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Evaluation of ultrasonic liquid flowmeters

by

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ABSTRACT

In 1992, Christian Michelsen Research (CMR) carried out a project in order to evaluate ultrasonic liquid flowmeters. The aim of the project was to characterize a selection of commercially available multi beam liquid flowmeters, with emphasis on future applications on crude oil. The test program included a calibration test, which was carried out with water at a certified calibration laboratory, and a functional test on diesel oil. Through the calibration test, the flow meter uncertainty during ideal conditions was established, along with an investigation of the installation effect caused by a bend. The functional tests included test with single phase diesel oil, diesel oil that contained small fractions of water, and diesel oil that contained small fractions of gas.

1 INTRODUCTION

Future developments of oil and gas reserves off the coast of Norway will largely concern small fields, most of which will be linked up with existing platforms, although independent developments may also take place. If the development of these small fields is to be profitable, reductions in development and operating costs will usually be necessary. A fundamental method of reducing costs will be to utilize simpler, more compact process equipment. Especially in cases where the well-stream from a satellite well is led to an existing platform, space requirements alone make it necessary to evaluate alternative methods of product metering.

Today, the turbine meter is almost universally utilized for measuring crude oil product. Alternative technologies include coriolis mass measurement devices and multi beam ultrasonic volume flow meters based on the transit time principle. Before ultrasonic meters can be brought into service offshore, it is necessary to test out their technology under controlled conditions similar to the test programs that have been performed on coriolis meters.

Therefore a project was initiated to investigate the performance of commercially available ultrasonic liquid flow meters, in particular their suitability for oil product measurements. Participants in the project were Den Norske Stats Oljeselskap (Statoil), Norsk Hydro and Saga Petroleum. Furthermore, the Norwegian Petroleum Directorate (NPD) engaged themselves in the project in order to obtain knowledge and experience with multi beam ultrasonic volume flow meters. The project was managed by Christian Michelsen Research AS (CMR), and largely performed by personnel at CMR and Hydro Porsgrunn.

The aim of the project was to characterize the performance of a selection of commercially available multi beam ultrasonic liquid flow meters based on the transit time principle, in particular their suitability for volume flow measurements of crude oil.

Based on the knowledge of the leading multipath ultrasonic liquid flowmeters, three manufacturers of ultrasonic liquid flowmeters were invited to participate in the evaluation project. On request, all three manufacturers put their meters to disposal for the project free of charge. Among the three flowmeters were the Danfoss SONO 2000 and the Panametrics Model 6468. The project work carried out in the project, as well as the test results obtained, was classified as confidential, and one manufacturer used his right not to have the results published.

The work presented in this paper merely describes the test program that was carried out, and is not meant as a thorough study and discussion of the ultrasonic flow meter technology. The extent of the project did not allow for more than a brief description of the meters to be evaluated.

2 TECHNICAL DESCRIPTION OF TEST METERS

2.1 Description of Danfoss SONO 2000

The Danfoss SONO 2000 is a two-track ultrasonic flowmeter based upon the transit time measurement principle, with each transducer acting both as transmitter and receiver [1]. The distance between the two tracks is 0.45 diameter, with the transducers configured in two parallel traces. Danfoss SONO 2000 has a 1 MHz signal frequency, and a counter frequency of 128 MHz, thus giving a 7.2 ns resolution for the signal detection system. However, Danfoss has implemented a special averaging algorithm, claiming a resolution of less than 1 ns. The resolution of the detection system is most critical at low flow rates, setting the lowest possible detectable flow rate for the system. Additionally, the measurement uncertainty rely upon this parameter.

The signal detection system is based on a simple level and zero-crossing detector. The first zero-crossing after the level detector is triggered, is registered. If the measured zero-crossing is detected within a given time window, set by the signal frequency, the measurement is stored and further processed. Otherwise, the measurement is rejected, and an error indication is given. The measured transit time is corrected for time delays in the electronics and the transducers. Furthermore, the transit time in the cavity in front of the transducers is compensated for.

20 measurements with the flow and against the flow form the basis for estimating the flow velocity for each track. The average value for the two tracks is the output value, representing the average flow velocity in the pipe. No comparison between the output values for the two tracks is carried out.

An Automatic Gain Control (AGC) is implemented in order for the SONO 2000 to adapt to different measurement conditions. The AGC assures constant peak-to-peak level at the received signal, thus enabling fixed trigger-level for the level detector.

2.2 Description of Panametrics Model 6468

The Panametrics Model 6468 is a two channel ultrasonic flowmeter based on the transit time principle [2]. The two channels operate as two separate channels, thus the operator can select between the average value or single channel values as output. The transducers are configured in such a manner that the two beams are crossing each other in the centre of the pipe. The two pairs form an angle of about 60°, with all transducers being oriented towards the centre of the pipe. All transducers act both as transmitter and receiver.

The signal frequency of the test meter was 1 MHz. Other signal frequencies are used dependent on the application. Various digital signal processing techniques, including cross-correlation, are used to determine the transit time and to calculate flow velocity. To assure correct transit time measurements, time delays in the electronics and in the transducers are corrected for.

The Panametrics Model 6468 has implemented an Automatic Gain Control (AGC) system. The AGC assures constant peak-to-peak level at the received signal, independent of different measurement conditions. Digital signal processing techniques used allow dynamic digital trigger level detection.

3 CALIBRATION TEST

3.1 Background

The central parameter in the evaluation of a flowmeter is the measurement uncertainty. It was therefore essential to perform a calibration test at a recognized laboratory whose reference measurements can be traced back to international standards. Accordingly, the meters were calibrated at Norsk Hydro's calibration laboratory for liquid meters in Porsgrunn.

3.2 Test conditions

The meters were calibrated at Norsk Hydro's calibration laboratory located in Porsgrunn. The calibration rig is primarily used for calibration of test meters, with water as the fluid medium. The calibration is based on a volumetric reference, which consists of several tanks with volume from 0.5 up to 12.0 m^3. The tank used depends on the meter size and flow rate. The volumetric tanks are calibrated against a calibrated weight every 3rd year. By using the volumetric tanks as the reference, a ± 0.05% reference uncertainty in the volume is claimed.

