Verification for Electromagnetic Flowmeters: its current state and its potential

Roger C BAKER & Pamela I MOORE (Institute for Manufacturing, University of Cambridge, UK),
Alun THOMAS (Information+Performance Services Ltd, Solihull, UK)

Abstract The validity of the claims made for currently available verification devices are reviewed. The theoretical requirements to achieve the verification measurements are suggested and the validity of the approach assessed accordingly. Likely achievable uncertainties are considered. There is a brief discussion of the administration of the verification procedure by users. Successful verification strategies will be dependent on the quality of the manufactured product and the necessary good housekeeping within the manufacturing company. The authors conclude by suggesting that the current concept is promising but may need to be developed if it is to yield a generally acceptable approach.

Keywords: Electromagnetic flowmeter, verification

1. Introduction

1.1 Brief explanation of the electromagnetic flowmeter (EMFM)

Figure 1 provides a cut-away diagram of an EMFM showing: the coils which generate the magnetic field; one of the electrodes (the other being at the opposite end of the diameter) which sense the voltage generated by the passage of an electrically conducting liquid through the magnetic field; and the liner which insulates the inside of the tube and prevents the voltages being shorted out. The signal from the meter in its simplest form is given by:

$$\Delta U = SBDV_m \tag{1}$$

where ΔU is the voltage generated between the electrodes, S is the flowmeter sensitivity, B is the magnetic flux density, D is the internal diameter of the pipe and V_m is the mean velocity in the pipe. For the special case of a meter having a very large and uniform magnetic field, and sufficient upstream pipe length to ensure the profile is axisymmetric, S can be shown to be unity[1]. Early designs of EMFM attempted to emulate these conditions.

Modern designs seek to achieve a meter which is little affected by upstream profile despite being comparatively compact and of short axial length.

1.2 Verification compared with calibration

The reader is reminded that the ideal for any modern flowmeter is calibration in a specially designed flow facility with a documented uncertainty and traceability. However, a range of alternative approaches are used which do not achieve full calibration and should be categorised under the term "verification". The following indicates this range for the EMFM:

a) *in situ* verification using flow measurement or flow estimation;
b) verification using measurements of field size within the sensor head, but outside the flow tube, and of total electrical integrity;
c) verification/simulation of the signals to assess the integrity of the amplifier and output signal circuits.

In this paper we are concerned with (b) and (c). These require tight control of production, an adequate level of measurement uncertainty and satisfactory administration of the verification systems on offer.

1.3 Motivation for verification devices

Electromagnetic flowmeters require wet calibration for traceability to a national standard, involving removal from the flow line and shipment to an appropriate accredited laboratory. This can be expensive if the line is shut down and the calibration itself carries a fee.

The accredited laboratory will calibrate the meter in a flow line with a well developed flow profile (wet calibration) against a traceable standard. Verification is a method of subsequently attempting to check the calibration without removing the meter from the line.

Field coil
Insulating liner
Flow
Magnetic flux direction in centre of coils
Electrode

Figure 1 Cut-away diagram of an electromagnetic flowmeter (EMFM)

This paper assesses the theory and performance of verification devices currently on the market, known to the authors and applied to electromagnetic flowmeters.

2. Background to verification devices

In the past the EMFM has been checked by simulating the flow signal at the electrodes to ensure that the electrical components were operating correctly. The idea of simulation possibly stemmed from the simplicity of Equation 1 and the sense that, if the performance of the amplifier which measures ΔU could be checked and the magnetic field held constant, the meter uncertainty would be confirmed.

The magnetic field was measured using a search coil signal, or from measurement of the field coil current. The flowmeter signal was compensated using the resulting current or voltage so that fluctuation in the magnetic field due to supply voltage fluctuation did not affect the reading of the flowmeter. The simulator inserted a signal into the electrode circuit and the ability of the amplifier correctly to measure it was checked. Furness & Smith[2] comment that 'The "calibration" of the secondary electronics consists merely of checking the zero and span errors of the transmitter. ..... If a system has both zero and span errors (and in some of the older transmitters the two are interactive) then quite large error can result ....' Their comments were particularly aimed at differential pressure transducers, but they have some relevance to the EMFM.

The pressure to achieve *in situ* calibration has caused flowmeter companies to develop simulation techniques and to extend them. The effect of this has been to explore the extent to which the new devices could be used as an interim verification between calibrations, allowing the calibration period to be extended. This leads to three matters:

- the validity of the technical approach;
- the predictive uncertainty achievable;
- the management and administration of the process.

We shall consider these in turn and then review the commercially available options of which we are aware.

3. The validity of the technical approach

The subject of verification of flowmeters verges on the wider topic of dry calibration[3]&[4]. We may identify several levels of verification/dry calibration as set out in Table 1. We consider these in turn

3.1 Checking electrode electrical contact with liquid

Manufacturers install various means of electrode cleaning, such as burn off or ultrasonic cleaning, which can be implemented and some may operate automatically if required.

