ULTRASONIC FLOWMETERS FOR THE GAS INDUSTRY

by

M E Nolan and J G O'Hair
British Gas

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M E Nolan and J G O'Hair

British Gas, London Research Station, London SW6 2AD.

R J W Peters

Daniel Industries Ltd., Larbert, Scotland.

S U M M A R Y

This paper describes the latest developments in the design, manufacture and operation of a multipath ultrasonic flowmeter. A number of meters have been in operational use on British Gas sites for several years now, and the experience gained during this time is reported.

Development has reached the stage where a commercial version of the meter is being manufactured. Performance tests of such a meter have been carried out on the British Gas Test Site, and the results of these tests are also reported. Plans for further developments of the meter are also described.

1 INTRODUCTION

A few years ago, British Gas reviewed all possible methods of metering large, high pressure, gas flows, such as occur in the National transmission system. It was apparent that, for a meter to have significant advantages over the widely used orifice plate meter, it should have similar (or better) accuracy, a higher turn-down ratio, simpler (and therefore cheaper) installation requirements and should have negligible pressure drop. An ultrasonic meter seemed the most likely type of meter to meet these requirements.

Evaluation of the established techniques, which had been developed primarily for liquid metering, indicated that a transit time technique would be the most suitable for accurate measurement. The theory of such meters has been included in previous papers(1,2), where the velocity of the gas (V) is shown to be given by the simple equation

$$V = L^2(T_2 - T_1)/ 2 X T_2 T_1 \quad \ldots\ldots (1)$$

where
T_2 is the transit time of the pulse travelling against the flow,
T_1 is the transit time of the pulse travelling with the flow,
and L and X are geometrical constants of the meter as shown in figure 1. This figure also shows, schematically, the positioning of the ultrasonic transducers, which act as both transmitters and receivers, with respect to the pipework or spoolpiece.

2 PRELIMINARY INVESTIGATIONS

2.1 Theoretical studies.

Though equation (1) is exact, and involves only measureable quantities, it gives only the mean velocity of gas in the section of pipe between the two transducers, not the mean velocity in the whole of the pipe. It is possible, in a fully developed turbulent flow, to relate a velocity measured across a diameter of the pipe to the required mean velocity. However, since one of the requirements was that the meter should have simple installation requirements i.e. no need for long straight lengths of pipe upstream of the meter, this option was discarded. It has since been our experience that, even in ideal metering installations, the expected, symmetrical flow distributions rarely exist, particularly so for low flows.

One method of obtaining a satisfactory value for the mean flow, even in disturbed distributions, is to make velocity measurements on several parallel chords spaced across the pipe. This enables a numerical integration technique to be used to compute the mean flow through the pipe. The accuracy of this integration is greatest if the chords are spaced as defined by the numerical technique used[3]. Also, the more chords the greater the accuracy.

Computer simulation of this integration technique was carried out using a number of mathematically defined flow distributions. Some of these were the standard symmetrical profiles, others were highly distorted. The conclusion was that, with four chords, the integration was unlikely to contribute errors which exceeded 0.5%. The use of five chords gave only a small improvement in accuracy whereas the use of only three chords gave a significant deterioration. We therefore decided to construct a four-path ultrasonic flowmeter and evaluate its performance.

2.2 Experimental Investigations.

The first meter to be thoroughly tested was 150 mm in diameter. The results of these tests have been reported in detail in earlier papers[1,2,4]. The conclusions were that the accuracy of the metering in fully developed flows was good and that, in highly disturbed flows, the integration technique performed with the predicted accuracy.

This same meter was later operated for 8 months in series with an orifice plate meter on an offtake station of the transmission system. There were no major problems, and the experience was used to guide the design of improved versions of the meter.

A number of meters, ranging in size from 100 mm to 1050 mm diameter, were manufactured and installed on British Gas sites. These sites were chosen to cover a wide range of operating conditions and our experiences are summarised in table 1 and described in the following section.

Where possible, each meter was tested on the British Gas test site at Bishop Auckland prior to installation on the operational site. The reference meters on the test site are turbine meters which have been calibrated against critical flow nozzles, themselves calibrated by NEL. The accuracy of the reference metering is within the range +0.5% to -0.7%. It is described further in reference (5).

Comparison against the reference meters is confined to primary metering i.e. to actual flows. Conversion to standard conditions can be by either of the commonly used methods, namely the measurement of density, or of pressure and temperature. The computations required to convert to standard conditions are carried out within the ultrasonic meter's microcomputer.

It is perhaps worth re-emphasing that the calibration of each ultrasonic meter is obtained from the measurements of the spool dimensions during manufacture. Comparisons with a reference meter serve to verify the principle of the meter and establish the accuracy of measurement. The data so gathered should assist in the writing of a recognised standard for the operation of ultrasonic meters.