Each calibration test started at zero flow and ended at zero flow, implying a transient flow at the beginning and end of the test run. The accumulated volume of the meters under test was compared to the volume filled in the reference tanks. In order to minimize the effects of the transition periods caused by the opening and closing of the valves controlling the flow rate, a minimum test period of 1 minute is required. However, the duration of the test runs for the calibration of the ultrasonic meters lasted from 2 minutes and 24 seconds, up to over 11 minutes, clearly assuring that the transition period effects were minimized.

3.3 Test with maximum straight pipe-length upstream

In order to obtain the meter performance, the meters were installed with as long upstream straight pipe length as possible. However, it should be noted that during this test the meters were installed in series, implying that the meters experienced different inlet lengths. As can be seen from Figure 1, the Danfoss SONO 2000 was installed 26D, and the Panametrics Model 6468 was installed 39D downstream of a 12" to 4" conical diffuser.

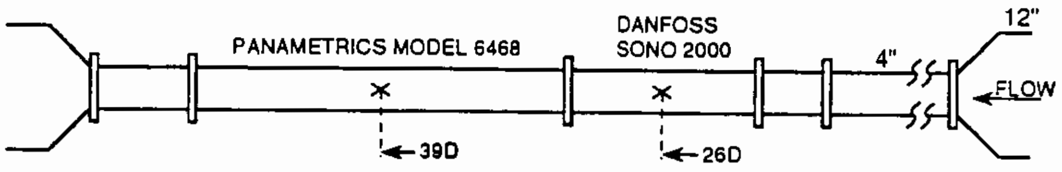

Figure 1 Layout of test section, maximum straight pipe-length upstream of flow meters.

3.4 Test with a 90° bend 10D upstream the flow meters

During this test the meters were tested one by one. The distance between the ultrasonic sensors and the 90° bend section was 10D for all meters. The meters were tested at 3 different flowrates, with 3 repetitive tests at each flowrate.

3.5 Test results for Danfoss SONO 2000

The Danfoss meter was calibrated at Danfoss calibration facility in Nordborg, Denmark, prior to the calibration test at Hydro Porsgrunn, see Table 1. Thus, the results from the calibration tests at Hydro Porsgrunn are compared with the pre-calibration results. Danfoss claims a ±(0.5% Reading + 0.5% FullScaleOutput) measurement uncertainty in the 10 - 100% flow range area for a 4" meter, see Table 3.

Reference volume flowrate	Deviation
34.3 m^3/hr	- 1.94 %
83.7 m^3/hr	- 0.86 %
83.7 m^3/hr	- 0.88 %
166.6 m^3/hr	- 0.30 %
228.5 m^3/hr	± 0.00 %
228.5 m^3/hr	- 0.05 %

Table 1 Danfoss SONO 2000 pre-calibration results. The meter was calibrated up to 70% of full scale flow, at 24.1 °C.

In Table 2, and Figures 2 and 3, the results from the calibration tests are shown.

Reference flow rate [m³/hr]	% deviation; Danfoss SONO 2000		% deviation; Panametrics Model 6468	
	26D Test	10D Test	39D Test	10D Test
300	- 1.01	- 1.85	- 2.38	- 2.29
300	- 1.22	- 1.50	- 0.64	- 3.05
300	- 0.94	- 1.78	- 0.80	- 3.13
260	- 0.80		- 1.22	
260	- 0.73		- 0.68	
260	- 1.27		- 1.34	
198	- 0.78	- 1.60	- 0.25	- 2.69
198	- 0.86	- 1.67	- 0.21	- 2.50
198	- 0.97	- 1.65	- 0.68	- 3.23
127	- 0.94		- 1.25	
127	- 0.98		- 0.94	
127	- 1.02		- 1.25	
127	- 0.88		- 1.31	
127	- 1.03		- 1.23	
65	- 2.26		- 1.49	
65	- 1.89		- 1.25	
65	- 1.99		- 1.02	
33	- 2.53	- 3.47	- 0.19	- 0.79
33	- 2.78	- 4.01	0.04	- 2.57
33	- 2.70	- 3.56	0.34	- 2.55

Table 2 Results from calibration tests at Hydro Porsgrunn. During the entire test period, the fluid temperature varied between 25.0 and 28.0 °C.

Volume flowrate	Uncertainty
28.3 m³/hr	± 1.56 m³/hr, or ± 5.5 %
56.6 m³/hr	± 1.70 m³/hr, or ± 3.0 %
113.2 m³/hr	± 1.98 m³/hr, or ± 1.75 %
169.8 m³/hr	± 2.26 m³/hr, or ± 1.33 %
226.4 m³/hr	± 2.55 m³/hr, or ± 1.125 %
283.0 m³/hr	± 2.83 m³/hr, or ± 1.0 %

Table 3 Danfoss SONO 2000 claimed measurement uncertainty for a 4" meter.

In principle, given that the calibration conditions were equal, one would expect the results from the two calibrations to be equal, within the repeatability of the meter.

However, it was not possible to repeat the results obtained during the pre-calibration of the meter. Since no information of the installation conditions for the pre-calibration of the meter is available, it is difficult to identify the reason for this deviation. If we compare the results in Table 2 with the specified meter uncertainty, see Table 3, the Danfoss SONO 2000 obtained results that were within the claimed measurement uncertainty of the meter for the 26D inlet length test.

It is well known that the flow profile has an influence on the performance of a single or multi beam ultrasonic meter. The effect of the 90° bend section on the Danfoss meter is shown in Figure 2, where the results for the maximum straight pipe-length tests and 10D tests are compared.