Table 1 Levels of action for verification and for dry calibration

Level	Options	Requirements for verification	Requirements for dry calibration
1	Checking electrode electrical contact with liquid	YES	YES
2	Checking for integrity of cables and earth shields etc.	YES	YES
3	Simulation of flow signals into the electrode amplifier circuits	YES	YES
4	Checking for constancy of the magnetic field during signal measurement	YES	YES
5	Checking for constancy and integrity of the magnetic field and field coils since manufacture	YES	YES
6	Checking that the wetted geometry is unchanged and that the generated signal will have a constant relationship with the flow profile		YES

To confirm electrical contact of the electrodes requires an impedance measurement between the flow sensing electrodes via the liquid, when the tube is full, to earth. The resistance will be in a range depending on the conductivity of the liquid. For instance[1] the approximate expression for the resistance, R, between electrodes is:

$$R \approx \frac{1}{d\sigma} \qquad (2)$$

where d is the diameter of the electrodes and σ is the conductivity of the liquid. With $\sigma \sim 4 \times 10^{-6}$ S/m for pure water and $\sigma \sim 10^{2}$ S/m for the best electrolyte, the range of measurements between the electrode and earth will be at least as great as 1 ohm to 25 megohms. The system will, clearly, have to be more discerning than this would allow.

3.2 Checking for integrity of cables and earth shields etc.

Due to the rigours of EMFM installation in some industries, in particular the water industry, it is common for the transmitter to be separated from the sensor head. This results in the need for connecting cables and sealed joints at their terminations. The sensor may be submerged in water and the danger of ingress may be high. The need to check the integrity of cable, its continued isolation from earth, the integrity of any shields, the integrity of the signal leads etc. is obvious. Again the system will need to operate like an ohm meter, but the likely limits for correct operation should be narrower than those for the electrode/liquid circuit.

3.3 Simulation of flow signals into the electrode amplifier circuits

Early versions of simulation devices were concerned with signals in milliamps, frequency or pulse modes. With advancing digital technology it is likely that most modern systems will incorporate digital signals. It will, thus, be necessary to insert a voltage into the signal input circuit and to measure the digital output for various values. The verification input voltage will need to be to an appropriate uncertainty. The analogue to digital converter (A/D) at output will need to operate to an appropriate level of uncertainty. In addition the conversions from digital to analogue and frequency/pulse will need to be to appropriate uncertainties.

The verification device will, therefore, be operating like a high quality multimeter and voltage source. The uncertainty on this will be set up at manufacture but will need to be certified at appropriate intervals.

However, there is a further complication. The signal from the electrodes, ΔU, will reflect the shape of the exciting magnetic field. In the past this was an AC generated field. In most modern designs it is some form of square wave. The input waveform will need to be simulated so that the measured voltage at each stage allows for this and the output can be measured to a certified uncertainty. This may introduce other questions such as the effect on the measurement of the unsteadiness in flow signal and baseline.

3.4 Checking for constancy and integrity of the magnetic field and field coils

There are two constancy requirements. The first is clearly that the field is constant over the period of signal measurement, Level 4. The second is the more complex problem of insuring that the magnetic field remains constant in size and unchanged in distribution over the working life of the meter since manufacture, Level 5. This will require some independent form of field measurement.

Early designs of EMFM used either the excitation current or a search coil to compensate the signal for variation in the magnetic field, essentially Level 4. These had strengths and weaknesses. One problem area was for the measurement of flows with magnetic particles entrained. For the new generation of EMFM the field excitation is held constant and one manufacturer (at least) has adopted the inductance of the field coil as a means to check its constancy. It is useful to consider these methods in turn:

i. ***Current measurement*** Provided there are no changes to the field coils or their positioning, and that the fluid is not magnetic, the measurement of the current should be sufficient. However, in the verification philosophy, the object is to pick up any changes which could affect the meter uncertainty.

ii. ***Search coil*** This method certainly measures magnetic field size, but may be limited to a particular region of the field or to a partial average, and may not sense change in the distribution of magnetic field. An alternative to the search coil would be a Hall effect probe or some other field sensing device.

iii. ***Inductance*** This provides an indirect method of checking the constancy of the magnetic field, and combined with the resistance measurement should be adequate for most eventualities, although it is possible that shifts in the magnetic field coils could fail to give a change in the inductance, while changing the actual field size.

