed to better characterise and accurately calibrate insertion electromagnetic probes.

The authors consider the historic development of the electromagnetic probe and the difficulties which calibration of a point velocity device brings. They will illustrate the difference between designs and will outline the problems which have to be overcome before such devices can be used with much increased confidence. Development of a transfer standard technique will be described and the way in which Traceability to SI Standards can be formulated is covered. The problems of assessing probe calibration Uncertainty are discussed and a practical technique to normalising performance demonstrated. The practical application and performance of two types of probe is briefly illustrated with discussion of the importance of data quality and Traceability, which is now required in order to comply with the demands of industry regulatory bodies. The authors call for both the development of common standards to cover probe calibration and for the implementation of best practice guidelines to regularise the present application of insertion electromagnetic probe technology.

Keywords: insertion probe;   calibration;   water industry;   velocity profiling

1. Introduction

At the beginning of this paper it is essential to ask why, in 2004, is the question of insertion probe calibration of current interest within the United Kingdom. The answer lies in changes in the water industry regulatory regime and the increased need by management within the water companies to understand and to quantify the performance of their key water supply meters.

Over the last ten years Severn Trent Water (STW) has operated a meter verification programme for its key source and strategic meters; meters typically in the size range 150mm to 2000mm. The backbone of this programme has been a verification procedure, run over approximately 20 hours, in which the volume passed by the meter being verified is compared with the volume of a check meter, comprising an electromagnetic insertion probe, installed in a location whose hydraulic characteristics have been previously assessed.

However, whilst improved methods have been developed for the process of on-site verification, including by Information+Performance Services, (reference 1), practically no effort had been expended in examining either (a) the validity of the probe manufacturer's calibration, or (b) in refining the methods and the equipment which could optimise the process of probe calibration.

The paper that follows reviews the historical development of insertion probe technologies, illustrates the reality of the data which point velocity probes produce and shows how improvements in the methodology of probe calibration in the laboratory can contribute to meter verification performance in the field, primarily through the introduction of digital recording and analysis techniques.

2. Development of the Insertion Probe

Insertion flowmeters have developed over the years through a number of stages.

1. Differential pressure.
2. Turbine.
3. 'Full bore' electromagnetic
4. 'Inside out' electromagnetic.
5. Boundary Layer Electromagnetic.

2.1 Differential pressure.

Differential pressure devices have long been used and are a well tried and tested method of measuring velocity. They work on the principle of sensing an upstream and a downstream pressure, thereby determining, through application of a square law relationship, average flowrate. D.P. probes are not well adapted to peripatetic use and such devices were most often employed as fixed meters, albeit with a limited turndown of 3 or 4:1.

2.2 Turbine.

In the Water Industry the mechanical insertion turbine type of probe has historically been most widely used. Typically this type consists of a turbine in a holder or simply an open turbine mounted on a support. (See figure 1 below).
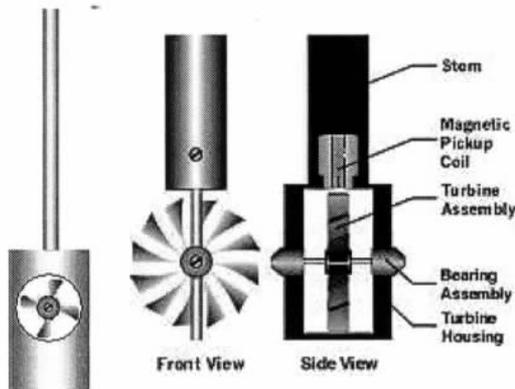

Fig 1

The principle of operation relies on the bulk movement of water turning the impellor with the probe's electronics counting the number of revolutions,

thus computing the mean velocity of flow through the impellor.

Practically such small turbines suffered from a need for (bearing) maintenance, which, together with their propensity to become easily damaged or blocked, imposed a continuous maintenance overhead on field technicians. In the low velocity zone, sub 0.3 m/sec, which predominates in the Water Industry, insertion turbines exhibit non-linear behaviour and are prone to stalling due to friction.

2.3 Electromagnetic devices.

The next probe development was to use the electromagnetic principle and was also made in two similar formats to the mechanical turbines.

The electromagnetic principle obeys Faraday's law of induction, which says that when a conductor (in this case the water), moves through a magnetic field, then an emf is generated :

$$E = B.L.V \qquad \text{Equation 1}$$

where

E = the emf generated

B = the applied field strength

L = the length of the conductor

Fig 2

In the example of the 'full bore" probe meter, the magnetic field is inside the circular bore of the insertion meter itself, whereas for the 'inside out'

meter, the field is spherical in shape, and the electrodes are on the outside.
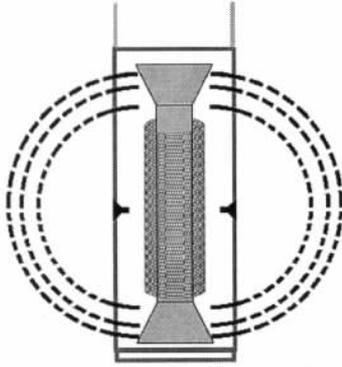

Fig 3

In practice, from the work of an insertion meter consortium undertaken back in 1990 the inside out device appears to be more accurate, and is better able to cope with the varying pipe materials than the 'Full-Bore' type.