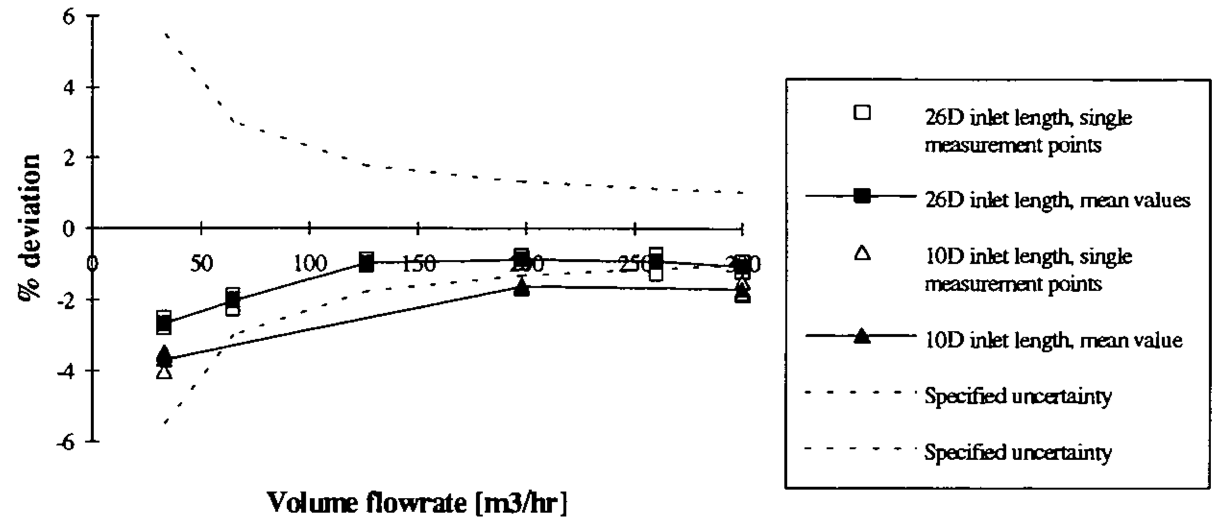

Figure 2 Danfoss SONO 2000, results from tests with 26D straight pipe-length upstream to a 12" to 4" conical diffuser, and 10D straight pipe-length upstream to a 90° bend. Temp = 25.0 - 28.0 °C.

3.6 Test results for Panametrics Model 6468

The Panametrics Model 6468 was not pre-calibrated prior to the calibration test. A zero-calibration was carried out on-site in the test rig at Hydro Porsgrunn. The zero-calibration procedure was based on the assumption that the speed of sound for the two ultrasonic paths were equal during the calibration period. Thus, this zero-calibration procedure requires steady state zero-flow conditions and a homogeneous temperature in the cross section. It is difficult to state that this was the case or not during the calibration period.

Panametrics claims a system accuracy of ± 1.0% of reading for velocities above 0.3 m/s. For a pre-calibrated system, a ± 0.5% of reading is claimed. The repeatability is claimed to be typically 0.2% of full scale, giving approximately 0.02 m/s for the 4" version with 330 m^3/hr full scale output.

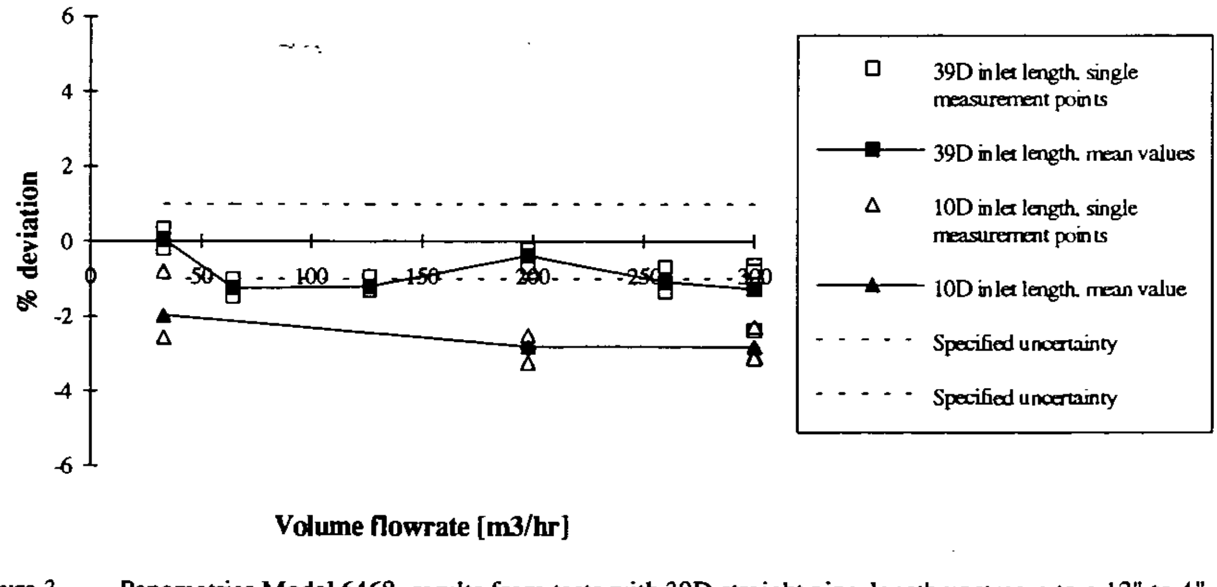

Figure 3 Panametrics Model 6468, results from tests with 39D straight pipe-length upstream to a 12" to 4" conical diffuser, and 10D straight pipe-length upstream to a 90° bend. Temp. = 25.0 - 27.7 °C.

Figure 3 shows the test results for the Panametrics Model 6468. The test results did not meet the specified ± 1.0% accuracy specifications for all flow rates, as indicated in Figure 3, although single measurement points were obtained within the ± 1.0% limit, see Table 2.

With reference to Figure 3, we can again observe the installation effect on the meter performance. As long as the flow profile is stable, the effect of a non symmetrical flow profile will result in an measurement curve offset.

4 FUNCTIONAL TEST ON OIL

4.1. Background

The main goal of the project was to determine the performance of the meters, particularly with regard to their ability to measure the volume flow of crude oil. In some applications, product flow must be measured before the oil has been completely separated, with the result that the oil may contain small quantities of water and gas. It was therefore desirable to determine how the meters performed under such conditions.

As it is a costly and comprehensive task to calibrate flowmeters in a crude oil flow-rig, they were calibrated with water at Norsk Hydro's calibration laboratory, and functional tested with oil at CMR.

