A NEW MULTI-BEAM ULTRASONIC FLOWMETER FOR GAS

by

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Paper No 5.1

NORTH SEA FLOW MEASUREMENT WORKSHOP
26-29 October 1992

NEL, East Kilbride, Glasgow

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10[th] North Sea Flow Measurement Workshop

A new multi-path ultrasonic flow meter for gas

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ABSTRACT

Offshore metering stations based on orifice plates are bulky and require much space. Accordingly, the platform costs are considerable, and can be significantly lowered if the size of the metering station is reduced.

Ultrasonic transit time multi-path meters will allow compact metering stations to be constructed due to increased flow meter capacity and reduced installation lengths. In addition these meters offer improved flow meter performance and potential for simpler maintenance procedures.

A new multi-path flow meter for gas has been developed by Christian Michelsen Research in Norway. The flow meter has undergone testing on natural gas at K-Lab, Norway. The flow meter (FMU 700) will be manufactured by Fluenta AS.

The FMU 700 features new technical solutions such as titanium housed ultrasonic transducers, automatic gain control, on-line measurement of transit time delay in cables and electronics, and software pulse detection.

The deviations between the K-lab sonic-nozzle reference mass metering system and the FMU 700 are less than 0.8% at gas velocities between 1 and 8 m/s. These results were achieved with 10D straight inlet pipe downstream of a 90° bend. Tests were also performed with the FMU 700 installed only 5D downstream a 90° bend. At gas velocities between 2 and 8 m/s the measurement uncertainty is not changed despite the reduction in upstream straight pipe length from 10D to 5D. The observed deviations were independent of the test pressure varying from 55 to 100 bar. The test results show that it is quite feasible to build a very compact and light metering station compared to conventional solutions and at the same time comply with the requirements set to fiscal metering stations.

The following procedure is suggested for proving of a multi-path meter in a fiscal metering station :

- Zero calibration of flow meter when delivered from manufacturer.
- Flow calibration prior to installation in the metering station.
- Use of the flow meter's self diagnostic properties to indicate if and when zero calibration should be repeated.
- On-site zero calibration of individual transducer pairs which are removed from the pipe line and installed in a zero calibration cell.

1 INTRODUCTION

Offshore metering of natural gas has been, and still is, based on the orifice plate. This technology is proven and well known both to the operators and the authorities. However, metering stations based on orifice plates are bulky and require much space. Accordingly, the platform costs are considerable, and can be significantly lowered if the size of the metering station is reduced [1,2].

Statoil, as a major gas producer, has been concerned with reducing the costs of offshore metering of gas [1]. Based on the general development within electronics and sensor technology during the 80's, it became clear that multi-path ultrasonic flow meters represented a realistic alternative to orifice plates. Specifically, multi-path meters would allow compact metering stations to be constructed due to increased flow meter capacity and reduced installation lengths. In addition these meters offered the advantages of :

- low uncertainty,
- no moving parts,
- no pressure loss,
- rapid response,
- potential for omitting flow calibration,
- self-checking possibilities,
- reduced maintenance.

Thus, it was recognized that introduction of ultrasonic meters would both reduce costs and improve flow meter performance. In a study carried out by Statoil, savings of 100-150 mill.NOK were estimated if offshore metering stations were based on ultrasonic rather than orifice meters [1].

On this basis Statoil and Christian Michelsen Research (CMR) launched a project in 1988 with the objective of developing a 12" multi-path meter. The project was funded by Statoil. The design phase was successfully concluded by the end of 1990 and it was decided to build and test a 12" prototype fiscal metering system (FMU 700). The prototype and testing phase of the development was funded by Statoil and Fluenta, a subsidiary of CMR. The FMU-project was carried out jointly by Statoil, CMR, Fluenta and Kongsberg Offshore (KOS).

CMR has been active within ultrasonic flow meter technology for more than a decade [3,4], and proposed as early as in 1981 to develop a multi-path gas flow meter.

These projects served as a technology basis for the FMU-project where CMR developed the ultrasonic transducers, the geometrical arrangement of the sensors on the spool piece, the hazardous and safe area electronics, the flow computer solution and software as well as the signal processing technique.

