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TESTING THE PERFORMANCE OF ULTRASONIC SINGLE PATH HOT- TAP FLOW METERS

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1 INTRODUCTION

In its gas transmission system Gasunie Transport Services (in this paper further called "Gasunie") uses hot-tap single path ultrasonic meters for process control purposes. For these meters, a number of minimal requirements has been established, relating to meter performance (accuracy, response time, reliability, output signals), operating conditions (gas properties, mechanical, environmental and safety requirements) and documentation (manufacturing log, hot-tap procedures).

For many of these requirements it can be determined relatively easy whether or not they are met. However, in most practical situations, the accuracy and response time of a hot-tap meter cannot be determined. Since accuracy and response time are important properties for applications in the systems of Gasunie, it was decided to set up a test program. At the Gasunie Research test and calibration facility in Westerbork (the Bernoullilab), it is possible to carry out a hot-tap installation of an ultrasonic meter under high pressure conditions (up to 65 bar) and to calibrate this meter against the Dutch high pressure flow standards.

Six manufacturers were invited for the testing of a single path 12" hot-tap ultrasonic flow meter. Three of these manufacturers (Instromet, Panametrics, Ultraflux) have offered a single reflection path meter. In the last three years (2000 to 2003) these meters have been tested at the Bernoullilab. The hot-tap activities have resulted in a spool piece with two nozzles and valves on which the insertion mechanisms for the transducers can be mounted. All three manufacturers used the same spool piece for the installation of their meter.

The purpose of the test was to answer the following questions:

- What is the quality of the hot-tap and installation procedures of the manufacturer?
- What is the accuracy of single path ultrasonic meters "in practice" ?
- What is the accuracy of the meters when the gas flow is disturbed by swirl?
- What is the effect on the accuracy of a disturbance at 20D and 30D?
- What is the dynamic response of the meter to changes of the flow?
- What is the effect on the accuracy of a single path ultrasonic meter when the transducers are not accurately positioned in the pipe (for example as a consequence of inaccurate procedures)?

The meters were calibrated with a straight upstream length of 20D, as prescribed by many manufacturers, and also with an upstream length of 10D and 30D (D = 12" = diameter of the pipe). For the swirl tests a swirl generator has been mounted 20D upstream of the meter. The sensitivity of the meters for swirl has been determined at various swirl angles (between -10 and +10 degrees) and at various flows. The disturbance at 20D and 30D was chosen as a horizontal plate of 6mm thickness. For the determination of the dynamic response, the flow was changed in two ways. One was the gradually opening and closing of a Mokveld control valve far upstream of the ultrasonic meter while the flow varied between 500 m3/h and 2000 m3/h. The other was the instantaneous opening and closing of a swirl valve downstream of the ultrasonic meter to create a step-like change of the flow.

The aim of the paper is to present a general impression of the performance of hot-tap single path US-meters. The aim is not to compare the performance of the three US-meters. Therefore the results of the three US-meters are presented in a random fashion, i.e. manufacturer 1 might be Instromet in graph 1 and Ultraflux in graph 2.

2 TEST CONDITIONS

2.1 Test and calibration facility

The US-meters have been tested at the Bernoulli laboratory, the high pressure research and calibration facility of Gasunie Research at Westerbork. This laboratory has been constructed as a bypass of two main transmission lines, operated at a pressure of up to 65 bar. Because of daily and seasonal fluctuations the pressure of the gas varied between 52 bar and 65 bar during the test of the three US-meters.

Closing the valve in one of the main transmission lines, forces natural gas to flow though the facility, where it flows through one or more of ten reference meters. These are turbine meters with a diameter of 300 mm and a maximum capacity of 4000 m3/h each. Then the gas flows through the test section where the meter under test is mounted. Two test loops are available, a smaller one for 8" – 16" meters and a larger one for 16" – 30" meters. The former was used for the test of the three hot-tap US-meters described in this paper (testloop 2 in figure 1). The maximum flow through the 12" ultrasonic meters is about 8000 m3/h, at maximum gas velocity of about 30 m/s. A schematic outline of the Bernoulli laboratory is shown in figure 1.