The CMR multiphase flow rig used for the functionality test is shown in Figure 4. It is based around a 4" flow loop including a separator. The rig is equipped with a reference system for measurements of flow rate, temperature, pressure and density of the test media. Additionally, the water and gas fraction can be determined by an on-line water-in-oil monitor in conjunction with the density meter. By closing the valves at A and B, the separator can be disconnected, enabling closed loop test runs. For single phase test runs, this feature is advantageous.

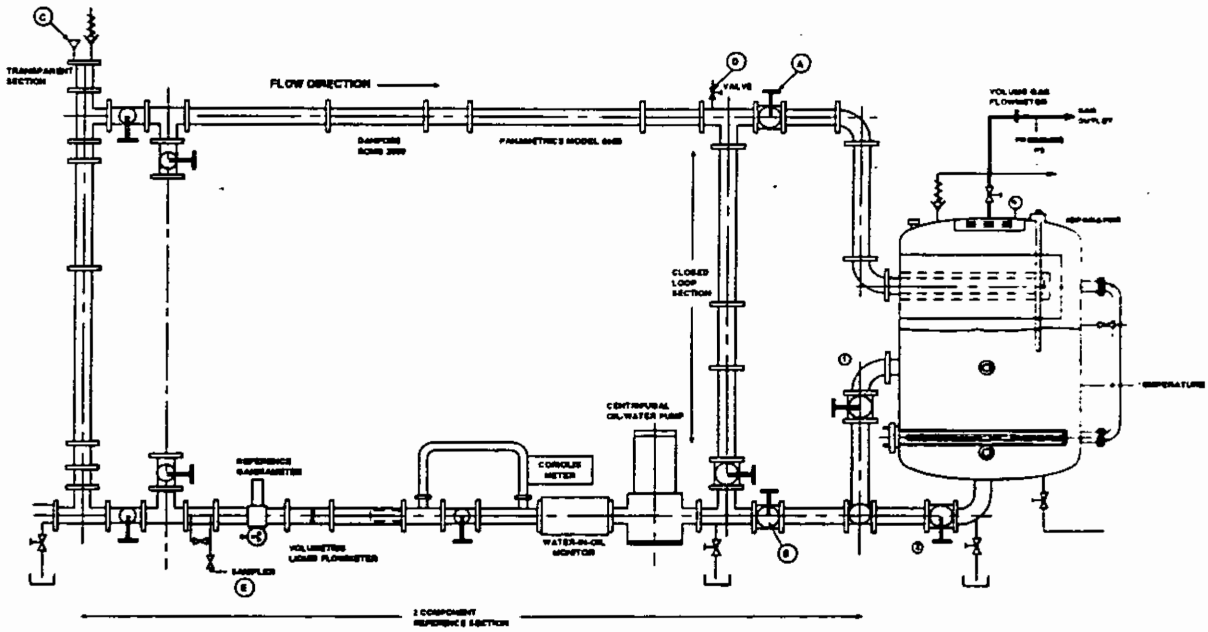

Figure 4 The CMR multiphase flow rig. The schematics shows the setup with the three ultrasonic flow meters installed in series.

4.2 Results from tests with low water fractions in the oil

The results from the low water fraction tests are shown in Figures 5 - 9.

During these tests, a 1.5" coriolis mass meter was used as the system reference. Thus, the maximum obtainable flowrate was approximately 27 m^3/hr. Thus, the tests had to be carried out at the lower end of the measuring range for the meters, increasing the measurement uncertainty. All measurements for the meters under test were carried out simultaneously, assuring identical reference conditions.

From Figure 5, we can observe the influence of water on the measurement performance for Danfoss SONO 2000. The % deviation for each of the 3 measurement points for each water fraction is shown. As can be seen, the deviation increases with increasing water fraction. However, it is not possible to state that the increase in deviation is solely due to an increase in measurement uncertainty of the ultrasonic meter. The influence on the coriolis meter must also be counted for.

The results for the Panametrics Model 6468 is shown in Figure 6. It should be noted that the Panametrics meter at this point probably was influenced by an internal error. This assumption was based on the observation that the volume flowrate output from one of the two channels seemed unstable with large variations at approximately steady flow. Accordingly, the total output from the meter was influenced by this instability. The cause of the error was not identified. The obtained measurements can not be said to be representative for the meter performance of the Panametrics Model 6468. Again, although the Panametrics Model 6468 most likely was influenced by an internal error, the measurement deviations must be viewed as a result of the water fraction influence on both the ultrasonic flow meter and the coriolis reference meter.

Figures 7 - 9 show of the test run measurement sequences for 0, 4.8 and 10 vol% water in the oil. These figures show the measurement instabilities of the Panametrics Model 6468. Compared to the performance of the Danfoss SONO 2000, it is very likely that the Panametrics Model 6468 did not operate properly during these tests.

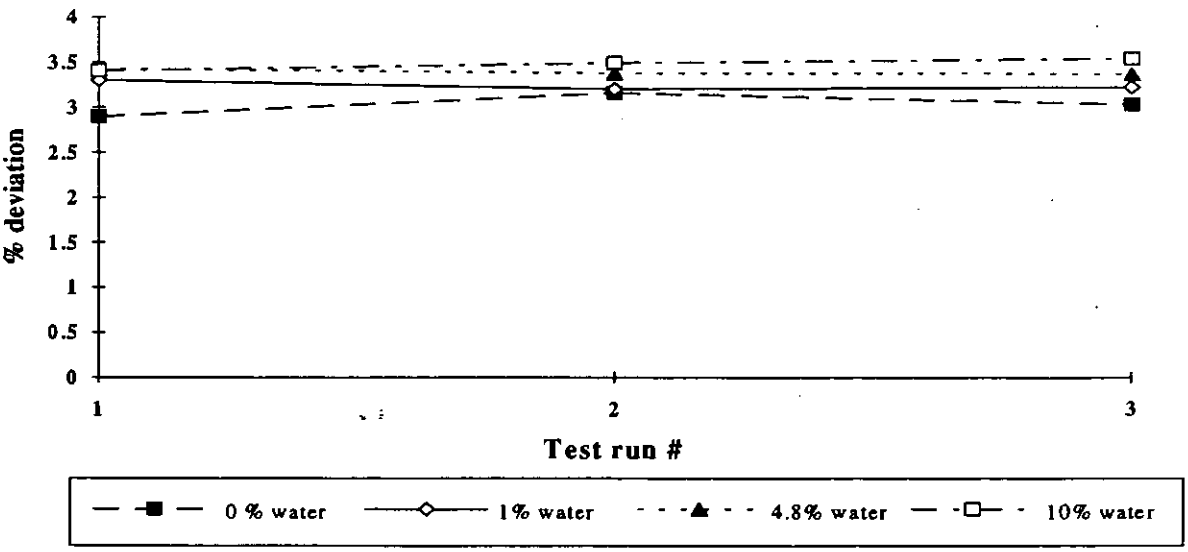

Figure 5 Results from functional test of Danfoss SONO 2000, with water fractions up to 10 vol%.