The project was coordinated by Fluenta which also will manufacture the FMU 700 flow meter.

KOS developed design solutions for metering stations based on multi-path meters and provided the secondary spool piece carrying temperature, pressure and density sensors.

The meter was tested on natural gas from mid November 91 to early February 92 at K-Lab which is a high-pressure flow calibration facility located at Kårstø, Norway. K-Lab is a joint venture between Total and Statoil and is operated by Statoil.

In this paper we describe the results of the FMU-project focusing on the flow meter concept, a discussion of some of the test results and finally a presentation of procedures for proving of multi-path ultrasonic gas flow meters.

2 MEASUREMENT PRINCIPLE

Transit time principle

The FMU 700 is based on the well established acoustic transit time principle. The measurement principle utilize the fact that the direction and propagation velocity of an ultrasonic pulse will be modified by the flowing medium. An ultrasonic pulse propagating with the flow will experience an increase in velocity while an ultrasonic pulse propagating against the flow will experience a decrease in velocity.

Basic formulas

In Figure 1 a single-path ultrasonic flow meter is illustrated with two ultrasonic transducers facing each other at an oblique angle to the pipe axis. The individual upstream (t_{21}) and downstream(t_{12}) transit times are given by [6]

$$t_{12} = L/[\ (c^2-v^2\sin^2\theta)^{1/2} + v\cos\theta\ ]\ , \quad (1a)$$

$$t_{21} = L/[\ (c^2-v^2\sin^2\theta)^{1/2} - v\cos\theta\ ]\ . \quad (1b)$$

It is readily shown that combining Eq.(1a) and Eq.(1b) yield

$$v = L(t_{21}-t_{12})/(\ t_{12}\ t_{21}\ 2\cos\theta\ )\ , \quad (2)$$

and

$$c = L[\ (t_{12}+t_{21})^2\cos^2\theta + (t_{21}-t_{12})^2\sin^2\theta\ ]^{1/2}/(\ t_{12}\ t_{21}\ 2\cos\theta\ ) \quad (3)$$

where

- v = Axial flow velocity averaged along a chord D which is the projection of L in a plane perpendicular to the pipe axis, see Fig. 1,
- c = Speed of sound in the fluid averaged along the chord D,
- L = The portion of the intertransducer center line lying in the flowing fluid,
- θ = Angle between the intertransducer center line and a line parallel to the pipe axis,
- t_{12} = Downstream transit time, from transducer 1 to 2,
- t_{21} = Upstream transit time, from transducer 2 to 1.

We observe that both the flow velocity v and the speed of sound c in the fluid are measured. Thus, the transit time flow meter also provides information on a physical property of the fluid.

In practice the transducers are often set back, i.e. the actual distance between the transducers is larger than L as e.g. shown in Fig. 1. Accordingly the measured transit times also incorporate the transit time in the cavity in front of the transducers. However, it is easy to implement a procedure in the flow computer which allows the measured transit time to be corrected for the unwanted time delay in the transducer cavity. For low Mach number flows this practical problem can also be solved as described in [7].

Volume flow measurement

By measuring along five different acoustic paths across the pipe, the gas volume flow can be measured accurately even when the flow profile is distorted. Figure 2 illustrates the positioning of the ten ultrasonic transducers in the FMU 700 ultrasonic gas-flow meter. The measured velocities v represent averages along the parallel chords shown in Fig. 2, i.e. the acoustic transit time technique in facts integrates the velocity profile along the parallel chords. The volume flow is given by

$$q = \int_{-r}^{r} D(y)v(y)dy \qquad (4)$$

where

y	= The axis across the pipe perpendicular to the chords,
D(y)	= The length of a chord perpendicular to the y-axis,
v(y)	= Axial flow velocity averaged along a chord D(y),
r	= The radius of the pipe.

The multi-path meter measures v along a limited number of chords and the integral in Eq.(4) can be approximated by

$$q = \Sigma w_i v_i \qquad (5)$$

where

w_i = Weight factors depending on the numerical integration technique applied in Eq. (5).