3 OPERATIONAL EXPERIENCES

In general, all meters were designed to operate over the temperature range of -10 to +50 ^{o}C, and over the pressure range from 35 to 75 bars, though one meter has been designed to operate at pressures up to 240 bars. The meters are basically similar, except for the very high pressure meter, and except for the fact that meters of 300 mm diameter and above incorporate a ball valve for each transducer, enabling each one to be independently isolated from the high pressure gas and removed for inspection or replacement.

3.1 A Meter on an Offtake Station (Pressure Reduction Station).

The first meter to be installed on an operational site was 300 mm diameter and was used on an offtake station near Cambridge to replace an ageing orifice plate meter.

Prior to installation on site the meter was tested at the Bishop Auckland test site. The results are shown in figure 2, from which it can be seen that the measurement accuracy, over the range from 340 to 4000 acm/h, is well within the specification of ± 1% of actual flow.

After installation on site a further test of its accuracy was arranged as part of the meter validation procedure. A radio-tracer technique was used as a check of the primary metering accuracy, the results of which are shown in Table 2. The agreement is well within the combined uncertainty of the two methods.

The meter has been operational on this site since November 1984. It was initially set to measure flows up to 85,000 scm/h, but the computer has been reprogrammed to scale the analogue output for a maximum flow of 113,00 scm/h. Since installation, there have been very few problems with the meter, and all have been minor faults, namely a poor solder joint on the back-plane bus, an integrated circuit which failed, and a mechanical relay (used to provide voltage free contacts for a remote flow totaliser) which also failed.

3.2 A Meter Measuring Compressor Station Flow

There are special problems in selecting meters for use on compressor stations where accurate flow measurement is required to optimise efficient use of the compressors. British Gas has used elbow meters, which have low accuracy and limited turn-down ratio, or orifice plate meters which, because of the associated pressure drop, result in an increase in the fuel consumption of the compressors. The ultrasonic meter should provide a better alternative since it has no pressure loss and it has a high accuracy, the calibration being defined by the geometrical measurement of the meter section.

An ultrasonic flowmeter was installed, for the first time at a compressor station, in December 1984. This meter was too large (1050 mm diameter) for it to be tested on the test site prior to installation on the compressor site. However, as part of the compressor performance trials carried out in March 1985, some flows were measured using the radio-tracer technique and comparisons made with measurements using the ultrasonic meter.

The results of these comparisons are shown in table 3. The precision of the radio-tracer measurements was degraded slightly by the site conditions. The presence of a Tee-junction with a closed leg and the build-up of background radiation due to gas recirculation round the site, made the pulse of radiation more difficult to detect and time accurately. None-the-less, all the ultrasonic meter measurements agreed within the uncertainty of the radio-tracer measurements.

This performance evaluation showed that the meter measured over the normal operating range of the unit, but this particular compressor has not run very frequently, so it has been difficult to monitor the performance of the meter since then. There have been few problems with the equipment, but the signal processing has been improved and new, more sensitive, transducers have been fitted to improve performance at high flows. During recent visits to the site whilst the compressor was being tested, the meter was observed to be working properly with a flow of 2.34×10^6 scm/h (full scale is set at 2.5×10^6 scm/h) though this high flow could only be maintained for a short while following start-up of the compressor.

3.3 Meters Measuring Fuel Flow to a Compressor

Two 100 mm diameter meters were manufactured to measure the fuel flow to two compressor units. Both meters were tested at the Bishop Auckland test site prior to installation on the compressor station. The results of these tests are shown in figure 3 where it can be seen that agreement with the reference meters is always within the nominal ± 1% error band and for 23 of the 26 points, the difference is less than 0.5%.

The two meters are each ranged to measure flows up to 7595 scm/h. They were commissioned on site during November 1985, and have been operational virtually continuously since then. Transducers have had to be exchanged on two occasions since then, but the improvements to the transducer construction, described in the next section, are designed to obviate any further problems. The only other faults that have occurred have been the failure of an integrated circuit (an A to D converter in one of the analogue input circuits), a broken solder joint, and an electrical connector which was accidentally damaged. All these faults were very minor and were easily and quickly rectified.

3.4 Meter Measuring Flows to and from a Storage Facility.

A 150 mm diameter meter has been installed on a salt cavity storage site. The ultrasonic meter is particularly suited to such applications since it is bidirectional. This meter was designed for use at pressures from 90 bar up to 240 bar (class 2500) and to measure flows up to 3,500 scm/h. This particular application presented us with conditions we had not encountered before, and necessitated some mechanical modifications, described below.