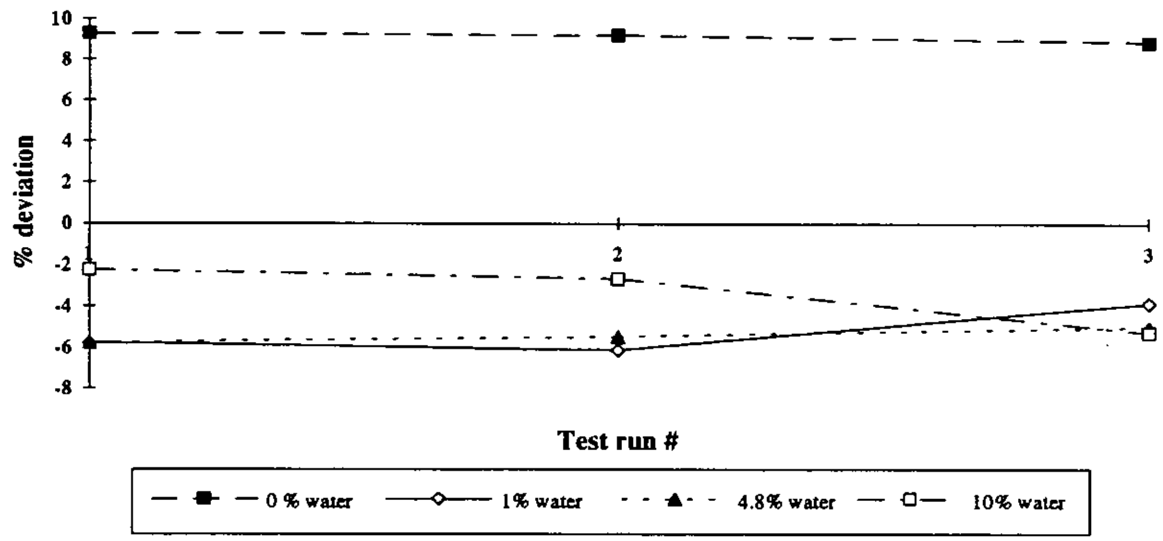

Figure 6 Results from functional test of Panametrics Model 6468, with water fractions up to 10 vol%.