The geometrical configuration of the ultrasonic transducers, or the position of the parallel chords in Fig. 2, therefore depends on the numerical integration technique which is applied.

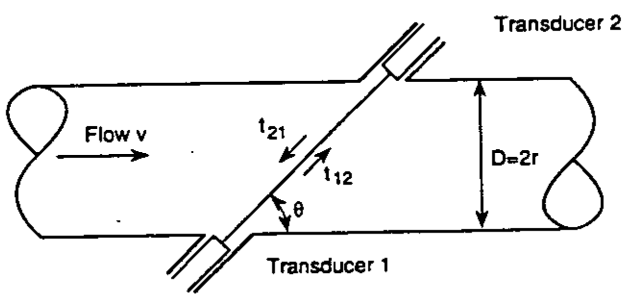

Figure 1 Illustration of the principle of a single-path ultrasonic transit time flow meter.

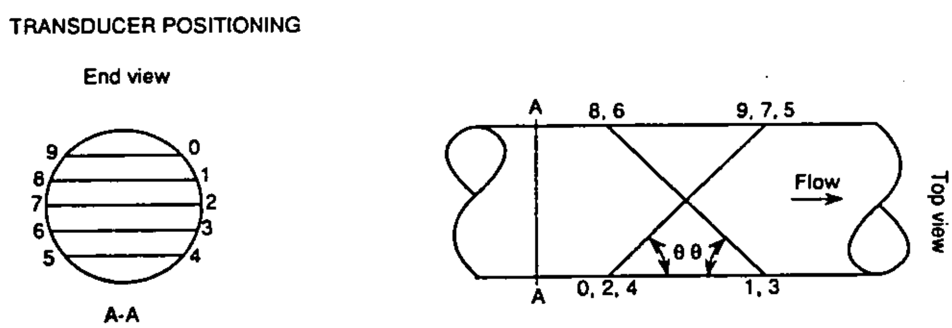

Figure 2 Transducer positioning in the five-path FMU 700 ultrasonic gas-flow meter.

3 SYSTEM DESCRIPTION

General description

The flow meter measures volume flow, flow velocities and speed of sound averaged along parallel chords, see Figs.1-2. Mass flow can be computed provided the density is made available to the flow computer.

The FMU 700 five-path ultrasonic gas flow meter consists of, see Fig. 3 :

A cabinet containing a computer and an electronics unit,
Two signal cables and one optical cable,
Intrinsically safe electronics,
10 titanium-housed ultrasonic transducers,
A flanged spool piece.

A secondary spool carrying temperature, pressure and density sensors, can be installed downstream of the flow meter. If required, the signals from the secondary sensors can be received and converted to physical values by the flow computer.

The flow computer can store all measured data and diagnostic parameters and transfer the information on digital format to an external computer via a series communication link (RS232).

Specifications

The following design specifications apply :

Diameter range	: ≥ 6"		
Operational temperature range	: -10	to	+70 °C,
Pressure range	: 50	to	200 bar,
Velocity range	: 0.4	to	20 m/s,
Velocity resolution (12")	: < 1.4mm/s,		
Volume flow sampling frequency	: appr. 10 Hz.		

The design temperature range for the pipe work, e.g. -46 to +105 °C, will normally exceed the operational temperature range. However the flow meter spool will comply with the requirements set for the pipe work. But as yet, the flow meter is not designed to operate over the entire pipe work design temperature range.

At K-Lab the flow meter was tested down to 20 bar and no change of the flow meter performance were observed. This indicates that the pressure range can be extended below 50 bar.

Installation requirements

The flow meter was designed to operate with 10D of straight pipe upstream of the meter spool and 3D straight pipe downstream of the meter spool. The total installation length amounts to appr. 16D. The total installation length does not change if the 3D downstream spool is equipped with a thermowell or an intrusive densitometer, i.e. if the downstream spool acts as a secondary spool.

For a bi-directional installation, the total installation length will be 23D without a secondary spool and 26D with a secondary spool.