Laboratory tests indicated that the performace of the existing transducers often deteriorated after pressure cycling tests up to the required operating pressure. The design was therefore improved, and all transducers are now manufactured to this new design. This means that their use at the more normal pressure of typically 70 bar is well within their design capability.

This meter was also tested at the Bishop Auckland test site, though only at a pressure of 70 bar, the maximum pressure available on the site. The results of these tests are shown in figure 4. It can be seen that, over the flow range tested, which was 1 to 32 m/sec, the difference between the ultrasonic meter and the reference meter was within ±0.4%.

The meter was installed on site in the summer of 1986. It was a while before the meter was used, and it was then very soon discovered that it was not operating properly. When the transducers were removed for inspection it was discovered that the acoustic interface between the crystal and the gas had been chemically attacked by something in the pipeline. Though we have not ascertained the cause of this trouble it is possible that liquid methanol was responsible. This required another change to the transducer design to incorporate a metal interface.

These new transducers were installed on site in the summer of 1987. Another problem was immediately apparent when gas began to flow out of the cavity. This was caused by a very heavy grease in the pipe, probably originating from the pipework at the head of the storage cavity, which quite quickly blocked the lower transducer ports, reducing the signal size considerably. This problem was solved by filling the associated pipework with methanol for a while to disolve the grease, and then flowing gas through to clear the grease from the system. The meter has since operated without any problems.

It is worth noting that, with many metering systems, the presence of this grease may have gone undetected and metering errors would have resulted. Also, the introduction of liquid methanol into the pipe section to clear out the grease served as a good test of the resistance of the new transducers to chemical attack.

4 RECENT DEVELOPMENTS

A modified design of the meter has recently been produced by the manufacturer. The transducers and drive circuits, though redesigned for ease of manufacter, are similar to those used in the batch of meters manufactured by British Gas for use on operational sites. The computer has undergone a more significant redesign, and now incorporates an integral display screen.

A 300 mm meter has been manufactured to this design and is being subjected to a rigorous program of testing. In particular, a series of tests were performed at the British Gas test site. The results of these are shown in figure 5. In developed flows the accuracy was well within the ±1% band throughout the range of flows from 76 acm/h to 6,500 acm/h.

Such performance in developed flows is not unexpected. Much more satisfying are the results obtained during measurements in the highly disturbed flows created when a partial blockage was mounted upstream of the meter. The blockages used, referred to as half-moon or quarter-moon plates, are shown in figure 6. They were installed 6 D and 10 D from the meter and with the orientations shown in the figure.

Figure 5 shows 57 comparisons between the reference metering and the ultrasonic meter reading with the disturbance plates installed. Of these, only one indicated a difference exceeding 1% and that, being the first of three readings at a new flowrate, may have been taken before the conditions had stabilised properly. The difference on all but three of the other readings was less than 0.8%.

The very high level of disturbance generated in the flow by these plates is shown in figure 6. The individual velocity measurements (V_i) made on each of the four chords ($i = 1$ to 4) have been represented schematically in this figure. They are shown as a ratio to the mean flow velocity ($\bar{V}$). Compared with the distribution in a fully developed flow, which can be seen to be virtually symmetrical, the distribution is highly distorted when the plates are installed either 6 or 10 diameters upstream.

In the cases where the plate, either quarter-moon or half-moon, was installed such that it blocked the top half of the pipe, the flow distribution, at both 6D and 10D distances, revealed that the flow was greatest in the top half of the pipe. This seems to suggest that the gas, having passed through the bottom half of the plate, tends to readjust so much that it over-compensates for the effect of the disturbance.

We also carried out tests in an extreme condition, with the half-moon plate located at the meter flange (1.5 D distant) blocking off the top half of the pipe (see figure 6). This gave a large negative flow in the top half of the meter, as the gas apparently swirled around behind the plate, and a very large flow through the bottom of the meter, almost three times the mean velocity on the bottom chord. Note the change of scale from previous figures for the figure representing this profile.

In this extreme condition the difference between the reference meter and the ultrasonic meter was still less than 2% for each of the three measurements at that flow, an amazingly good accuracy for such a distorted flow profile. Of course, with such large flows through the bottom half of the meter compared with the mean flowrate, the maximum measureable mean flow was much less than normal. We would not recommend the meter be installed and operated in conditions such as this, but the test serves to prove how well the meter can perform in the most extreme of conditions.

5 PROPOSED FUTURE ENHANCEMENTS

The most recent design, described in section 4, incorporates many improvements to the earlier British Gas design, though it is fundamentally similar. The present design requires a custom Flow Computer Unit which is discretely connected to a custom Transducer Drive Unit. Several disadvantages exist with this concept; a Flow Computer must always be provided, tailored to customer requirements; all flow measurements must be carried out by a single microprocessor in the Flow Computer while the same microprocessor is performing several other tasks; and the Drive Unit must be physically situated close to the Flow Computer due to the discrete connections between the two units.