2.4 Boundary layer Electromagnetic probes.

These are similar to the above 'inside out' electromagnetic probes, except that instead of intruding significantly into the pipe, they tend to be flush with the walls of the pipe, measuring the velocities in the boundary layers. Unfortunately, sampling the flow in that particular location they are less accurate than many of the other devices, unless the conditions of the flow and pipeline are both well established and highly stable. In the Water Industry neither of these conditions prevail.

In summary, the following table compares the key attributes of each type.

Type	DP	Turbine	Emag	Boundary Layer
No Moving Parts	✗	✗	✓	✓
Maintenance Required	✗	✓	✗	✗
Linear / Square Law	✓	✗	✗	✗
Affected by Flow Profile	✓	✓	✓	✓

3. Accuracy Issues deriving from the use of

Probe Meters.

Remembering the verification context in which insertion meters are being used it is important to review the factors which, aside from the baseline probe calibration, impact upon the overall measurement result. Many of these factors are equally applicable to the laboratory situation as to that found in the field.

A number of authors have reviewed these in detail but the opinion of Ginesi (1987), who estimated that a ±2% to ±5% accuracy for 'typical' meters was possible, is in the authors' opinion about the best that one could expect in all but ideal conditions. It contrasts with the slightly later and more realistic work undertaken by Sanderson and Thomas at Cranfield University, UK, in 1988 where an ±8% limit was derived.

Therefore, consider in turn each of the major influence factors which impact on the accuracy of flow measurement using an insertion flowmeter, and which must be taken in account during calibration. These are :

    i.   Intrinsic Instrument accuracy
    ii.   pipe diameter measurement error
    iii.   pipe area calculation error
    iv.   profile distortion error
    v.   position error   and
    vi.   blockage error.

3.1 Intrinsic instrument accuracy

This is reasonably well understood, but it is the interaction between the insertion meter and the velocity of the fluid at the measurement point which is key.

3.2 Pipe diameter measurement error.

Pipe diameter measurement is genuinely difficult to achieve with a good degree of accuracy and sadly, many operators do not measure this at all, simply using the nominal diameter of the pipe for this figure.

This practice can result in errors of anything up to 15%, and in extreme cases, where the nominal diameter is incorrectly measured, then even larger errors can be made.

It is therefore essential that this diameter is measured to the highest precision available. In the field this is normally undertaken using a proprietary gauging rod, which has the capability to measure to better than ±1mm. Regrettably, due to poor industry practices, the actual result can often be very much worse.

In the laboratory both internal and external callipers, plus calibrated ultrasonic thickness gauges were utilised to generate confidence in the mean diameter figure.

3.3 Pipe area calculation error

Pipe area calculation is, on the face of it, just a mathematical calculation but of course if the pipe is not round and the 'diameter' previously measured is used in the normal formula

$$A = \frac{\pi.D^2}{4}$$
Equation 2

then additional error will ensue.

3.4 Profile distortion error.

If the point velocity measurement is converted to a mean velocity measurement, using the relationship between the point velocity and the mean or bulk flow velocity, and if this relationship is derived from the accepted relationship given a known flow profile, then any distortion of this profile will cause a measurement error.

3.5 Position error.

This is the difference in the actual position of the measuring element of the insertion flowmeter from the expected position. Depending on the relative position in the pipe and therefore the rate of change of velocity with distance, the error may be very small or very significant. Both in the laboratory, and in the field, position setting at anything better than ±1mm is very onerous. However, one of the useful and practically important actions which can now be achieved using the specialist I+P insertion probe software is the ability to move the probe to a nominal distance and, after having accurately measured the probe's actual position, input the true position achieved, *without affecting the computational rigour which integrates the point velocities*.

3.6 Blockage error.

This is the error stemming from the fact that the probe is necessarily in the flow and therefore blocking the passage of flow. Most manufacturers of insertion devices publish a correction factor, typically labelled as its Insertion Factor (F_i), which allows the User to largely negate this source of error.

A note of caution, however, F_i is not just a mathematical calculation of area reduction due to the 'blocking' effect of the probe in the pipe, but has to take account of the new boundary layer introduced when the insertion probe is introduced into the pipeline.

4 The Development of Improved Probe Calibration Methods

4.1 Historical Calibration Methods

As a result of insertion probes' historic development within the hydrometric fraternity, most types were originally calibrated in tow tanks. This is a large rectangular tank which is as long as practically possible and has a carriage which moves along the length at a controlled speed. The output of a probe being velocity, this can be compared with the speed reading of the travelling carriage and a calibration for velocity established. The drawback with this method is that is bears no hydraulic resemblance to a closed conduit pipeline and, due to the obvious restrictions on length, the time available for each calibration run is

severely limited.