The tests at K-Lab indicate that downstream of a 90° bend, the upstream length may be reduced to 5D. In this case the installation lengths reduce to 11D for an installation with a fixed flow direction. For a bi-directional installation the total installation lengths may reduce to 13D(no secondary spool) and 16D(including secondary spool).

Flow computer

The flow computer is based on an industrial PC with keyboard and color graphics screen. The computer controls the entire measurement process in real time according to a pre-set measurement procedure stored in file during the configuration of the meter. Instructions to the hazardous area electronics from the flow computer is transmitted via an optical cable to ensure fast and reliable transmission of the control parameters. The sensor signals are transmitted via two cables between the control room and the flow meter.

The operator can only get access to the flow computer by specifying the correct password, and the flow computer program can only be halted by specifying the correct password. In a practical measurement situation the keyboard can be removed or locked to increase the security. Further, the flow computer operation will be made independent of the hard disk by storing all programs in ROM. If the hard disk fails this will not influence the meter performance.

The computer initiates the transmission of ultrasonic pulses and then reads a representation of the received pulse into the computer's memory in real time. In a measurement cycle each of the 10 transducers act once as a transmitter and once as a receiver and 10 pulse representations are recorded during the cycle. Based on the 10 recorded pulses, 10 transit times are computed representing a single sample of the volume flow. When volume flow samples have been acquired over a user specified time interval, 10 mean times-of-flight are computed in software from the individual transit times recorded during the interval.

From the 10 calculated times-of-flight the flow velocities and speed of sound along each of the five acoustic paths are calculated. The volume flow is calculated by integrating the flow velocities across the pipe profile. The mean flow velocity in the pipe, mass flow, total volume and mass are then calculated along with statistical data. Readings are displayed on the computer screen and are sent in digital format to e.g. the computer in the fiscal measurement station.

There is no additional microprocessor in the system except for the standard processor installed in the PC.

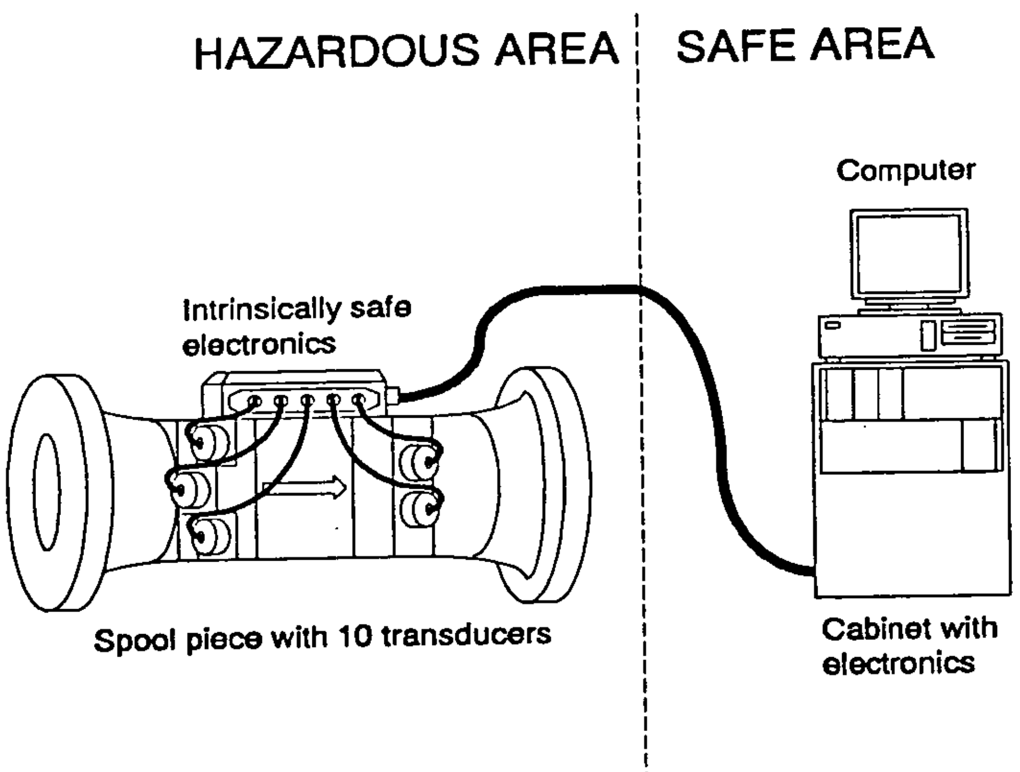

Figure 3 The FMU 700 ultrasonic gas-flow meter.