Several enhancements have been identified to the present design which is seen as a two phase product development (see figure 7). The first phase would be to introduce intelligence into the Drive Unit and to comply with an industry standard form of communications protocol between the Flow Computer and the Drive Unit. The Drive Unit would still, as in the present design, require an intrinsically safe circuit to drive the transducers over an appropriate cable. The Drive Unit would be able to measure flow and carry out error checking on the measurements before communicating this information on the standard serial communications bus to any form of flow computer configured to accept this data.

The second phase of the development would be to remove all the intrinsically safe aspects of the circuits in the drive unit and place all the electronics in an explosion proof and/or sub-sea enclosure. This enclosure would then be mounted on the spool piece and would become, effectively, a "smart transducer". The same standard communications would be used to transfer up-to-the-minute flow data to a supervisory process control computer.

The first phase of the design would take into account any environmental conditions required for the second design phase. Therefore the two designs would be electrically similar; the main difference being in the more stringent mechanical and environmental requirements of the Explosion Proof version.

6 CONCLUSIONS

We have now obtained, after several years of development, a substantial body of operating experience for the four-path ultrasonic meter. We have established that the meter is very reliable, that it is accurate and that it maintains its accuracy well, even in very disturbed flow conditions. Most of our experience has been with the chords arranged in a "criss-cross" configuration, as described in our earlier papers[1,2]. This has been shown to give good cancellation of errors due to cross-flows or to swirl.

6.1 Information for the Operator

Like all other flowmetering techniques, the four-path ultrasonic meter is more suited to some applications than to others. Unlike most other techniques, an operator should always be able to tell when the primary flow measurements are not correct. This is possible because the operator can access a number of parameters and can compare values on each of the four measuring paths. Some examples of this are given below.

(a) Unreliable measurements on one or more paths due to weak signals or due to a high noise level, are easily recognised by the high percentage of rejected readings.

(b) Severely disturbed flow profiles are revealed by observing the measured velocities on each of the four chords. On the offtake station described in section 3.1 we found that a substantial amount of swirl was generated by the header arrangement and that the direction of swirl could be altered according to where the gas entered the header tube, i.e. according to which of the three filters were being used. The level of swirl present was not sufficient to affect the accuracy of the ultrasonic meter, but would have affected the accuracy of many other types of meter.

(c) Incorrect triggering, or variation in gas temperature across the pipe, can be observed as a change in the velocity of sound, which should be the same on all four chords when the meter is functioning correctly.

Other useful information can be obtained from the measurement of the velocity of sound. Variations in the velocity of sound at a constant, or known, temperature and pressure are related to the gas composition and may be used to monitor changes in composition or to control gas blending.

6.2 Installation Recommendations

Our experience also enables us to make some tentative recommendations concerning the use of such meters.

(a) We have established, through our extensive tests, that the existing design works well in high pressure (> 40 bars) natural gas. We have also done a limited amount of testing, with good results, in low pressure (5 bars) natural gas and have also operated the meter, for demonstration purposes, in the laboratory using air at atmospheric pressure.

(b) A conservative recommendation for the installation of such a four-path ultrasonic meter would be to have a minimum of 10 diameters of straight pipe upstream of the 1 diameter long metering section, and a minimum of 3 diameters downstream.

(c) For accurate measurement of low velocity flows in high pressure gas the meter should be lagged. This requirement is primarily necessary for accurate secondary metering measurement of temperature. Without lagging, the temperature of the gas at low flows can vary significantly across the pipe, so the measured temperature may not be the true mean temperature of the gas.

(d) The maximum mean gas velocity at which the meter works well is reduced if the transducers pick up a lot of acoustic noise in the gas or if the velocity distribution is extremely distorted. It is therefore best not to mount the meter too close to a compressor or very near a flow disturbance. Quantifying these effects can be difficult.

(e) The meter should be mounted with the measuring paths horizontal, primarily to avoid problems of dirt, or liquid, collecting in the transducer ports and blocking the passage of the sound pulse.

We have found the ultrasonic meter to have substantial advantages over alternative meters for the measurement of high pressure gas flows. Many of these advantages are particularly relevant to metering off-shore, where high reliability, easy servicing, low weight, and short installation lengths, are particularly beneficial.

7 ACKNOWLEDGEMENTS

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We would also like to thank British Gas and Daniel Industries for permission to publish this paper.