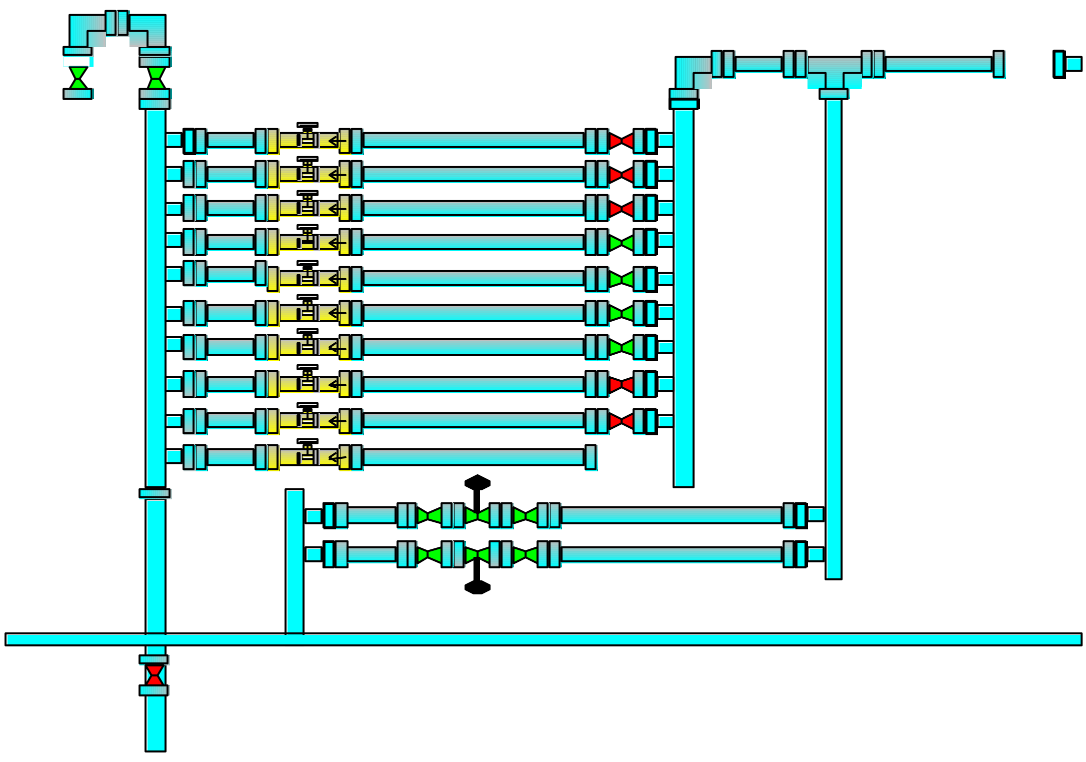

Fig. 1 – Gasunie Research Bernoullilab Westerbork with testloops

2.2 Preparation of the test

The three meters were consecutively mounted on a 12” spool piece of 3.6 meter length, prepared by Gasunie. During the test the hot-tap activities were carried out by Gasunie’s special services team, using the documentation for which the manufacturers were responsible. This resulted in a spool piece with two ball valves at the desired distance on which the insertion mechanism of the US-meters could be mounted and the transducers could be inserted. The manufacturers carried out the installation of the US-meters, including the measurement of the relevant geometrical variables. In this way a typical hot-tap installation of US-meters in the Gasunie transport system was simulated. No gas composition data were made available to the manufacturer on beforehand.

2.3 Testloop and requirements

Testloop 2 (figure 1) has been used for the tests of the three hot-tap US-meters. The meters have been calibrated in several configurations, with a “straight upstream length” of 10D, 20D and 30D (D is the inside pipe diameter, 12”)

The “straight upstream length” is defined in this paper as the distance from the “centre” of the US-meter in the 12” spool piece (the point between the two transducers) to the 16” => 12” reducer.

An example of a configuration with a straight upstream length of 10D is shown in figure 2.

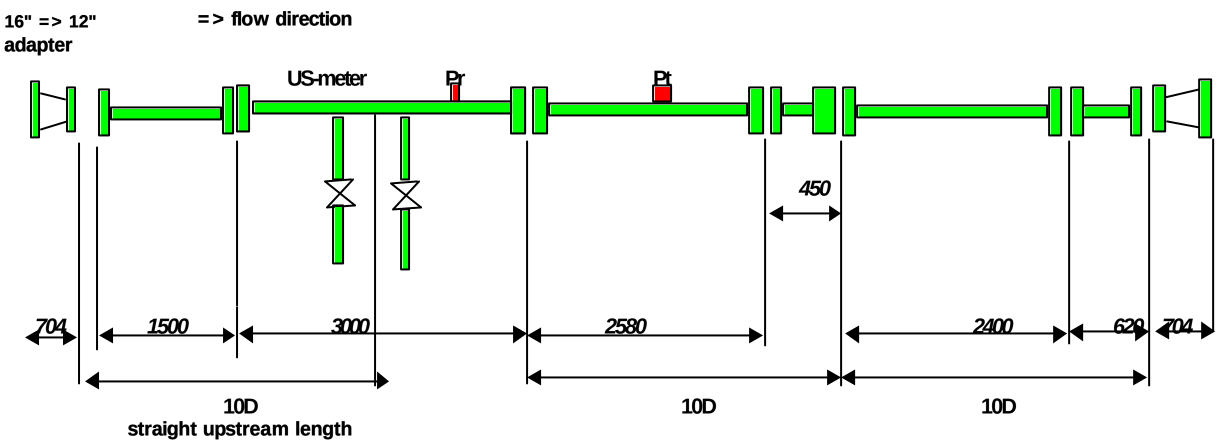

Fig. 2 – Configuration with 10D straight upstream length

During the calibrations the meter errors were determined in general at seven flow rates (2.5%, 5%. 10%, 25%, 40%, 70% and 100% Qmax). The “accuracy requirements” of Gasunie for process flow meters are given in table 1. These requirements are based on the gas velocitiy.

REQUIREMENTS GASUNIE FOR PROCESS FLOW METERS			
Gas velocity	Flow during test		Requirement GU
	actual m3/h	% Qmax	
30 m/s	8000	100%	± 3%
21 m/s	5600	70%	± 3%
12 m/s	3200	40%	± 2%
7.5 m/s	2000	25%	± 2%
3 m/s	800	10%	± 2%
1.5 m/s	400	5%	± 2%
0.75 m/s	200	2.5%	± 4%

Table 1 – Accuracy requirements Gasunie for process flow meters

3 ACCURACY OF US-METERS

3.1 Calibration results at 20D and 30D straight upstream length

The ultrasonic meters of the three manufacturers have been calibrated in a configuration with 20D straight upstream length, the minimum distance as prescribed by the manufacturers of the US-meters, and in a configuration with 30D straight upstream length. The results are presented in figure 3 and 4.