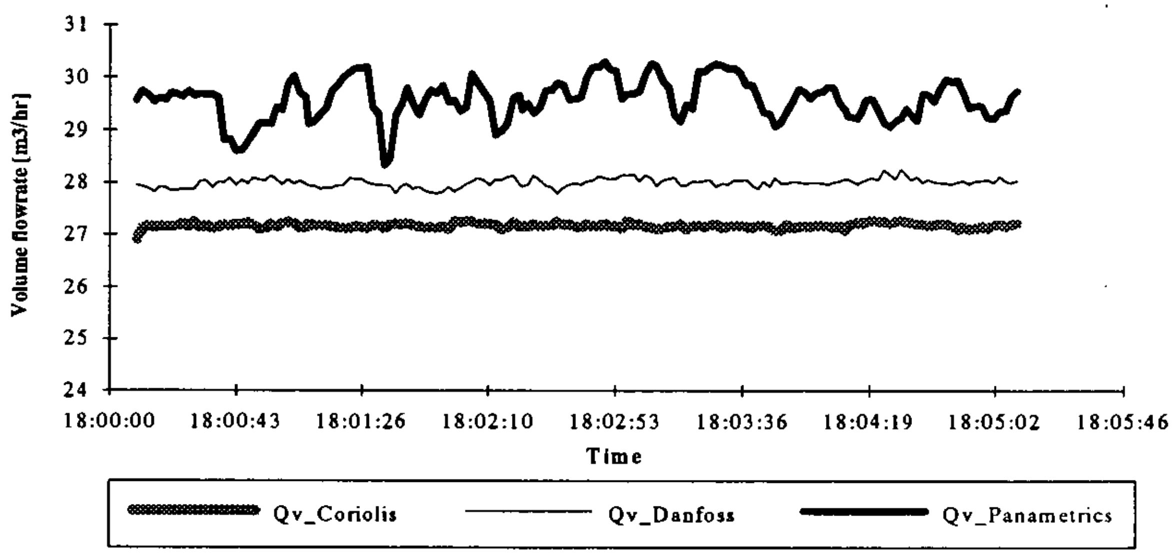

Figure 7 Functional test on diesel oil, 0 vol% water, test run # 3

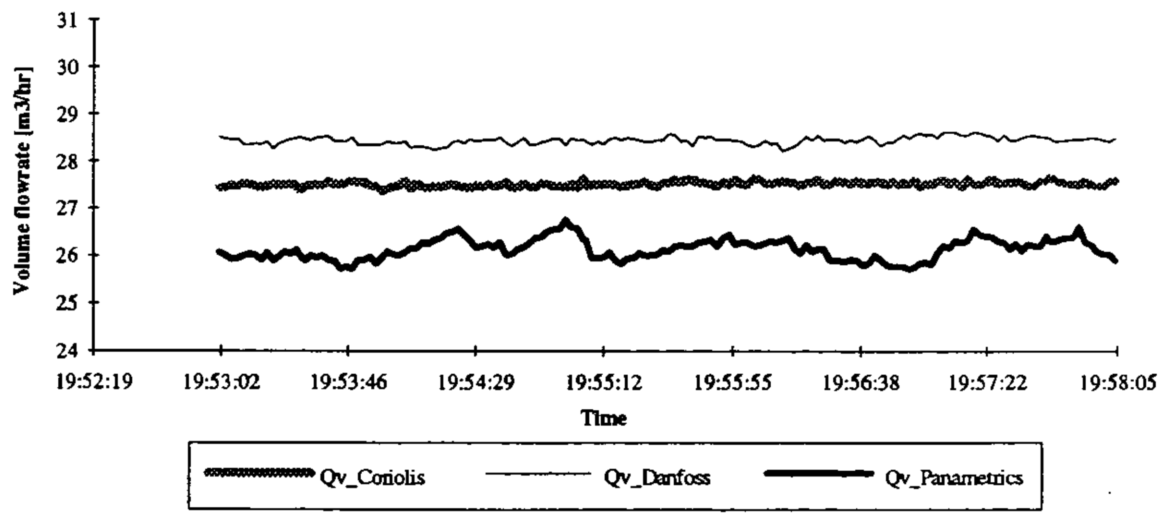

Figure 8 Functional test on diesel oil with 4.8 vol% water, test run # 3

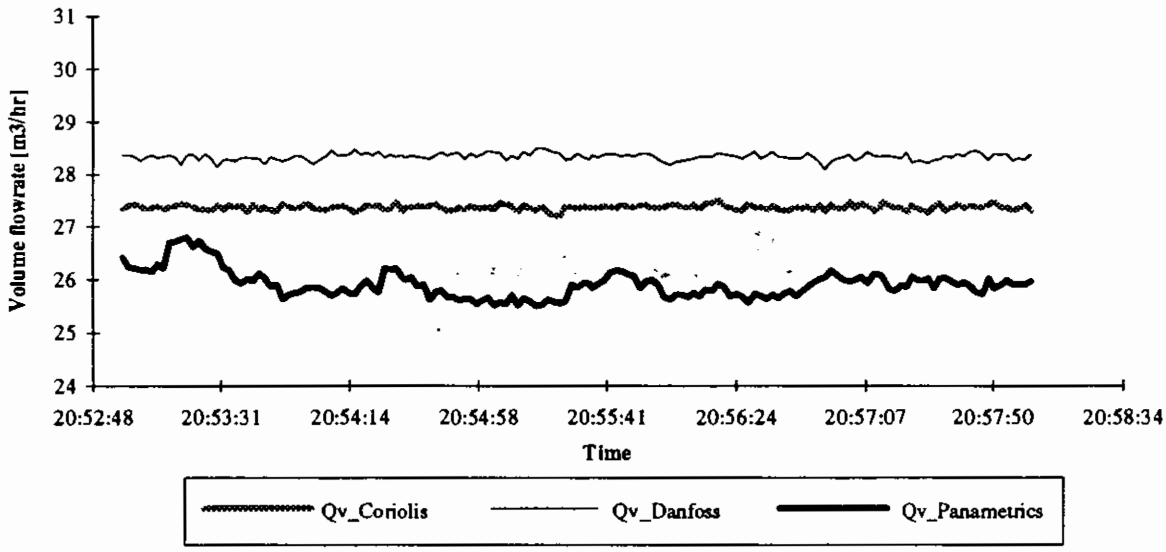

Figure 9 Functional test on diesel oil with 10 vol% water, test run # 3

4.4.3 Results from tests with low gas fractions in the oil

Initially, the test program was outlined in order to investigate how the meters performed with 1, 2 and 3 vol% of gas in the oil. However, at the initial gas fraction of 1 vol%, none of the meters operated properly. Thus, it was decided to revise the test program. By injecting 0.1 vol% of gas at a time, the aim was to determine the maximum gas fraction the flow meters could handle. With a total rig volume of 175 litres, the amount of gas to be injected at each step was 1.75 dl. The injection of gas was carried out by draining 1.75 dl of oil, and substitute that volume with air. The oil was drained from the sampling outlet, see Figure 5, E, and air injected through the valve at D. The measurement sequences were logged to files in the reference system computer, so that the test run sequences could be visualised through a spreadsheet. The results from the low gas fraction tests are shown in Figures 10 - 12.

In Figure 10, no air has been injected in the rig, i.e. the rig is completely filled with oil. Different flow rates are tested. In order to assure best mixing of oil and air, a highest possible flow rate was desirable. However, since the test was carried out as a closed loop test, a high flow rate would imply a temperature and pressure increase. To comply with these potential problems, a flowrate of approximately 40 m^3/hr was chosen as the test flow rate. At this flow rate, the increase in temperature and pressure was minimal.

In Figure 11, the measurement sequence during the period of which up to 0.4 vol% gas was injected in the rig is shown. The sequence shown in Figure 11 was started just after 1.75 dl of oil was drained from the rig. When the oil was drained, the valve at the top section of the rig, see Figure 15, D, was not opened. As can be seen from Figure 11, the injected air had little influence on the meter performances. At time A, another 1.75 dl of oil was drained from the sampling outlet. During this draining period, the valve D was opened, so that the drained oil was substituted with air. Now at least 0.1 vol% of gas was injected in the rig. The effect of the injected gas can easily be seen immediately after the pump was started. The Danfoss SONO 2000 did not perform correct measurements. However, the Panametrics Model 6468 is less influenced by the injected gas, although giving varying measurement output.

At time B, Figure 11, another 0.1 vol% of gas was injected. As can be seen, both meters are clearly affected by the increased gas fraction. The Danfoss SONO 2000 did not give any measurement output hereafter. Accordingly, 0.1 - 0.2 vol% was the maximum gas fraction at which the meter operated.