The 'Full Bore' type of insertion flowmeters can be calibrated by passing fluid at a known velocity just through the hole in the probe. This has the advantage of being simple, but again has the disadvantage of there being no hydraulic resemblance to a normal pipeline flow.

The best way to calibrate an insertion flowmeter, however, has to be in a pipe of approximately the minimum size recommended for use on a traceable rig. This will give reliable calibration information, but in this case, it is closely tied in with the hydraulic effects of the probe in the pipe.

4.2 The Specific Task facing ABB and Severn Trent Water

During the 1990's the insertion probe of choice changed from that of the mechanical turbine to the electromagnetic design. At that time the manufacturer, ABB Limited, offered a d.c. powered version of its Magmaster transmitter, the power for which was provided by a large car type battery. Importantly the MagMaster transmitter was equipped with the standard forms of output, i.e. pulse and 4-20mA current.

However, with the launch of the AquaMaster in 2001, the older MagMaster design was gradually replaced with the twin, internal Lithium D cell powered, all digital AquaMaster transmitter. The task in hand was therefore to ensure that the Manufacturer's calibrations for the new design matched those of the older units whose provenance had been established in a joint exercise with ABB during the mid 1990's.

Following an initial check of one, ex factory probe, a calibration difference outside that allowed by the Manufacturer's meter specification was found. On repeating the error remained, whilst that of the reference probe from the first car battery d.c. powered MagMaster units gave admirable reproducibility, as had indeed been the case over the previous eight years.

A complete review of the calibration methods employed both by Messrs ABB limited and by Information+Performance Services Limited acting on behalf of Severn Trent Water, was then initiated, beginning with the independent calibration Laboratory's velocity profile.

4.3 Determination of Calibration Laboratory Reference Velocity Profile

At the heart of all the probe calibrations has been the flowplant reference velocity profile, the determination of which was undertaken using a beam pitot. Testing was done on a 260 mm diameter pipe with approximately 10 m upstream straight length and with the 6 mm diameter beam pitot connected to a 60mbar-range transducer used to measure differential pressure.

Each test consisted of a 17-point traverse across the diameter of the pipe at a nominally constant flow rate, the differential pressure being averaged over about 1 min at each point. The point velocity is proportional to the square root of the point differential pressure. The flow rate was measured in the normal way before and after the traverse to confirm no substantial variation.

Tests were done at 3 different nominal flow rates of 65, 150, 200 l/s and with the pipe containing the pitot rotated with the pitot in both the horizontal (N-S) and vertical (T-B) orientations. The nominal line pressure for the tests was 3 bar but two extra tests were done at 150 l/s at about 0.4 bar.

The profiles obtained were compared with the Pai (1953) Turbulent Flow Velocity Profile Equation. This is dependent on Reynolds Number R_D and pipe roughness.

Point velocity V_p at radius r of pipe radius r_p and friction factor f is given in terms of maximum velocity V_{max}

$$V_p = \left[1 + \frac{s-n}{n-1} \left(\frac{r}{r_p} \right)^2 + \frac{1-s}{n-1} \left(\frac{r}{r_p} \right)^{2n} \right] V_{max}$$