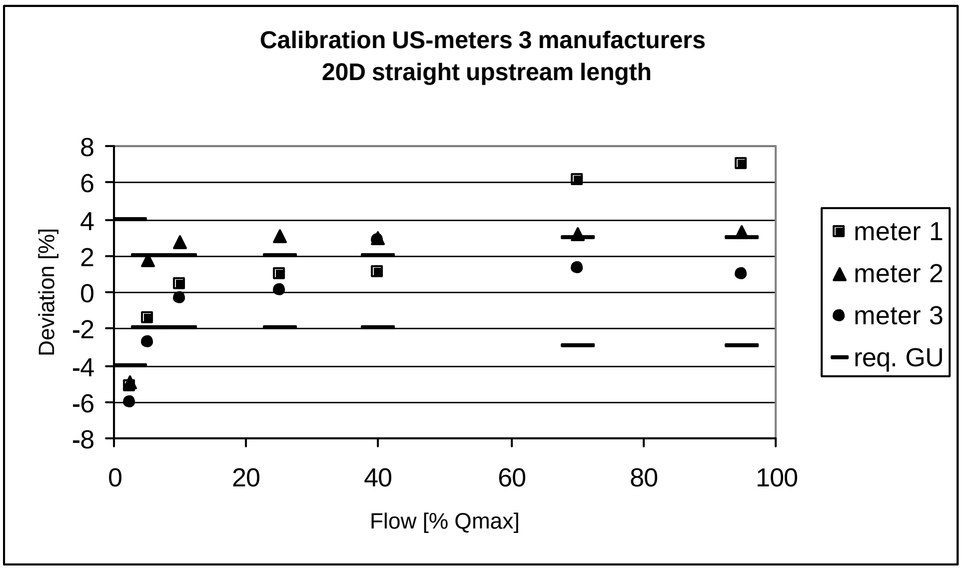

Fig. 3 – Calibration results US-meters at 20D straight upstream length

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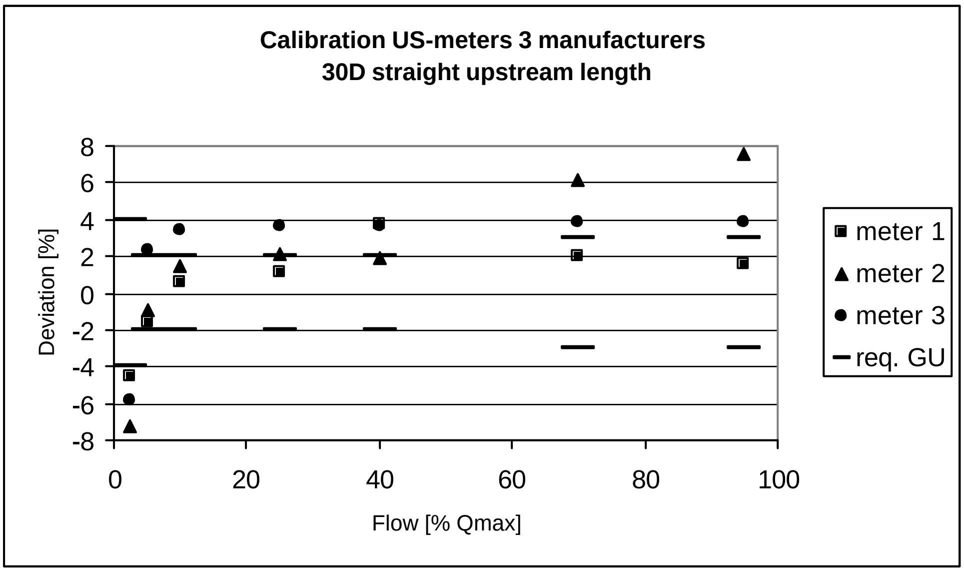

Fig. 4 – Calibration results US-meters at 30D straight upstream length

Conclusions:

- The US-meters show a positive meter error for "higher" flow rates (> 10% Qmax), i.e. the flow indicated by the US-meter, is more than the actual flow through the US-meters. One US-meter has (strong) positive meter errors for high gas velocities.
- For decreasing flow rates the meter errors are increasingly negative (< -4% meter error at a flow rate of 2.5% Qmax)
- In a configuration with 30D straight upstream length the US-meters indicate more flow than in a configuration with 20D upstream length.

3.2 Sensitivity of the US-meter to straight upstream length

In order to get more information about the sensitivity of single path US-meters for the upstream straight length, one of the meters was calibrated with 10D, 20D as well as 30D straight upstream length. The results are presented in figure 5.

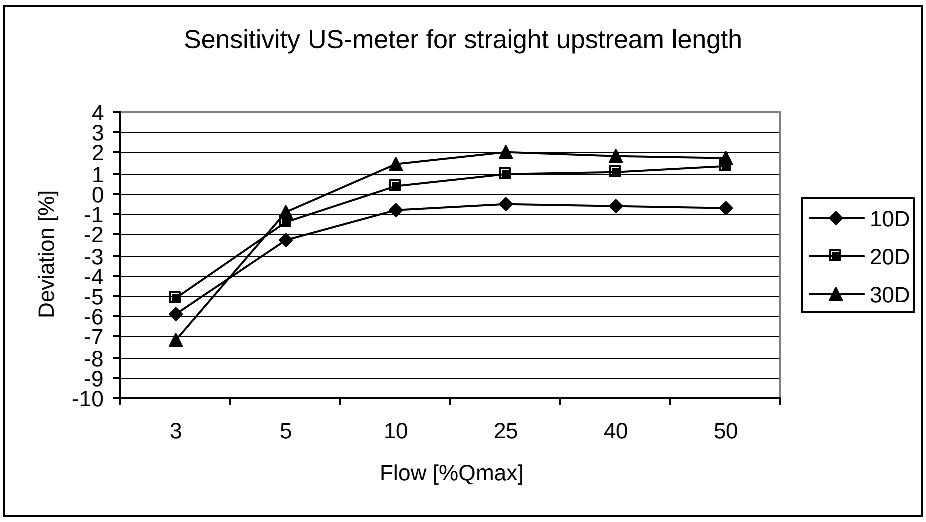

Fig. 5 – Calibration results US-meter at 10D straight upstream length

From these results it may be concluded that the flow indicated by the US-meter increases with increasing upstream straight length. In general when the straight upstream length increases with 10D, the meter indicates about 1% à 2% more flow.

As presented above, all three meters have been calibrated in a configuration with a straight upstream length of 20D and 30D. In figure 6 the difference of the meter errors is presented (30D – 20D values).