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TABLE 1 SUMMARY OF OPERATIONAL METERS

Meter Size	Site and Duty	Installed Commi'ned	Pressure bars	Flow scm/h
300 mm	Flow through an offtake station	Oct 84 Dec 84	35 - 75	0 - 113,000
1050 mm	Flow through a Compressor station	Sep 84 Mar 85	35 - 75	0 - 2.5×10^6
100 mm	Two meters, each measuring fuel flow to compressors	Nov 85	35	0 - 7,595
150 mm	Flows to and from Storage facility	Summer 86	90 - 240	+ 55,000 to - 125,000

TABLE 2 RADIO-TRACER TESTING OF 300mm METER

Station flow as % of full scale flow		56.5	39.1	25.0
Flow rate acm/h	Radio-tracer	783.1 ± 7.8	544.1 ± 9.9	349.0 ± 4.6
	Ultrasonic	791.7 ± 7.9	549.7 ± 5.5	350.7 ± 3.5
Combined uncertainty %		2.0	2.8	2.3
Difference % between methods		1.10	1.03	0.49

TABLE 3 RADIO-TRACER TESTING OF 1050mm METER

Flow rate by Radio-tracer Thousand acm/h		25.87	31.38	37.00	41.34
Radio-tracer uncertainty %	method 1	1.72	0.93	2.04	2.96
	method 2	0.97	0.93	2.37	2.23
Flow rate by Ultrasonic meter Thousand acm/h		25.99	31.67	37.22	40.97
Difference % betweeen methods		0.48	0.92	0.59	-0.84

Note: The flowrate shown for the radio-tracer technique is the mean of two methods used. The uncertainties of these two methods are shown individually.