where

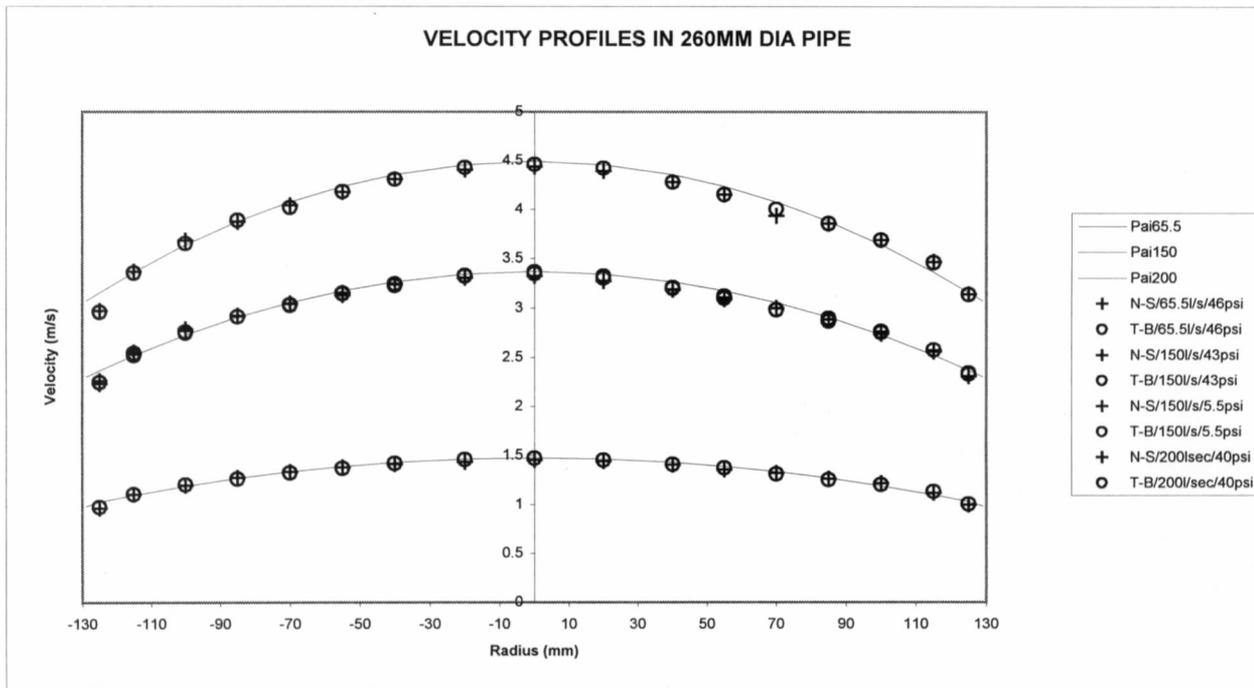$$s = \frac{fR_D}{32 + 46.08\sqrt{f}}$$

and

$$n = \frac{2 - fR_D/32}{1.44\sqrt{f} - 1}$$

Equations 3, 4 and 5

A Moody friction factor diagram was used to obtain values for f using an estimated pipe roughness of 0.2mm.

For profile comparison purposes, each test and formulated profile at a particular nominal flow was scaled such that the mean flow for each profile was the same as the nominal flow. Figure 4 illustrates the profiles.

Figure 4: Calibration Laboratory Reference Profile

between test and formulated velocity points. This might be less if the pipe roughness could be determined more accurately. The test profiles also show a small asymmetry, but given that this is the same shape for each test it was concluded that the asymmetry relates either to pitot positioning error or to the section of pipe holding the pitot, rather than to the flow rig itself.

The effect of changing the orientation of the pitot (horizontal/vertical) and the effect of changing the line pressure seem to be insignificant.

4.3 Quality of the Observed Data

Given the task of comparing data from the two transmitter types a decision was taken to adopt an all digital approach to the data collection. For the calibration laboratory this posed a problem as to date the basic deliverable had been a plot of probe meter factor against flowrate derived from pulse counting and the laboratory's gyro based weigh tank.

Using software developed by I+P, a series of trials were run to examine the digital time series flow data at varying flowrate. The results are shown in Figures 5, 6 and 7.

VELOCITY PROFILES IN 260MM DIA PIPE

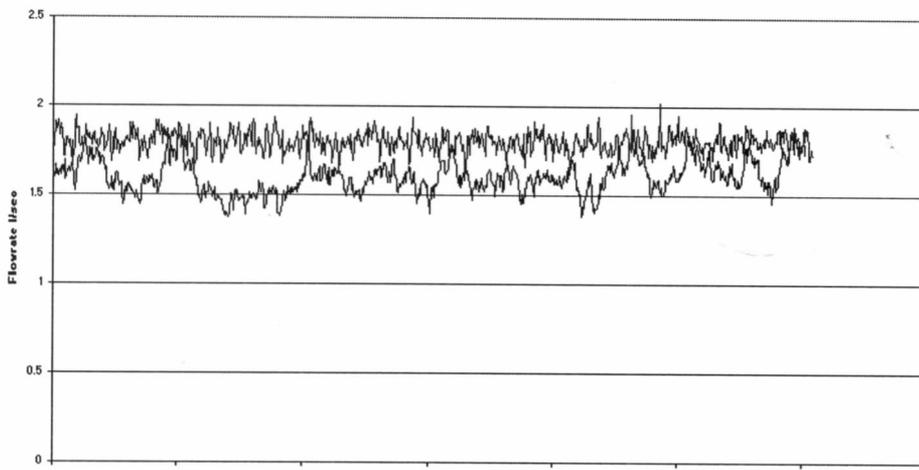The results show an average difference of about 1.5%