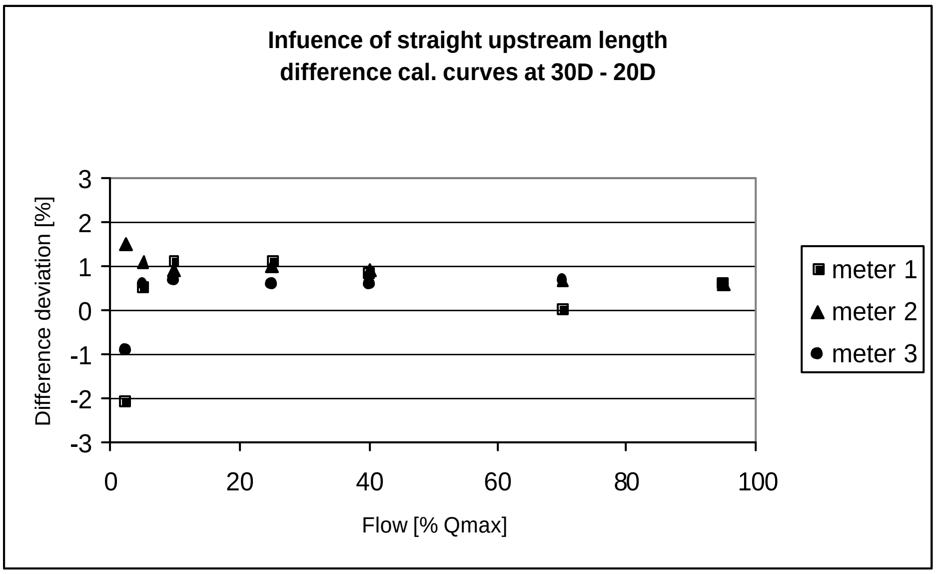

Fig. 6 – Difference of calibration results at 30D – 20D straight upstream length

Conclusions:

- The flow indicated by the US-meters increases with increasing straight upstream length (for flow rates higher than about 5% Qmax).
- In the configuration with 30D straight upstream length (where the flow profile may be considered as "well developed") the meters indicate 0.5% to 1% more flow than in the configuration with 20D straight upstream length.

3.3 Sensitivity of the US-meter to disturbance at 20D and 30D

In order to investigate the sensitivity of the US-meters for a disturbance, a horizontal plate of 6 mm thickness (a swirl generator with both plates at 0^0 , see figure 9) was placed at a distance of 20D upstream from the US-meter, just behind the 16" => 12" reducer (see figure 2). The three meters have been calibrated with and without this disturbance. The result of one meter is presented in figure 8. This result (i.e. the differences between the calibration results with and without the disturbance) is representative for all three meters.

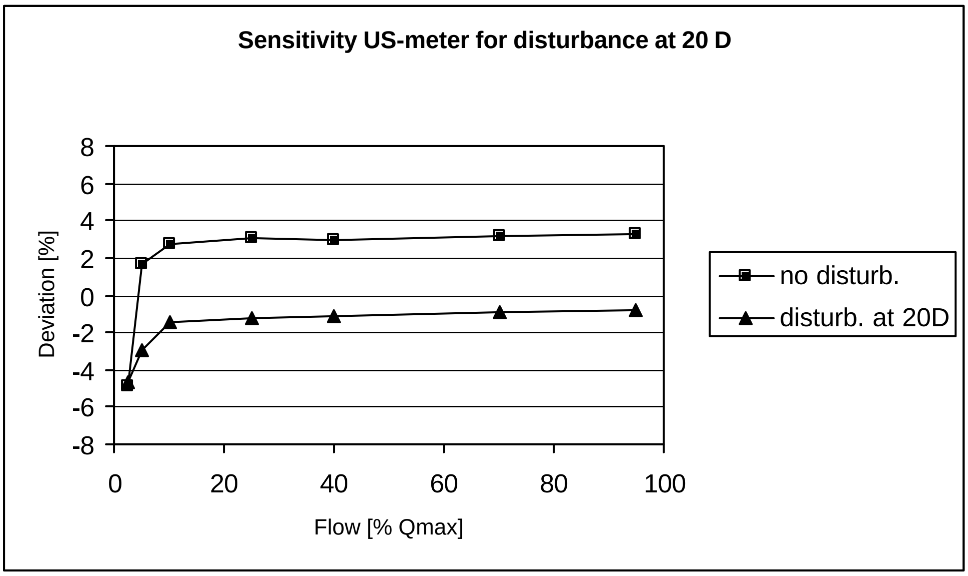

Fig. 7 – Calibration results of one meter with and without a disturbance at 20D

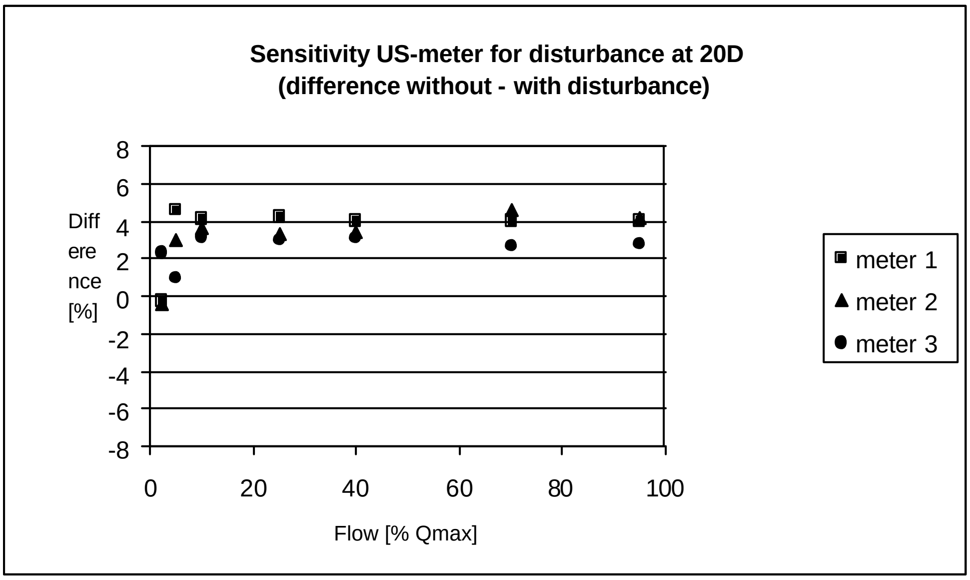

Fig. 8 – Difference of calibration results for the three meters
(without – with disturbance at 20D)

Conclusions:

- In the configuration without the disturbance at 20D the meters read about 2.5% to 4.5 % higher than in the configuration with the disturbance (for flow rates higher than about 10% Qmax).
- The mean differences for each meter (averaged over these flow rates) are resp. 4.1%, 3.8% and 3.0 %.
- For two of the meters these tests also have been carried out with the (same) disturbance, but placed at 30D upstream from the meter (again just behind the 16" => 12" reducer).The differences (without – with disturbance) turn out to be somewhat greater than for the 20D configuration. The "overall" average of the differences of the meters changes from 3.6% to 4.3%.