3.5 Referencing back to manufacture

The philosophy of the verification is to ensure that no change has occurred to the meter since manufacture. The measurements set out in the previous sections must, therefore, be referenced back to the values at manufacture. This has important implications for the manufacturing systems used. Either the average values of each parameter must be obtained or the specific values for each product manufactured must be recorded and filed. If the first course is chosen, then the manufacturing system must yield a very low variation in its manufacture, so that the standard deviation from the average is small enough to make the verification useful. If each product is measured, then each product will need to be followed and recorded preferably in an electronic file. In either case the manufacture and general housekeeping of the company will need to be of a very high order

4. The predictive uncertainty achievable

The verification device will act, possibly in conjunction with internal systems in the meter design, as a high quality multimeter. In Figure 2 a diagram of the common components of the verification system are shown. The flowmeter is coupled to the hand-held verification device which is programmed to run a check on the flowmeter's systems. A laptop may be coupled up to the verification device, either *in situ* or after the verifications are complete, in the office. We consider the likely uncertainty budget which could reasonably be expected for such a device. It is likely that a claim for the digital output from the EMFM as delivered will lie in the range of ±0.5% to ±1.0%. The figures which follow are indicative only as an example.

Uncertainty in injected voltage from verification device to EMFM amplifier input ±0.2%
Uncertainty due to square wave excitation ±0.2%
Uncertainty in analogue to digital converter (A/D) in EMFM output ±0.2%

Assuming the same uncertainties apply at manufacturing set-up and for *in situ* verification, the total uncertainty will be $\sqrt{[(0.2)^2 \times 3 \times 2]}$% ±0.48%

Measurement of magnetic field using search coil, Hall probe etc. ±0.4%

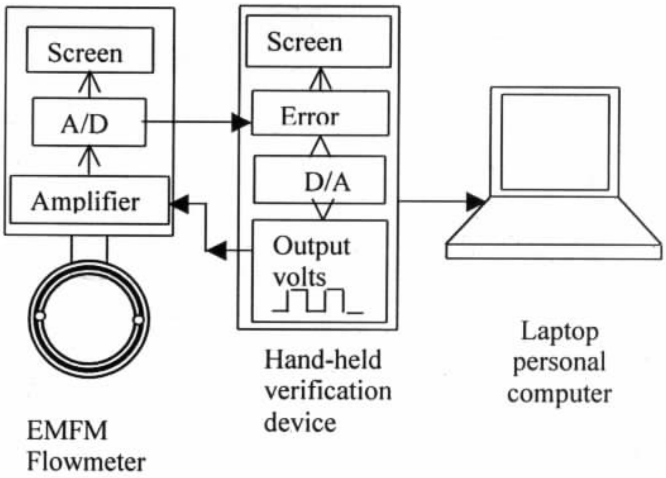

Figure 2 Typical set-up for verification tool, EMFM and computer

Total field uncertainty for manufacturing set-up and *in situ* verification ±0.56%

Temperature variation uncertainty ±0.4%

Total uncertainty due to voltage, magnetic field and temperature variation ±0.84%

There is, of course, no check on the constancy of the wetted end of the EMFM, and this could be upset by problems with the liner becoming detached or blistering (unless this causes a short to earth) or due to deposits in the tube.

It is, therefore, unlikely from this example that overall uncertainty following verification could be claimed as better than ±1%, even assuming there is no change in the relation between flow signal and mean velocity in the tube.

Johnson[5] discussed the use of the ABB CalMaster system in the Detroit Water & Sewage Department (DWSD).and the benefits which they claimed were:

- ISO certification of the complete flow metering system without having to remove the EMFM's primary sensor from its location;
- keeping the meters on line thus reducing down time;
- verifying that the original calibration data was still valid;
- periodic calibration and performance checks providing a diagnostic and condition monitoring tool.

While the system provides a valuable check as indicated by Johnson[5], some of these claims appear to go beyond the capability of the system. The final check on the actual wet calibration is not possible from this system, and this appears to be confirmed by the manufacturers.

It is important to note that there are implications for the manufacture of these devices in terms of low manufacturing variation, particularly if an initial fingerprint is not taken, but even if one is, the manufacturing variation and the internal "housekeeping" must be of a high standard.

5. The management and administration of the process

5.1 Management and administration within the manufacturing company

The achievement of a satisfactory verification system places certain requirements on the manufacturer:

- ***low variation in manufacture*** - the quality and stability of the instrument have to be of the highest order to ensure that data on manufacture can be used with confidence as a datum or "fingerprint" of the initial product;
- ***manufacturing housekeeping*** - the record keeping on products, components and calibration certification must be immaculate to ensure that all details of initial product set-up are traceable;
- ***manufacturer's requirements for users*** - the manufacturer must set up communication and scheduling with customers to ensure that, within reason, advice and access to data is always available to the customer.

5.2 Management and administration within the user company

The user will need to adopt clear procedures for control and documentation of verification and recalibration routines. These should include:

- ***who controls and who uses the verification equipment;***
- ***how and where documentation is kept;***
- ***who is authorised to modify meter settings.***

6. Devices available commercially and of which the authors are aware

The authors are aware of four devices which appear to fall into the category of verification devices as discussed in this paper. The information available on these devices indicates that they lie in categories (b) & (c) in Section 1.2. These are devices, which go beyond simulation and make use of various accuracy checks, both internal and external. They may also include electrode cleaning systems.