Figure 5 : Comparison of signals for differing meter modes   - Low flow
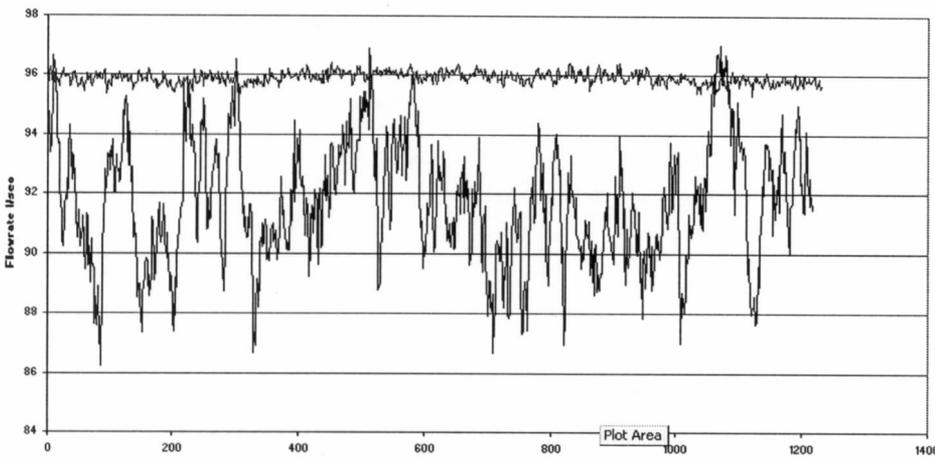

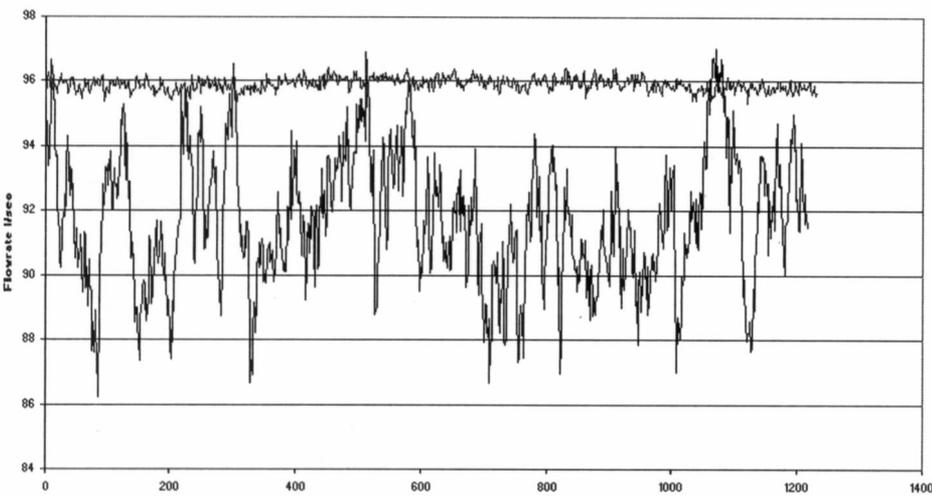Figure 6 :   Comparison of signals for differing meter modes   - Medium flow.

Figure 7 :   Comparison of signals for differing meter modes   - High flow.

As is quite obvious, the differences in data quality immediately prompted an examination of the underlying mechanisms and especially it became clear that statistically very much longer test times than had been used historically would be required, in order to eliminate the effects of short term noise.

5 Development of a Transfer Standard (IPTS) & Specialist Analysis Software

Figure 8 illustrates the Insertion Probe Transfer Standard (IPTS) solution adopted to enable both ABB and STW to resolve the observed probe calibration difference.
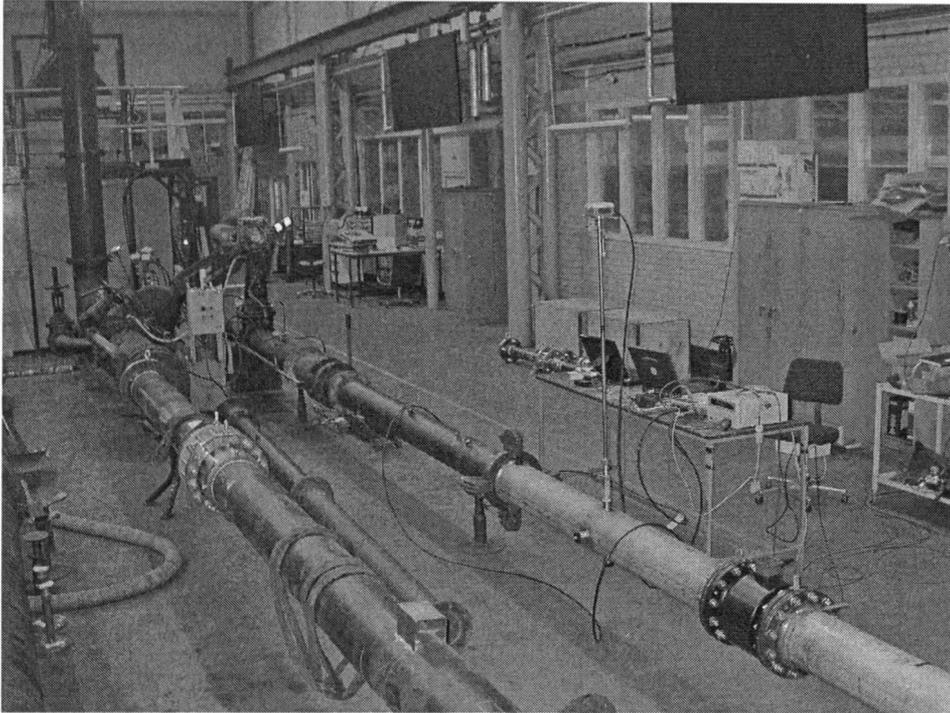