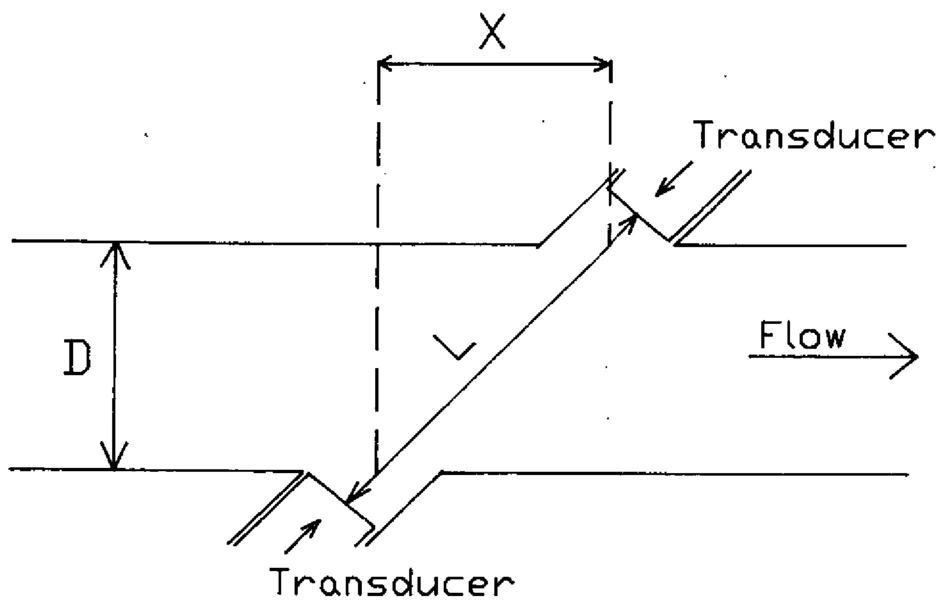

Fig.1. The schematic representation of the ultrasonic flowmeter

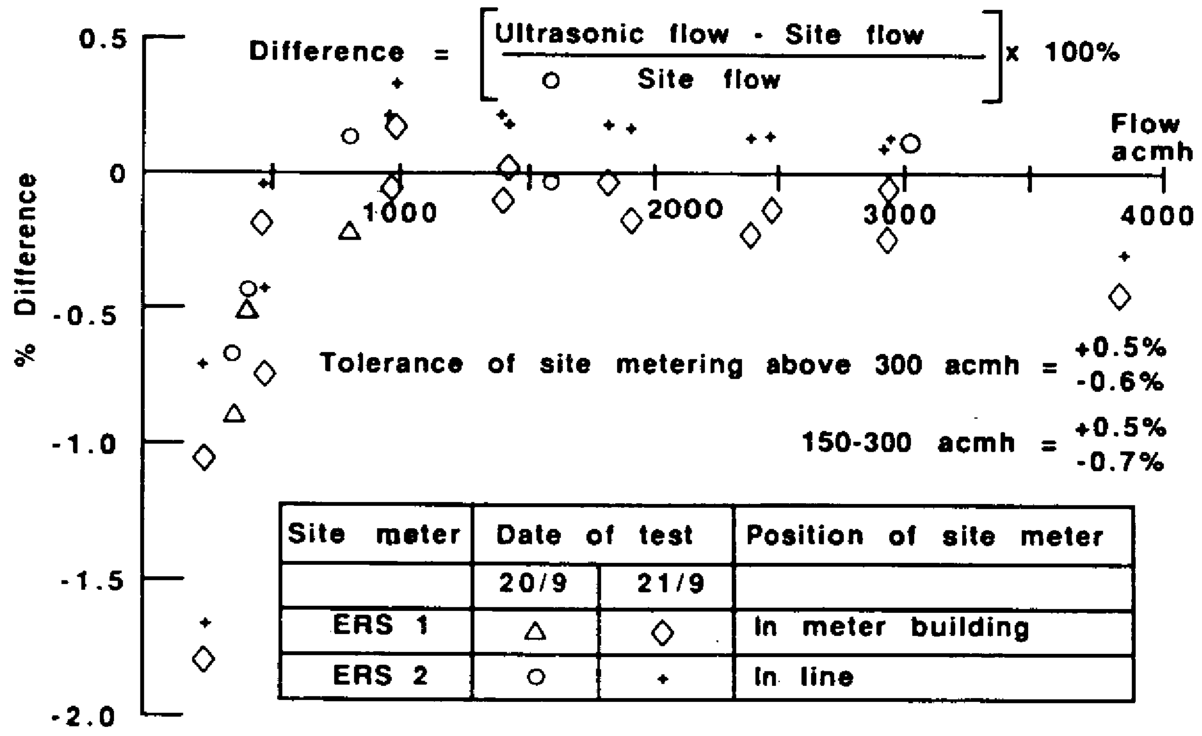

Fig. 2. Comparison between 300mm ultrasonic meter and test site metering

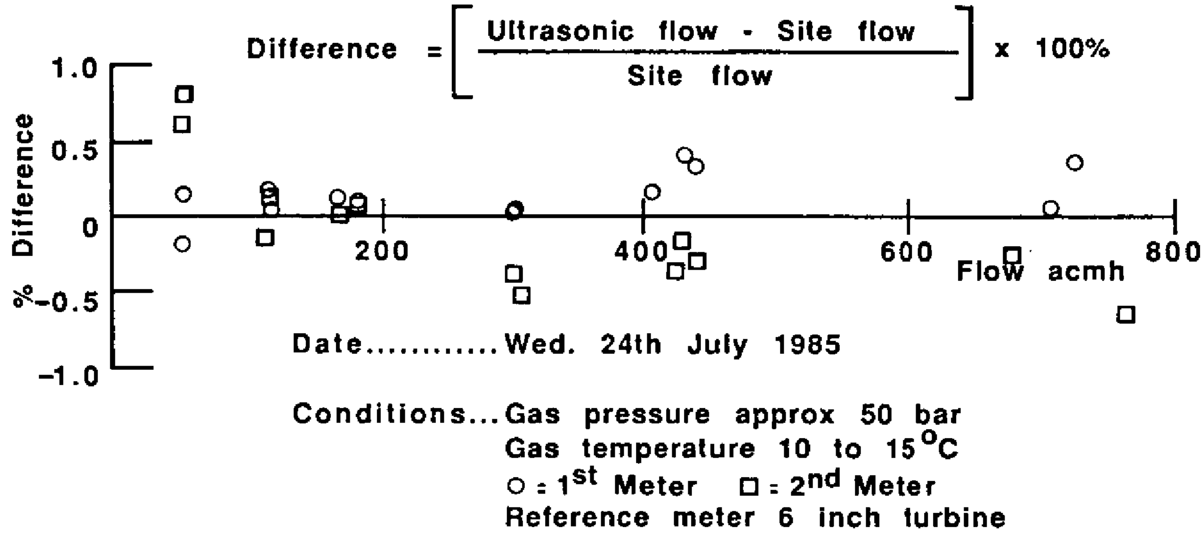

Fig. 3. Comparisons of 100mm ultrasonic flowmeters and Bishop Auckland test site meters