3.4 Sensitivity of the US-meter to swirl

In order to test the sensitivity of the US-meter to swirl, the three US-meters have been calibrated in a configuration with 20D straight upstream length and the 12" Gasunie swirl generator placed 20D upstream from the US-meter. By means of this swirl generator it is possible to create a swirl in the flow with an adjustable angle. In figure 9 the swirl generator is shown.

Fig. 9 – Gasunie swirl generator

This test has been carried out with swirl angles of 0, ± 1, ± 2 , ± 5, ± 10 degrees at a flow rate of 3200 m3/h (40% Q max). A positive / negative swirl angle corresponds with a "clock wise" resp. "counter clock wise" rotation of the flow. The results are presented in figure 10.

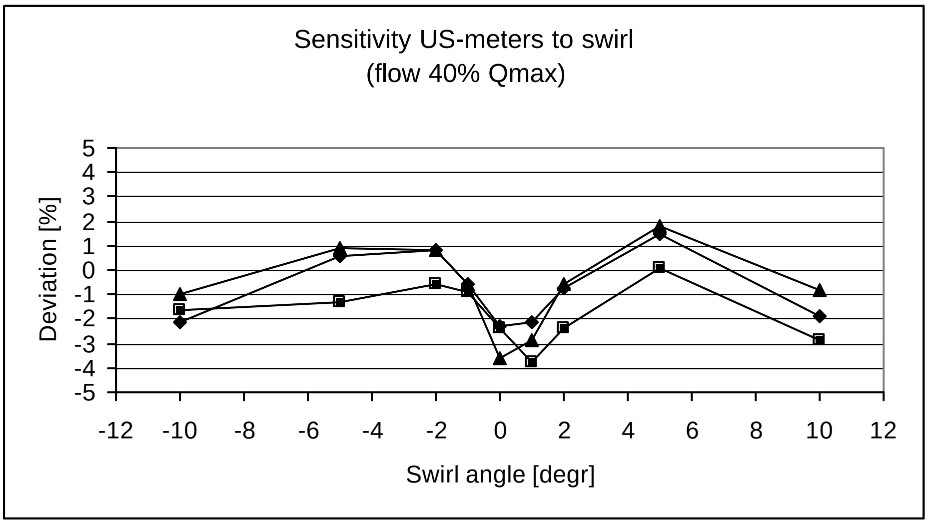

Fig. 10 – Calibration results US-meters for various swirl angles (flow 40% Qmax)

Conclusions:

- Single path US-meters are sensitive to swirl, even if it is created at the minimum required straight upstream length.
- When the swirl angle in the flow through the US-meter varies between -10^0 and $+10^0$ maximum differences of about 4% occur in the flow indicated by the US-meters.
- The meter errors at positive swirl angles have about the same magnitude as the meter error at negative swirl angles (symmetry around zero swirl angle).
- For all swirl angles, positive as well as negative, the US-meters indicate more flow than in the situation without swirl.

For two of the US-meters it has been investigated in which way the meter error depends on the magnitude of the flow through the US-meter for swirl angles between -10^0 and $+10^0$. This has been tested for flows with a magnitude of 10%, 40% and 70%. The results of this test for the two US-meters turned out to be similar and are presented in figure 11 for one of the meters.

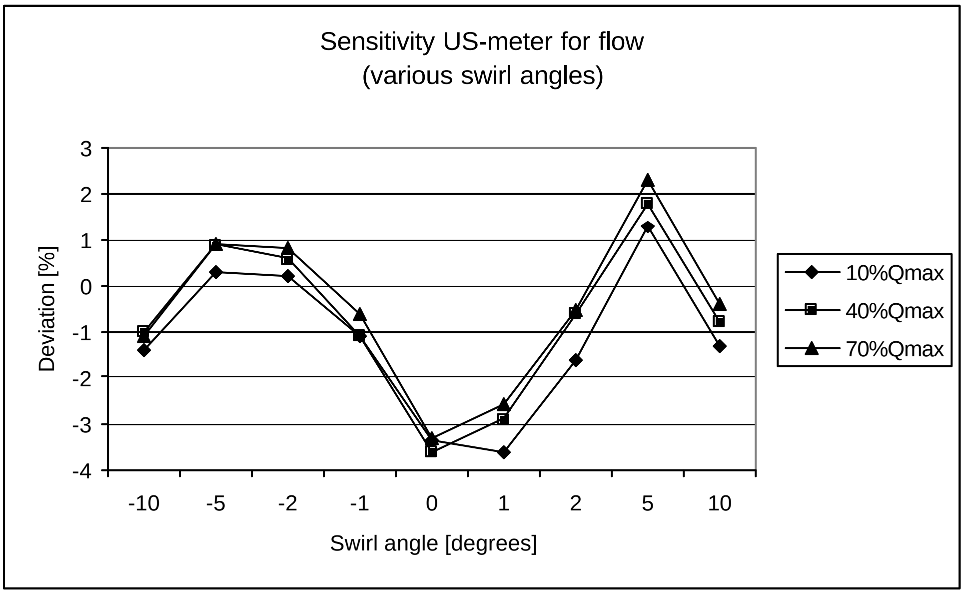

Fig. 11 – Calibration results US-meter for various flows
(swirl angles between -10^0 and $+10^0$.)

From the results presented in figure 10 and figure 11 it can be concluded that the sensitivity to swirl of single path US-meters varies little with flow rate.

The actual results allow no prediction about the influence of swirl on the meter performance in other configurations. Configurations with a different pipe diameter, position of the swirlgenerator / US-meter would probably have led to different results. Yet the conclusion about the sensitivity to swirl will not be affected.

4 DYNAMIC RESPONSE OF US-METERS

The dynamic response of the three single path US-meters have been tested in two ways:

- The flow was changed gradually by opening and closing the Mokveld valve far upstream from the US-meters.
- The flow was changed instantaneously by opening and closing both plates of the swirl generator, which was placed at a distance of 15D downstream from the US-meter.