Figure 8:Transfer standard with probe installed

As can be seen the IPTS consisted of a section of stainless pipework into which a series of tapping were made. Integral with the spool piece was a full bore ABB MagMaster electromagnetic meter, the transmitter outputs of which could be interfaced both to the PC software recording digital flows and the calibration laboratory accredited pulse counting hardware. The simple aim of the IPTS was to enable calibration work to be undertaken between the independent UKAS accredited Laboratory and the facilities of the manufacturer, some of which were also UKAS accredited but not in the same pipe sizes as the independent facility.

The true utility of the IPTS was that calibration of the IPTS Reference meter could be undertaken without

any probe testing and to the best level of test uncertainty available on the particular flowplant. For the independent UKAS accredited Laboratory this was ±0.1%, for the Manufacturer's smaller rig ±0.25%. The IPTS Reference could then be used directly as a Master meter against the probe under test, *without the need for interruption of the flow* due to flowplant diverter operations, etc, as had been the case previously. The defined need to undertake long period calibration runs to improve the quality of the end result therefore no longer posed any difficulties.

However, in order to be able to make best use of this hardware specialist logging and analysis software was required that was capable of addressing both the full bore Reference meter output and that from the probe under test. This was provided by I+P and examples of the display from this software are given in figures 9

and 10.

Vindication of the approach adopted was that operation of the IPTS and the I+P Analysis software proved successful in identifying the source of the calibration discrepancy between the two flowplants.

6   The Key Influence of Probe Transmitter Operation on Performance Determination

At the heart of the exercise was the difference between the two insertion probe transmitter designs, the "wet end" i.e. the electromagnetic sensor remaining the same throughout. Between the two designs and even within the newer all digital AquaMaster electronics, a variety of differing operation Modes were possible. These differing Modes reflected the way in which power can be deployed and are a key element for Users when long term continuous operation is wanted.

Intertwined with the Mode options is the frequency of measurement. Given that when profiling each individual run or point of measurement is typically of a relatively short length, normally 30 – 60 seconds, the frequency of measurement in is critical. On the other hand, when being operated over a 20 hour period the relative importance of the effect of measurement frequency is substantially reduced. When deciding how to calibrate differing probes models the number of potential variables became crucial, in order to ensure true like for like testing.

An illustration of the effect of differing Modes, taken not from the Calibration exercise but from field-testing is shown in figures 9 and 10. As can be seen from the results, the profiles are very different with corresponding differences in the calculated profile factors. If any of the methods available previously to that of I+P had been used, then these differences would have been difficult to understand and would most likely have been attributed to hydraulic or Operator variability.

When attempting to standardise probe calibration and to define a repeatable methodology, details of the operation of the secondary instrument clearly represent a playing field that needs flattening before one starts. This was a key lesson in reconciling the observed calibration differences.

As is quite obvious, the differences in data quality immediately prompted an examination of the underlying mechanisms and especially it became clear that statistically very much longer test times than had been used historically would be required, in order to eliminate the effects of short term noise.

7   Practical Issues and the Need for Normalisation of Calibration & Profile Factors.

The use of electromagnetic insertion probe meters has, from the outset been predicated on the stated view that the measurement technique is linear with flowrate. Because of this the manufacturer calibrates at one or two points only and is content to set an Uncertainty band around this calibration, based on his experience of build quality.

Work by I+P, although not challenging the underlying assumption of linearity, has shown that over a flowrate turndown of 10 to 20 to one, typical in the water Industry, the insertion electromagnetic probe demonstrates a falling meter calibration, factor which can cause rejection of the instrument when compared to the Manufacturer's Specification.

Normalisation of the calibration Factor is therefore advocated, if only because it allows for standardisation of the data recorded by different people in different places. As a spin off it also generates standard statistics that on a year-by-year recalibration basis are very useful e.g. when looking for deterioration in performance, due perhaps to sensor mechanical damage.