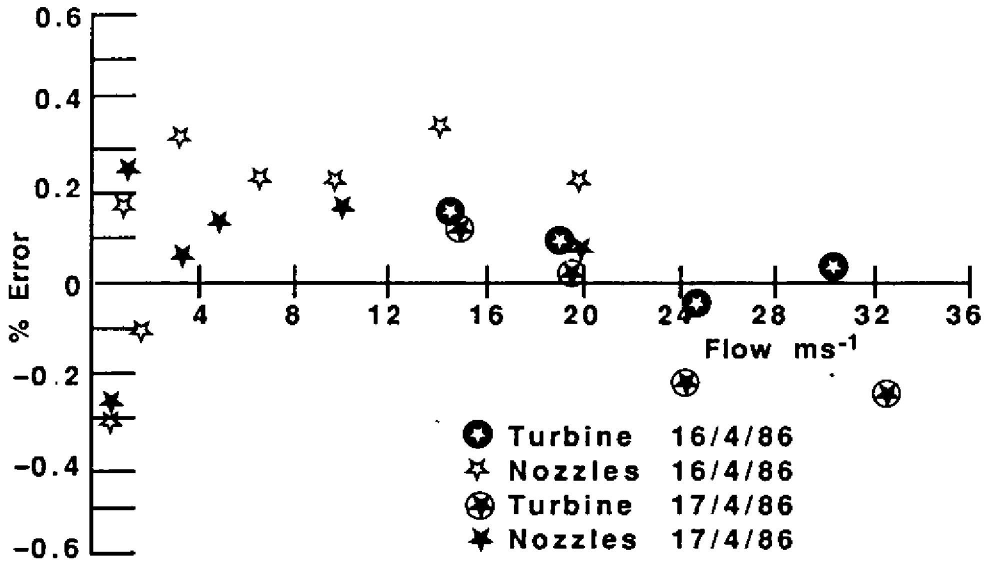

Fig. 4. Comparisons between 150mm ultrasonic meter and Bishop Auckland site metering

FIGURE 5

TEST RESULTS FOR A 300mm METER ON A BRITISH GAS TEST SITE.