Both tests have been carried out in the configuration with 20D straight upstream length.

4.1 Response of US-meters to a gradual change in flow

During this test the flow was changed gradually from about 2000 m3/h to about 500 m3/h in a time period of about 25 seconds (and vice versa). The delay could be estimated with an accuracy of about 0.5 second. The total delay is a combination of " dead time" and a time constant.

The dynamic response of two of the US-meters can be characterised as smooth. One meter had a total delay time of about 1 second, the other meter had a total delay time of about 2 seconds. A typical example of the dynamic response of these two meters is shown in figure 12.

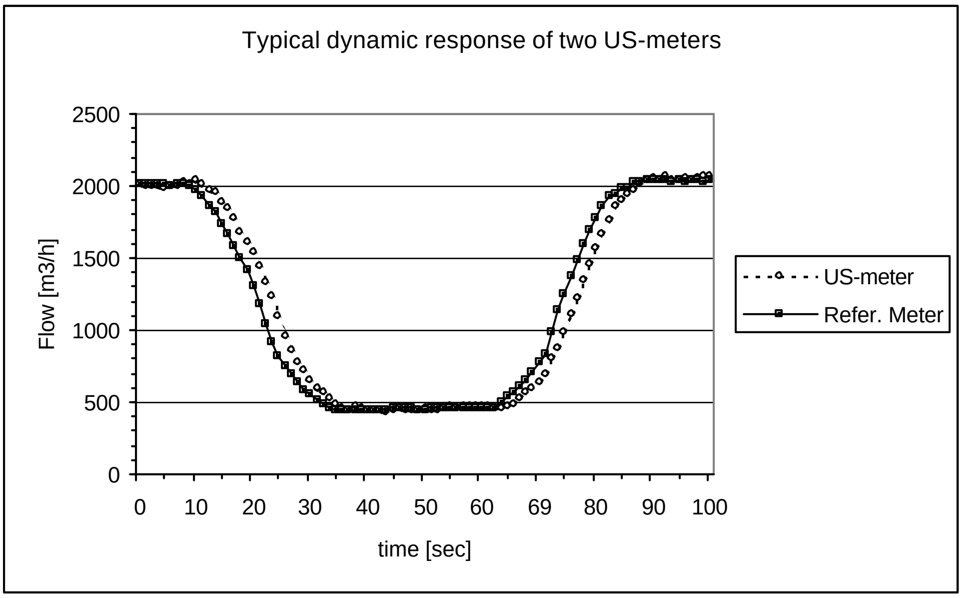

Fig. 12 – Dynamic response typical for two tested US-meters

The dynamic response of the third US-meters is shown in figure 13. The total delay time of this meter is 3 to 6 seconds. The response of this meter can be characterised as “stair-like”. This meter updates its flow value every 2 to 3 seconds. It should be noticed that this US-meter has several operation modes. The test results shown in figure 13 are obtained in the “standard” mode. Modes with a faster response are also available, but have a negative effect on the accuracy of this meter.

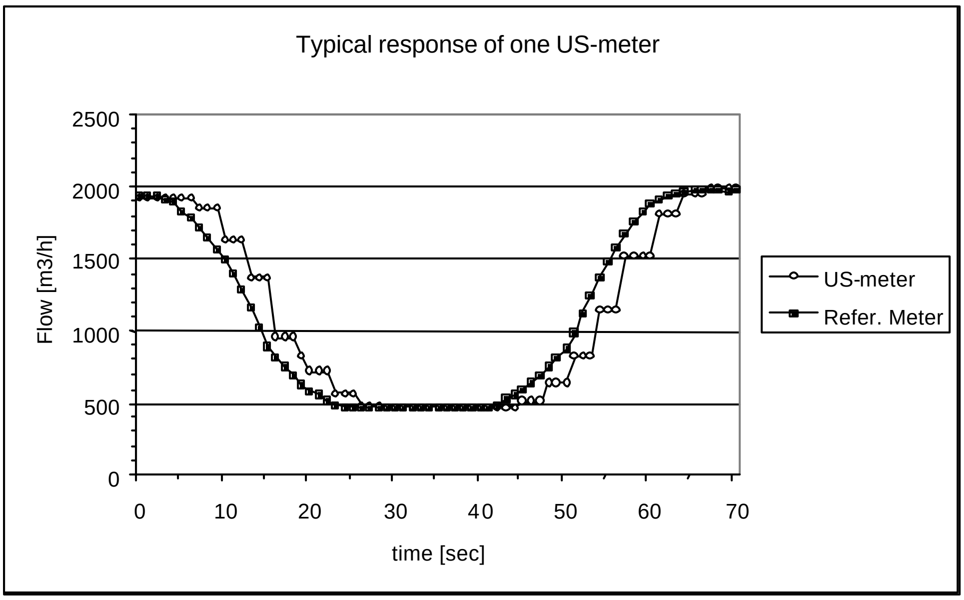

Fig. 13 – Dynamic response of one tested US-meter

4.2 Step response of the US-meters

The response of the three US-meters to a step-like change in the flow has been determined by opening and closing instantaneously both plates of the Gasunie swirl generator, which was mounted downstream from the US-meter. The flow was changed rapidly from a "high" value (between 900 m3/h and 1250 m3/h) to a "low" value (between 200 m3/h and 350 m3/h) and vice versa. The steps in the flow were created within a few seconds. This enabled accurate estimation of the "dead time" of the US-meters.

Two US-meters show a smooth response to a step-like change of flow. The dead time of these meters is about 1 second, the total delay time for the two meters is 1 and 2 seconds. A typical example of the response of these two meters is shown in figure 14.