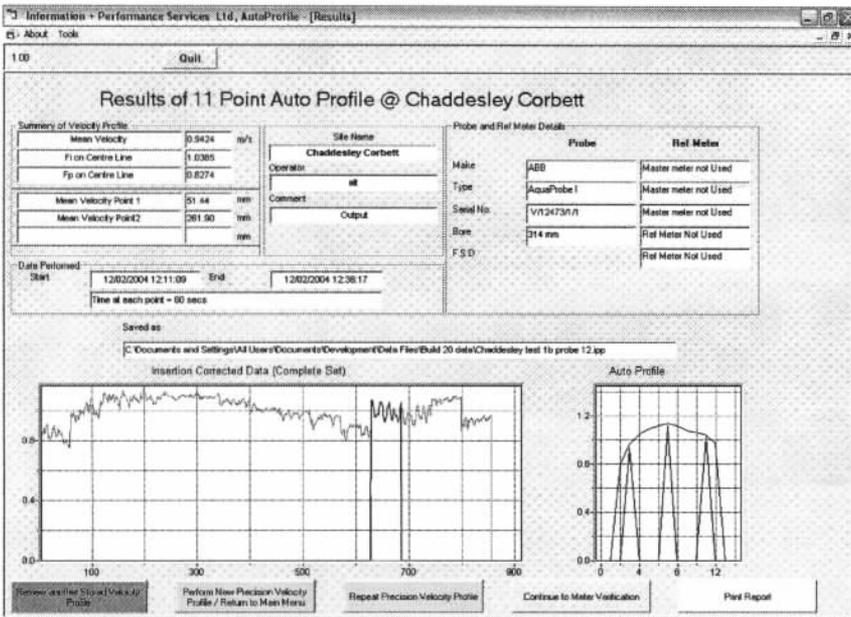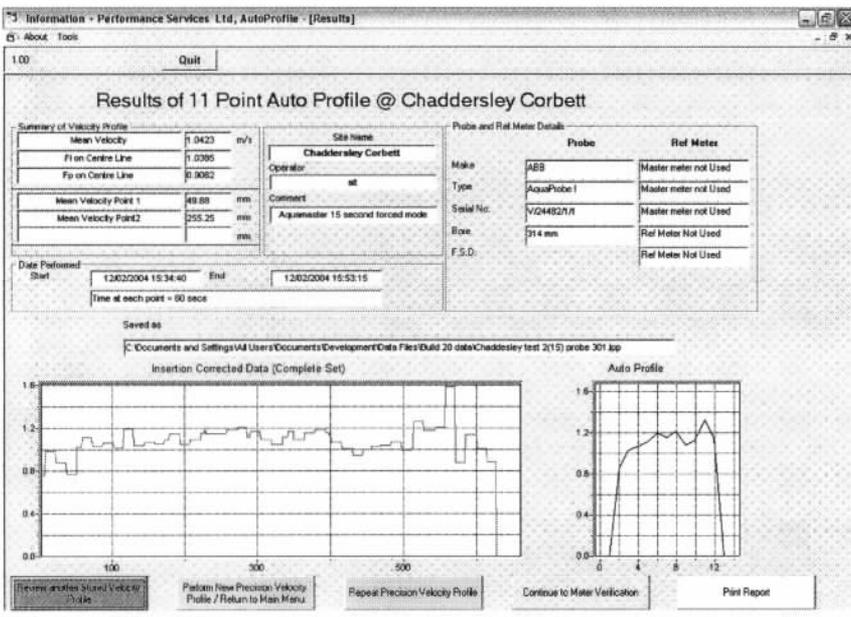More importantly, when it comes to profiling

Fig 9

Fig 10

flowrates in the Laboratory and especially in the field, flowrates are variable, sometimes dramatically so. Therefore one of the design features of the I+P software has been the ability to use the Master Meter to normalise for changes in the flow which are reflected in the probe output during a test. In the Laboratory this is usually a second order effect, in the field it is a first order concern.

At this point experience requires that certain practical problems, alluded to earlier, be re-emphasised as continuing areas of real difficulty. These are (i) accuracy of pipe measurement; (ii) Stability of flow and (iii) selection of appropriate run time. Consider each in turn:

(i) Pipe Measurement.   The measurement of the inside diameter of the pipe is critical since all insertion

devices measures velocity and require that the diameter be translated into area in order to obtain the flowrate. If the pipework used in calibration, or in the field, is long and straight as is required hydraulically, it becomes very difficult to measure the internal dimensions in these situations. Moreover, as is frequently found the pipe into which the probe is introduced is often far from round. Basically, area is extremely difficult to measure accurately and when measured, its uncertainty is often optimistically stated, as Operators do not like to be thought unskilled in reading from a ruler!

(ii) Stability of flow. The nature of flow is that it is unstable and this is reflected most when testing in the field. If the velocity at point number 1 is, for example, 1 m/sec, and the velocity at point number 2 is 1.1 m/sec, then is the difference (0.1m/s) due to the difference of velocities in the flow profile, or due to the bulk flow changing due to its instability? As the answer is effectively unknowable then quantifying and recording the level of the change over time, as a guide to the relative quality of the measurement, is a feature that is strongly advocated as part of the standardised calibration process. It is an intrinsic feature of the specialist I+P analysis software.

(ii) Run Time. For the purpose of improving the statistics, run times should be a long as possible, yet for reasons of stability, they should be as short as possible. Whatever time is taken, it will have an effect on uncertainty so quantification and recording to produce similarity between differing tests is advocated as good practice, even though it holds no solution as to what is "best".