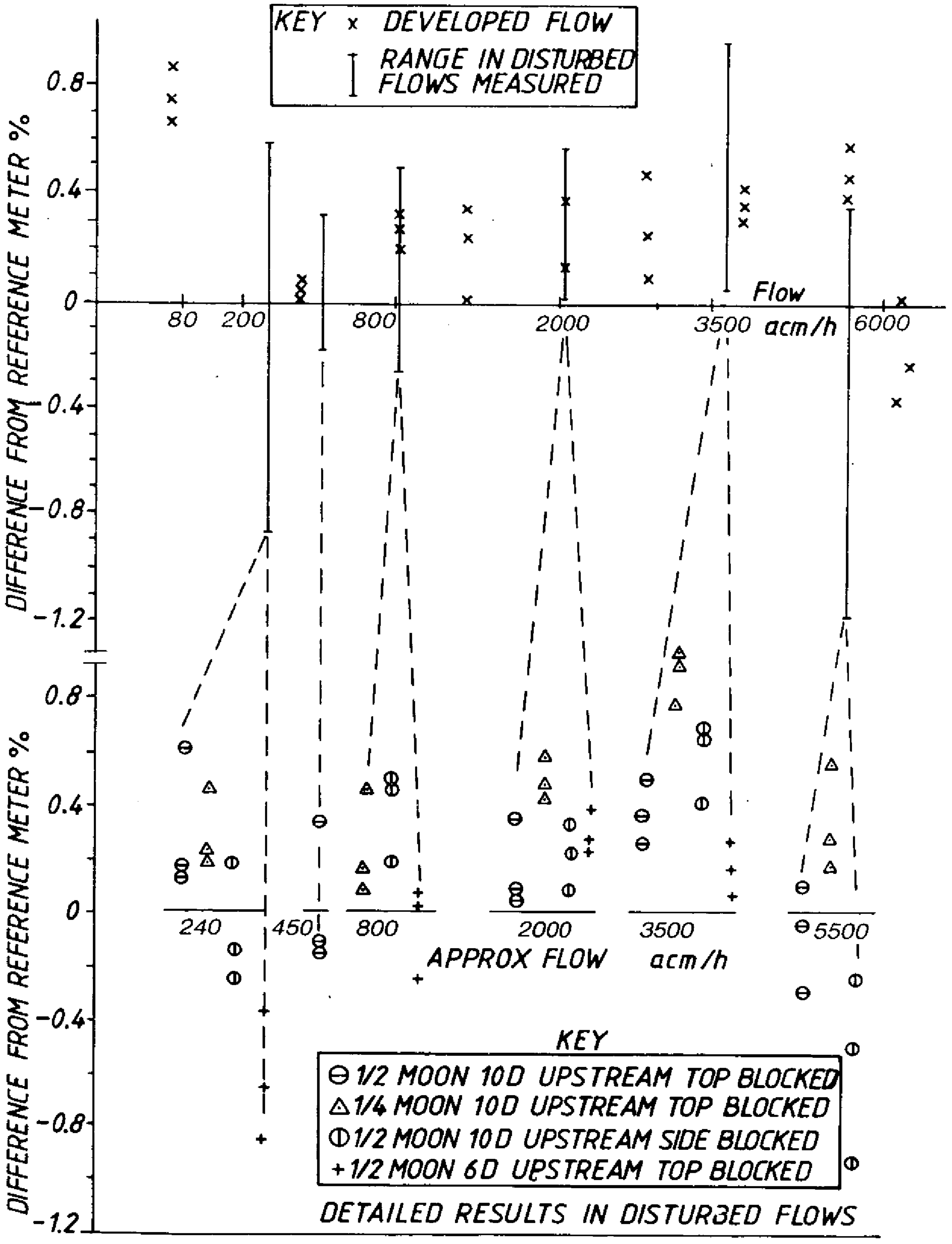

FIGURE 6

PLOTS OF MEASURED VELOCITY RATIOS

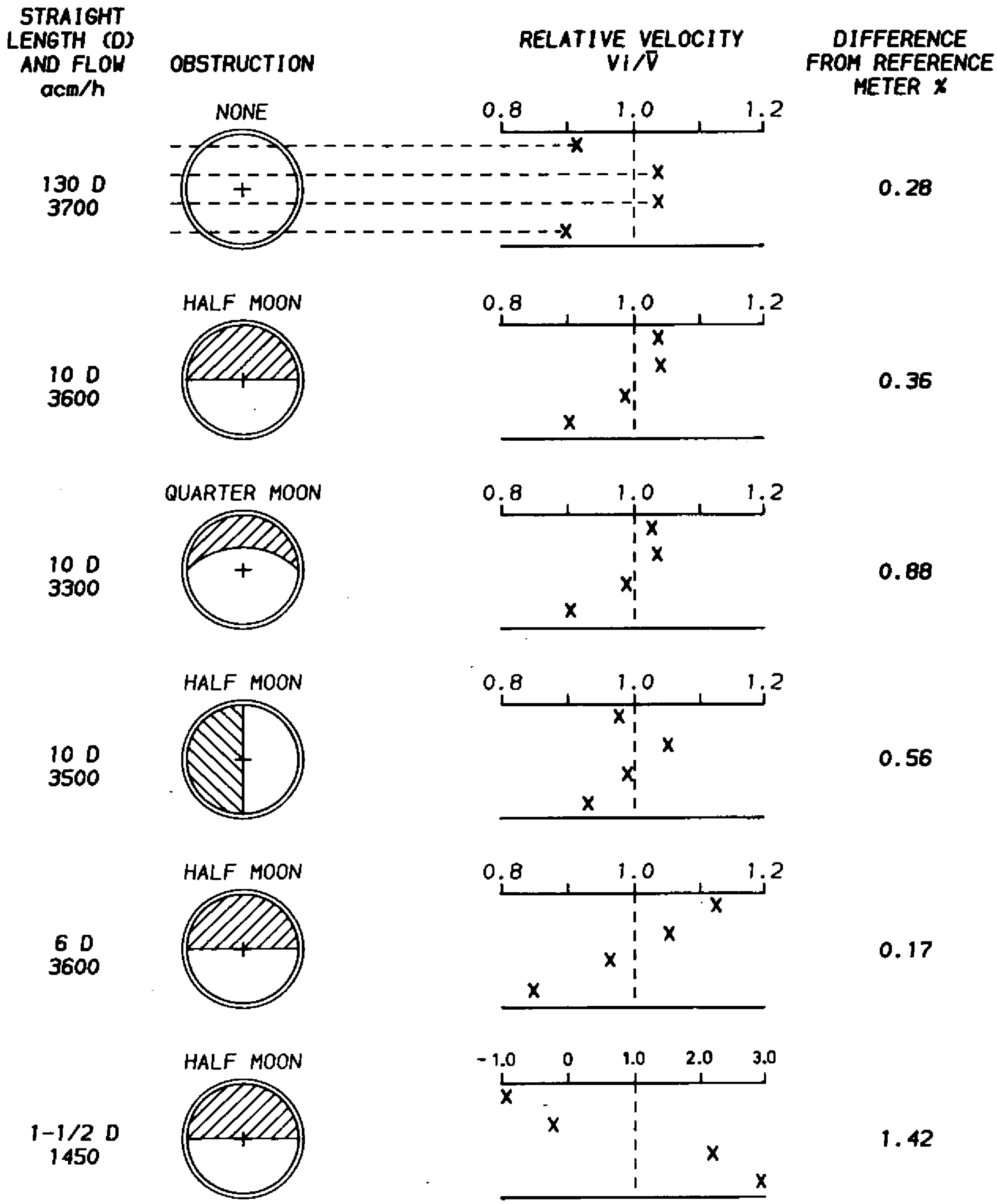

Figure 7   PROPOSED ELECTRONIC DEVELOPMENT