The influence of the injected gas on the Panametrics Model 6468 can be observed at time B and C, Figure 11, and further at time D and E in Figure 12. At time E, a total of 0.6 vol% of gas had been injected in the rig. An identical procedure was used each time the gas fraction was increased; the pump was stopped, the oil drained from the sampling outlet E, Figure 15, and the valve D opened in order to inject gas. As can be seen from Figures 11 and 12, the Panametrics Model 6468 started operating a while after the pump was started each time the gas fraction was increased. The period of which the meter was not operating became longer as the gas fraction increased. Possible explanations for this behaviour may be:

1. An introduction of gas bubbles in a liquid will affect the transmission of sound in the fluid, [4]. The velocity of sound will change, and the acoustic absorption will increase. Both these parameters will influence the ability of an ultrasonic transit time flow meter to perform correct measurements. In order to investigate the effect of a possible change in the velocity of sound, a simple test was carried out. The receiver time gate of the Panametrics Model 6468 was varied, but with no apparent effect.

2. A decrease in the void fraction will reduce the acoustic absorption of the fluid. In similar tests with small gas fractions, (< 5 vol%) in a closed loop rig, the void fraction decreased towards zero with time if the liquid in the rig was circulated continuously, [5], because the gas is dissolved in the liquid. This is the most probable cause for the observed behaviour of the Panametrics Model 6468.

3. Also, we can not exclude the possibility that some of the injected gas was deposited in small cavities in the rig, e.g. in the coriolis mass flowmeter loop, reducing the amount of free gas in the circulating fluid.

From the figures, we can observe that the Panametrics Model 6468 gives a constant output value for limited periods of time, e.g. as in Figure 12, at time 14:09:36. This is due to a "hold last value" feature, i.e. if the meter does not carry out correct transit time measurements, the unit holds the last value until this is accomplished.

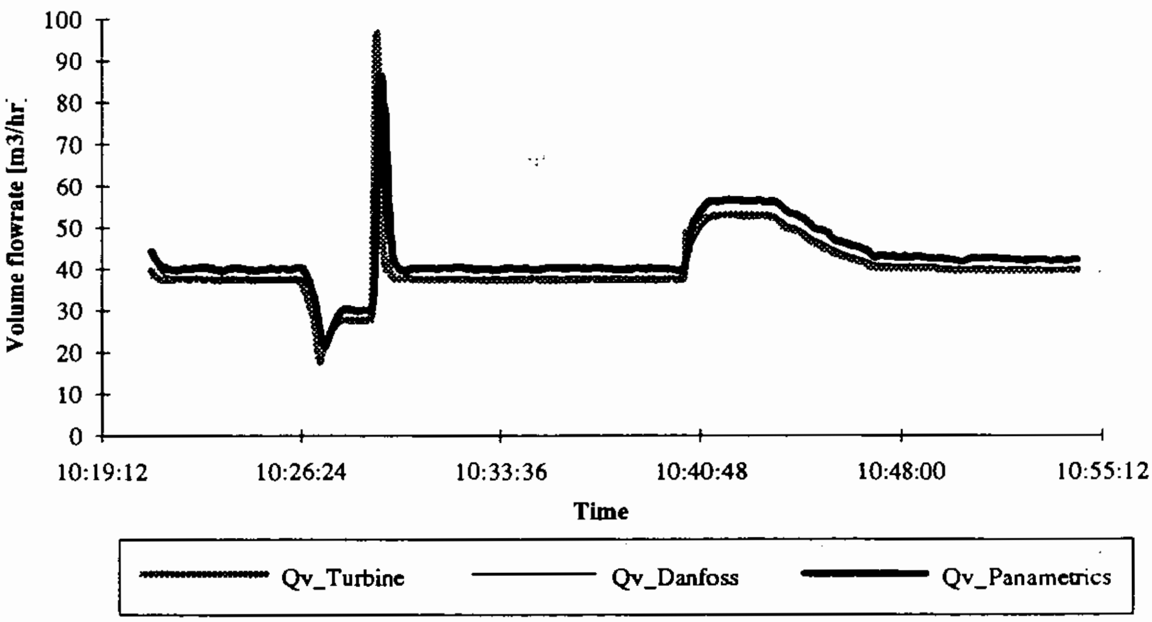

Figure 10 Functionality test on oil with small amounts of gas.
Measurement sequence with rig completely filled with oil.

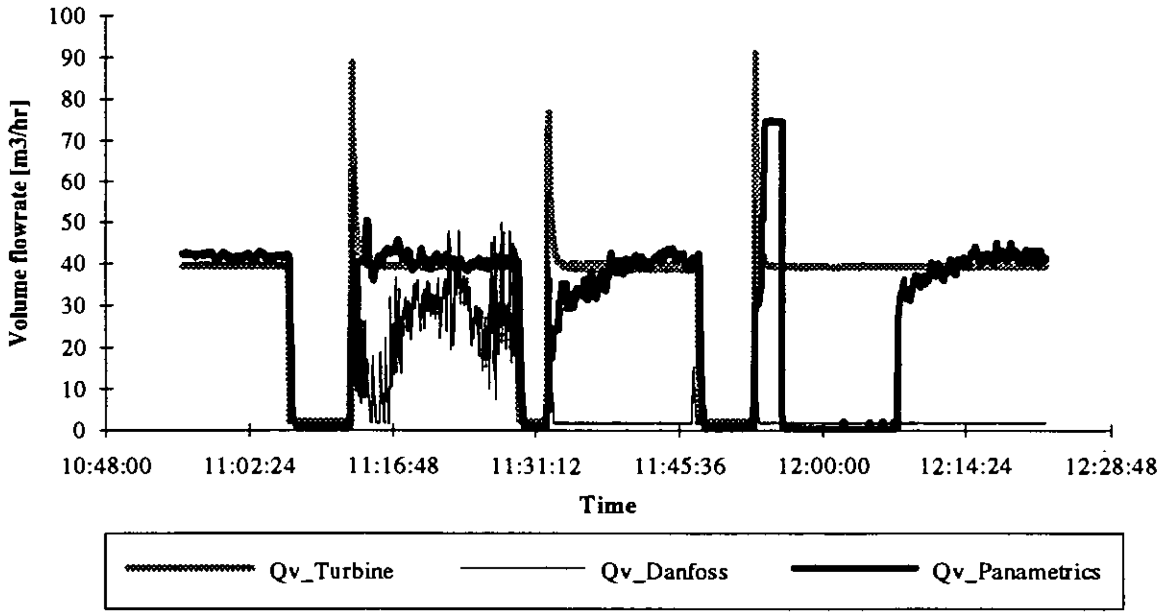

Figure 11 Functionality test on oil with small amounts of gas.
Injection of up to 0.4 vol% gas in the oil flow. Note that the Danfoss SONO 2000 does not give measurement outputs after 0.3 vol% gas have been injected in the oil, at approximately time 11:31:12. Also note the repeated measurement sequence for the Panametrics Model 6468 for each gas injection.