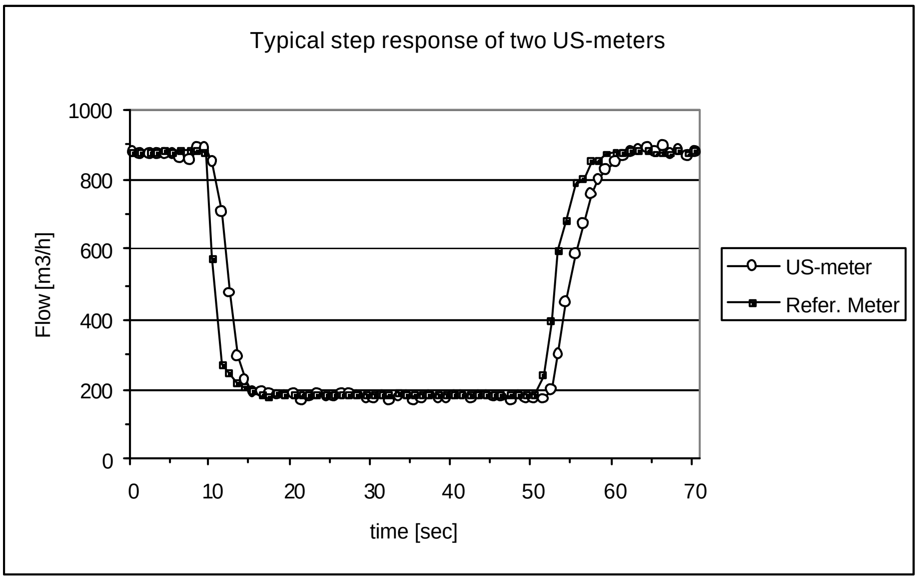

Fig. 14 – Response to a step-like change in the flow, typical for two tested US-meters

The step-response of the third US-meters is shown in figure 15. The dead time and total delay time are both 3 to 6 seconds.

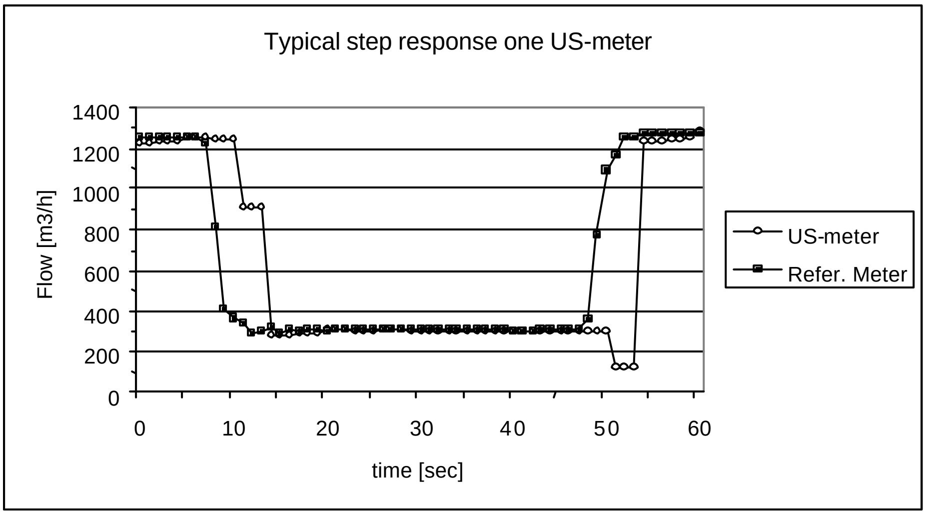

Fig. 15– Response to a step-like change in the flow for one tested US-meter

4.3 Results of the dynamic response of US-meters

The results can be summarised as follows:

Two US-meters show a "smooth" dynamic response behaviour, the response of the third meter can be characterised as "stair-like".
The delay times are summarised in table 2. In this table are presented: the update time of the US-meter (time interval to generate an updated value), the dead time and the total time delay. The values in the table are estimated with an accuracy of ± 0.5 sec.

US-meter	US-meter a	US-meter b	US-meter c
General behaviour	Smooth	Smooth	Stair-like
Update time	1 sec.	1 sec.	2 – 3 sec.
Dead time	1 sec.	2 sec.	3 – 6 sec.
Total delay time	1 sec.	2 sec.	3 – 6 sec.

Table 2 – Dynamic response of the three US-meter (summarised)

5. INSTALLATION PROCEDURES

5.1 General

Assessing the quality and fulfilling of the installation manuals and procedures was an important part of the project. A good quality of the manuals means that they are complete, clear, accurate and consistent. A good quality of the procedures means that they yield the required results (accurate transducer positions and instrument set-up), that they are documented, carried out according to the documents, and that they comply with safety regulations etc. The ultimate goal is to ensure an ultrasonic flow meter as accurate as possible for a single-path meter. Metering accuracy depends, of course, on transducer position accuracy and on instrument set-up.

Gasunie's special services team has carried out the hot-tap activities, it welded two nozzles and ball valves on a 12" spool piece, and drilled the holes. It used documentation with geometrical requirements for which the manufacturers were responsible. The manufacturers were given the opportunity to measure the relevant quantities (pipe diameter, pipe wall thickness, geometrical position of the nozzles etc.) and to "witness" the resulting spool piece, which was considered as the "starting point" of the project as described in this paper. After completion of the hot-tapping the manufacturers mounted their ultrasonic meters.

5.2 Documentation of the manufacturers

One manufacturer had an almost complete and accurate set of documents and drawings, which complied with Gasunie requirements. However, the straight upstream length specified in this guide was based on water as fluid, so it should be adapted for gas.

The procedures of the other two manufacturers were incomplete at the first test. They lacked, for example, references to other relevant documents. Furthermore, a crucial inconsistency existed: the path length correction was not identical in all documents. This correction is necessary because the acoustic centre of the transducers is located off the shaft centre-line.
From one manufacturer not all forms for the calculation of the geometrical quantities were present. The units of the quantities to be measured had not been printed on all the forms of two other manufacturers. This caused human errors in the initial calculation and setting of software parameters (i.e. cm instead of mm, or vice versa). The manufacturers themselves during the installation of the US-meter traced these errors. The procedure of one manufacturer was provided in a draft version only. The two manufacturers have adapted their documents after the first test.