In all of this type of work, it is clear to the authors that Rules and Tools dominate and that collected flow data must be time-series and rate-based, as only with this format does the User gain truly useful comparative information. The Rules are still open to refinement but a good start has been made with the Tools in the form of the software developed by I+P Services, further details of which are given in a separate FLOMEKO paper.

8 Traceability and Operational Management

Traceability when undertaking this type of work, whether in the laboratory or in the field, is notoriously difficult, principally due to the difficulties in ensuring reproducibility of measurement and of test conditions.

In the case of the work undertaken by I+P, normalisation both of the acquired test data and the resultant probe meter factor has proved to be an excellent approach, eliminating many spurious results and building a platform of calibration data which can confidently be used over time for comparative purposes.

The adoption of a transfer standard, all digital collection of data and a calibration technique traceable to two independent UKAS accredited laboratories allowed a more realistic view to be taken with regard to overall uncertainties. Furthermore, by standardising the range of test flows within fixed velocity limits, so as to mimic as closely as possible real site conditions, the insertion probe calibration is as well matched to the User 's application as possible.

Adherence to a traceable and auditable data chain using data logged directly from the insertion probe transmitter output and stored in linked databases constitutes another important feature, previously disregarded. This ensures that the high precision digital calibration data is held in the same manner as subsequent site measurements undertaken with the probe, thereby completing the traceable data chain. Only with this type of precise data logging and storage can the data become, in the hands of the end User, truly qualified information. Past practices that used separate low frequency pulse loggers linked to probes can neither provide the precision of time series data nor the evidence of actual time varying flowrate changes. Such changes are an intrinsic part of point velocity measurement and are of great importance

when independently auditing or assessing the quality and uncertainty rating of any results.

Clearly both when calibrating and utilising insertion flowmeters as tools for meter verification there is currently a pressing need for the deployment of standardised methodologies which are linked to formal data archives in order to retain as much source information as possible for Quality Management and Audit purposes.

In the work carried out to resolve the insertion probe calibration differences between the ABB factory and the independent flow laboratory the specialist software previously developed by Information+Performance Services Limited proved highly successful. Its success was precisely because of the all encompassing nature of the data acquisition and archiving software design. The deployment of such a methodology, applied to both calibration and site work, is therefore commended as a suitable approach to be adopted across the industry.

9   General Discussion

With meter Verification programmes now well established in the UK the role and application of the insertion probe has become a key element in the Regulatory framework. As such probes are here to stay and their widening use will necessitate industry agreement on methods of calibration standardisation.

For the particular case of the insertion electromagnetic probes from ABB Limited, the introduction of an improved model utilising low power technology has opened up the possibility of additional application areas, which in turn has made definition of the baseline performance all the more important.

Until the present work no attempt had been made to cross check the uncertainty of calibrations on differing flowplants and initially unexplained errors of the order of five per cent were discovered. These have now been resolved but the process took considerable time effort and the development of not only a transfer standard but also of formalised test methods supported by the necessary means of collecting and analysing the output of the insertion meters.

It is in the area of Traceability that operators should focus their future attention and here it was fully demonstrated that resort must be made to collecting, recording and archiving the raw velocity data at all stages of the calibration process. This necessity applies equally to the application of the insertion probes in the field, a subject covered by a separate FLOMEKO paper. (Reference 1).

Derivation of adequate velocity profile data proved to be very difficult, although excellent agreement between the results of beam pitot and electromagnetic probe was demonstrated. Alongside the measurement of pipe cross sectional area, these two represent the true calibration challenge, a challenge which is repeated for technicians in field.

The authors hope to be able to improve the performance of the probe transfer standard in the coming year and are examining the use of portable LDA tools to achieve this.

What started out as a simple task calibrate a new Model of insertion probe had the unintended outcome of a complete re-examination of probe calibration technique. The moral is clearly to avoid simple tasks!!

10   Conclusions

The introduction of digital, battery driven electromagnetic insertion probes, together with increased requirements to demonstrate Traceability of the meter verification data chain, forced a change in probe Calibration technique.

As a result of the forced change, new, software based calibration tools were developed. These have revealed far greater variability in the time series probe data than previously understood.

Measurement of flow profile and of the ancillary calibration pipework parameters is crucial to demonstrating probe Traceability and is an area where improvements are still required.

Optimisation of operating mode, for the battery driven insertion electromagnetic probes manufactured by ABB Limited, has been demonstrated both in the laboratory and in the field, with important practical results.

Anomalies between differing probe calibrations undertaken on separate accredited flow plants have been resolved. They confirm the Manufacturer's published claim that of an uncertainty of +/-2% for mean probe velocity measurement may be achieved.

Measurement and procedural variables were found to be significant in achieving flowplant to flowplant reproducibility. The case for developing common calibration guidelines is thus clear.

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