The authors have had the opportunity to undertake thorough assessments of two of these devices[6]&[7] both in the laboratory and in the field. They differed in the extent to which they dealt with all the levels in Table 1. Equally, for the other two devices known to the authors, there is some uncertainty, from a perusal of their literature and websites, as to the extent that all levels in Table 1 are covered.

Some systems allow adjustment *in situ* which may require an authorisation protocol.

Other manufacturers have options such as EMFM simulators. One manufacturer appears to claim, for instance, that their EMFM transmitter is self-calibrating and no verification device is required. They achieve this by using an internal reference voltage in the transmitter, set during factory calibration, and checked in the field using a digital multimeter with calibration certificate.

As acknowledged by manufacturers, the verification devices do not check the integrity of the internal flow tube unless there is a short to earth or a similar fault. Provided there is no wear of the internal liner, no internal build up in either the flowmeter tube or the tubes each side of it, nor other flow-related problems within the tube, the verification device may provide a valid interim check on the calibration of the meter. But inability to make these checks on the flow tube itself is the key limitation in these devices, and a major uncertainty in the verification procedure. There would, therefore, be great benefit from further careful study to simulate possible situations where these devices may fail to identify change in calibration.

7. Discussion

How well is calibration checked? At least four elements are required:
a) integrity of the electrical circuits - this appears to be checked in all devices with various levels of uncertainty claimed;
b) magnetic field measurement - at least two of the devices claim to check the magnetic field to ensure that it is within specification;
c) internals of pipe unchanged e.g. blistering of liner - none claim to be able to check this;
d) flow conditions unchanged e.g. build up in the pipe - none claim to be able to check this.

The overall claims for the verification process appear to lie within 1% to 2%. So how useful are these devices? If we assume that electrical changes could be in a short timescale, τ_1, that magnetic field changes will probably occur over a longer period, τ_2, that liner or other structural changes will probably occur over a longer period again, τ_3, and that flow changes will again probably occur over a longer period, τ_4, we could reasonably say that

$$\tau_1 < \tau_2 < \tau_3 < \tau_4$$

However, the likely period of changes may be difficult to predict with any confidence. The assumption that τ_4 is the longest, is also open to question. On the other hand, severe liner problems would probably be picked up by some of the systems.

8. Conclusions

In this paper we have indicated the capability and the limitations of the new breed of verification devices. We have shown that all appear to undertake an updated form of simulation. Some appear to check the size of the magnetic field. None are able to assess the state of the inside of the flow tube unless this causes a change in the electrode and magnetic field earth connections.

It remains open to question to what extent these methods can help. It could be argued that changes not covered by these measurements would be exceedingly rare, and that the verification can be trusted to ensure that the initial calibration holds. If this were the case, then there would be a strong argument to cease re-calibration of EMFMs. We have not yet reached that situation.

There is, however, a need for some careful research on the extent to which changes, actual or artificially created, can change the calibration of the meter without a verification system identifying that a problem exists.

With increasing numbers of verification devices likely to become available commercially, electromagnetic flowmeter standards should ensure that the expectations and limitations of these devices, and their ability to extend the period between calibrations, are clearly set out for the user.

Acknowledgement

The authors wish to acknowledge support for this work from Evaluation International and from the Gatsby Charitable Foundation.

References

[1] Baker, R. C. Flow measurement handbook. Cambridge University Press 2000.

[2] Furness R A. and Smith, D. J. M. *In situ* verification and calibration of liquid flowmeters. Flow Measurement and Instrumentation Consortium (FLOMIC) September 1987.

[3] Al-Rabeh, R. H. and Baker, R. C. On the ability to dry calibrate an electromagnetic flowmeter. J. Phys. E.: Sci. Instrum. 19:203-206, 1986.

[4] Baker, R. C., Moore, P. I. and Wang, T. Rethinking dry calibration. FLOMEKO 2004 12th International Conference on Flow Measurement, September 14-17, 2004, Beijing, China.

[5] Johnson, R. Keeping meters on line: accurately measuring drinking water and sewage. Water Engineering and Management, 149(9): 14-19 2002.

[6] Baker, R. C. and Thomas, A. L. *CalMaster electromagnetic meter calibration verification instrument.* Evaluation International Report E 1801 X 02, August 2002.

[7] Baker, R. C., Moore, P. I. and Thomas, A. L. *Assessment of the validity of the claims made for the Endress+Hauser FieldCheck, SimuBox and FieldTool verification devices and software when applied to electromagnetic flowmeters.* Evaluation International Report E 1812 X 04, 2004.