5.3 Sensitivity of US-meter accuracy to transducer position

In order to verify the influence of transducer position on measuring accuracy, the transducer insertion depth was varied + or – 3 mm relative to the original position as set by the manufacturer, which corresponds to + or - 1% of the nominal meter diameter. The transducer position was varied perpendicular to the pipe wall. An inward translation, towards the centre of the pipe, was given a negative sign. Both transducers were moved 0 mm, +3 mm and –3 mm, so a total of 3 x 3 = 9 combinations of transducer-positions were tested plus one as a final reference. All tests were done at a flow rate of 5500 m3/h, which is about 70% of the maximum flow rate for a 12" meter. For each combination of transducer positions the meter error was determined as usual, relative to the high pressure standards at the Westerbork facility. Furthermore, the speed of sound as measured by the ultrasonic meter was compared with the "real" value (394.13 m/s), as calculated from the actual gas composition, temperature and pressure. Table 3 shows the results.

Table 3 – Sensitivity of US-meters to transducer position

Test Nr	Pos(A,B)	error(%)	Relative error (%)	VoS (m/s)	VoS error(%)
1a		-1.91		392.80	-0.34
1b		-1.80		393.00	-0.29
1 (ref)	(+0,0)	-1.86	0.00	392.90	-0.31
2a	(+3,0)	-2.36	-0.50	391.25	-0.73
2b	(0,+3)	-2.70	-0.84	391.10	-0.77
3a	(-3,0)	-1.13	0.73	394.10	-0.01
3b	(0,-3)	-0.90	0.96	394.30	0.04
4a	(-3,+3)	-2.08	-0.22	392.70	-0.36
4b	(+3,-3)	-1.36	0.50	392.80	-0.34
5	(+3,+3)	-3.14	-1.29	389.85	-1.09
6	(-3,-3)	-0.31	1.55	395.40	0.32

Transducer positions are indicated (A,B), where A denotes the upstream transducer and B the downstream one. Geometries with identical path length, like for instance (0,-3) and (-3,0), have been pair wise aligned, labelled with extension “a” and “b”. With the transducers at their nominal (0,0) position, the results of the initial (1a) and final (1b) tests were combined as a reference value.
The third column shows “relative error", defined as the meter error relative to the one (-1.86 %) measured with the transducers at their reference position (0,0).

The table clearly illustrates the sensitivity of a hot-tap meter to misalignment, causing meter errors of more than 1 %. When hot-tap meters are installed in the field, these errors cannot be recognised because usually no reference is available here.
From the table it also appears that “mirror” geometries with identical path length (labelled “a” en “b”) yield (almost) identical speed of sound measurements. This is not amazing since the measured speed of sound mainly depends on path length. Geometries with different path lengths produce different speed of sound errors. This demonstrates that the measured speed of sound might be used to adjust the meter's path length as entered in the instrument set-up, providing that a proper speed of sound reference is available.

Measuring the speed of sound is the only means for a customer to independently verify the manufacturers' installation accuracy. So if a customer would want to do so, it is important not to provide the manufacturer with data that enable the calculation of a speed of sound reference value.

Different meter errors result from different geometries: the measured flow not only depends on path length, but also on path angle and velocity profile, which both cannot be corrected through speed of sound measurements. Table 4 shows the meter error as measured, the speed of sound error, and the corrected meter error, calculated by adjusting the path length according to the speed of sound error. In most cases, but not all, the correction is an improvement (i.e. the absolute value of the corrected error is closer to zero).

Table 4 – Effect of correcting meter error by VoS error

Test Nr	pos(A,B)	error(%)	VoS error (%)	Corrected error(%)
1a		-1.91	-0.34	-1.57
1b		-1.80	-0.29	-1.51
1 (ref)	(+0,0)	-1.86	-0.31	-1.54
2a	(+3,0)	-2.36	-0.73	-1.63
2b	(0,+3)	-2.70	-0.77	-1.93
3a	(-3,0)	-1.13	-0.01	-1.12
3b	(0,-3)	-0.90	0.04	-0.94
4a	(-3,+3)	-2.08	-0.36	-1.72
4b	(+3,-3)	-1.36	-0.34	-1.02
5	(+3,+3)	-3.14	-1.09	-2.05
6	(-3,-3)	-0.31	0.32	-0.63

6. GENERAL CONCLUSIONS

The results of the tests outlined above have lead to the following general conclusions:

Gasunie is satisfied with the quality of the hot-tap and installation procedures of the manufacturers. Although some documents need completion, in general their quality meets Gasunie's requirements.

The three meters tested show positive meter errors: the flow indicated by the meters is more than the actual flow if no “strong” upstream disturbance is present.
For straight upstream lengths between 10D and 30D without disturbances the meter errors are in a range from about 0% to + 4% for gas velocities higher than about 3 m/s. One meter had a larger meter error (about +7%) for high gas velocities. For lower gas velocities the meter errors become more negative.
Single path hot-tap ultrasonic meters are sensitive to straight upstream length: the error curves shift downward with decreasing upstream length. The differences are up to about 2% from 10D to 30D at constant flow rate.
Single path hot-tap ultrasonic meters are sensitive to upstream disturbances. With a disturbance of a horizontal plate of 6 mm thickness (open swirl generator) placed at 20D or 30D upstream from the meter, the error curves shift downward with about 3% to 4% for gas velocities higher than about 3 m/s. It should be remarked that such a plate will probably not be present in practical situations.
By changing the meter factor in the software, of course, the error curves could be shifted to values around zero. But even then, the accuracy of single path hot-tap ultrasonic meters “in practice” at best is of the order of plus or minus 2 %. Basically this reflects the sensitivity of a single path ultrasonic meter to variations of the velocity profile of the flow.

Since swirl leads to changes in the velocity profile, it is not surprising that single path meters are sensitive to swirl. For swirl angles between -10^0 and $+10^0$ the meters indicate up to about 4% more flow than in a situation without swirl.

The dynamic response of two meters can be characterized as “smooth”, with delay times of 1 to 2 seconds. One meter showed a stair-like dynamic response with a delay time of 3 to 6 seconds.

The installation procedures should be executed with care in order to obtain accurately positioned transducers. Misalignment of the transducers of 1% of the nominal diameter in a direction perpendicular to the pipe can cause additional meter errors of the order of 1%.