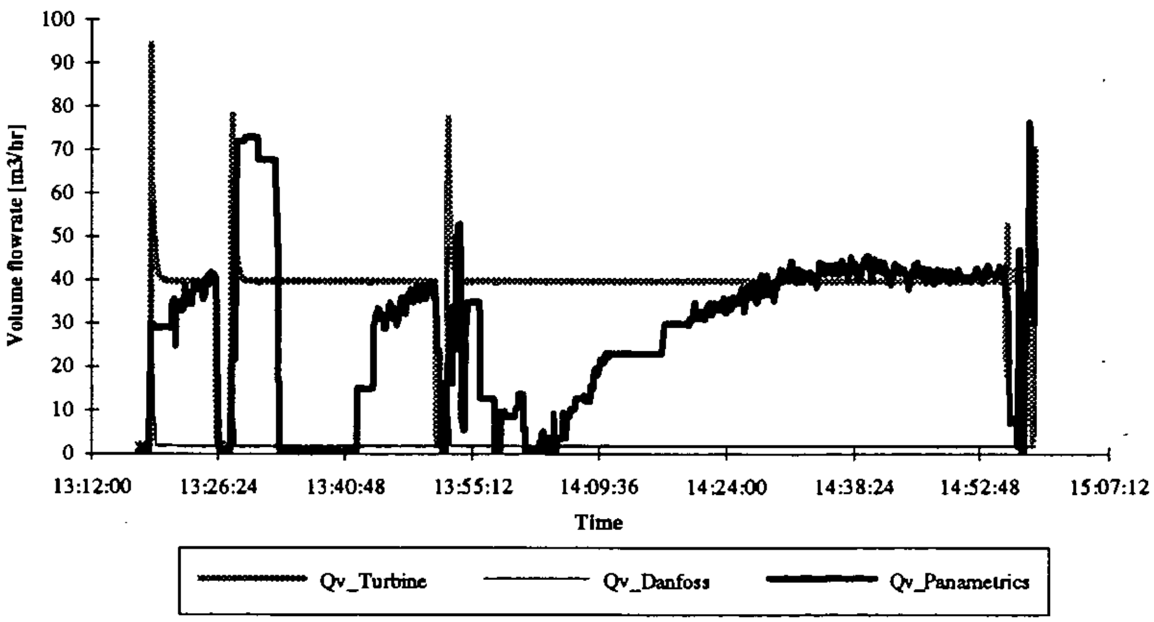

Figure 12 Functionality test on oil with small amounts of gas.
Injection of up to 0.6 vol% gas in the oil. Note that during this test sequence, the Danfoss SONO 2000 did not give measurement outputs, and the repeated measurement sequence for the Panametrics Model 6468 for each gas injection.

5 CONCLUSIONS

Calibration test
In order to obtain the meter performance for the ultrasonic meters, they were tested on water under ideal conditions. The aim of this test was to establish the measurement uncertainty. The calibration tests visualized the upstream pipe-length requirement for a two-beam ultrasonic meter. The results obtained with "maximum" and 10D inlet pipe showed that flow profile variations will affect the measurement uncertainty of the meters. Reducing the inlet pipe length from 26D to 10D resulted in an approximately 1% shift in measurement uncertainty. More than two beams are required in order to decrease the flow profile sensitivity, [3]. Furthermore, on-site calibration is required if the lowest possible measurement uncertainty is required. Comparing the results from the pre-calibrations and the calibration test at Hydro Porsgrunn supports this conclusion. The results from the tests deviate with approximately 1 %.

Functionality test with oil
The ultrasonic meters were tested on oil, at flow rates from 10 m^3/hr up to 90 m^3/hr. All three meters operated without any problems. The flow meters should operate equally well on stabilized crude oil.

Effect of water in oil
The meters were tested with up to 10 vol% water in oil, and operated without any difficulties. However, as the water fraction increased, the measurement deviations compared to the reference system increased. It is not possible to state that this is an effect solely due to an increase in the measurement uncertainty of the ultrasonic meters, since the reference meter also is influenced by the increased water in oil fraction.

Effect of gas in oil
The ultrasonic meters under test were designed for operation on liquids only, although Panametrics claims to handle "a small percentage of entrained gas", [2]. In [1], Danfoss states that the gas fraction should not exceed 1-2 vol%, in order for the meter to perform properly. The functionality test using oil with small amounts of gas injected, showed clearly that none of the meters on test managed to handle flow conditions with as little as 0.5 vol% of gas in the rig. It is though difficult to identify the exact void fraction, as we believe that some of the injected gas is dissolved in the oil with time, reducing the amount of free gas in the fluid.

However, the advantage of an ultrasonic meter is that it will either provide a "correct" measurement result, or give a warning to the operator. In the same measurement situation, most flowmeters will provide a seemingly normal reading without any error indication.

Future work
In order to be able to handle small percentages of entrained gas in the oil, ultrasonic meter design must be improved. Based on our experience with ultrasonic flowmeter technology, it is our opinion that the current designs can be improved to handle gas fractions which will make it possible to install an ultrasonic meter downstream of e.g. a 1st stage separator. It is not within the scope of this paper to state which technological improvements that are required. It is our impression that manufacturers of ultrasonic flowmeters are aware of the requirements of the oil industry, and are continuously making efforts to improve the performance of their flowmeters.

6 ACKNOWLEDGEMENTS

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Also, the manufacturers should be acknowledged for putting the ultrasonic meters to disposal for the project free of charge, and a special thanks to Danfoss and Panametrics for the opportunity to publish the project results.

Finally, I appreciated the service and the enthusiasm shown by Bjørn M. Realfsen, Hans F. Drange and the rest of the staff at the calibration site during the test period at Hydro Porsgrunn.

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