4 FLOW METER PERFORMANCE

4.1 Calibration tests

Test procedure

During the tests, the gas density in the test section was calculated based on measured pressure, temperature and gas composition (AGA 8). The mass flow was computed from the FMU-metered volume flow and the calculated density. The FMU 700 was configured to average the volume flow, flow velocities and the speed of sound for each path over a period of 10sec. The number of samples in a 10sec period is approximately 110. The flow meter readings were continuously transmitted to the K-Lab computer on digital format.

The reference mass flow rate for a single comparison test was defined as a 300sec average reading of the nozzles, and the FMU 10sec-readings were averaged over the same time interval. During each run the flow conditions were kept as stable as possible.

At each velocity, at a given pressure, 5 or usually 3 consecutive runs were made.

The temperature during the tests reported here varied between 36.7 and 37.9 °C. The velocity range was 0.4 to 8 m/s which is the maximum value in a 12" pipe at K-Lab, and the pressure was set to 55, 70 or 100 bar. The flow meter was tested 10D and 5D downstream of a 90° bend. The 3D long secondary spool was installed downstream of the meter spool "flange to flange", carrying a pressure sensor and a thermowell.

The uncertainty of the K-lab reference mass metering system is estimated by K-lab to be 0.3%.

Comparisons with sonic nozzles

The deviations between the K-lab sonic-nozzle reference mass metering system and the FMU 700 are less than 0.8% at gas velocities between 1 and 8 m/s, see Figure 4. These results were achieved with 10D straight inlet pipe downstream of a 90° bend. Tests were also performed with the FMU 700 installed only 5D downstream a 90° bend. At gas velocities between 2 and 8 m/s the measurement uncertainty is not changed despite the reduction in upstream straight pipe length from 10D to 5D. From Figure 4 we can also see that the measurement uncertainty is independent of pressure changes. In Fig. 5 the individual 300sec readings are plotted to give an impression of the repeatability (2σ-uncertainty) of the meter under test. As can be observed, the repeatability is satisfactory, see below.

The sonic nozzle readings were also converted to volume flow and compared with the volume flow measured by the FMU meter. The observed variability of the FMU and nozzle readings were quite similar.

It should be noted that the test results referred to above, were achieved without using any calibration or meter factor in the FMU 700 meter. The FMU 700 flow meter was zero-calibrated independently of the K-lab reference system and then installed at K-lab, see Section 6.

2-σ uncertainty

The 2-σ uncertainty is defined here as 2σ/(average reading) where σ is the sample standard deviation of N flow meter readings recorded in a given time interval where the flow rate is constant.

An important property of the FMU 700 flow meter is the stability of the flow meter, see Figure 5. During the tests at K-lab it was demonstrated that the observed repeatability is comparable to a good turbine meter, which is recognized as a very stable and repeatable flow meter.

Table 1 displays 3 different estimates for the 2σ-uncertainty of the FMU 700 during the tests at K-lab during a period when the flow rate was particularly stable. It is important to be aware of that the ultrasonic flow meter measures the turbulent fluctuations of the flow and turbulence will contribute to the 2σ-uncertainty together with the contribution from the finite resolution of the transit time measurement. The 2σ-uncertainty will decrease when the time averaging interval increases because the average reading gets closer and closer to the true mean, and this is also observed from Table 1[1]. In Figure 6 some of the data in Table 1 are plotted.

Table 1 2σ-uncertainty for the FMU 700 based on 150 consecutive flow meter readings. The 150 readings represent either 10sec averages, 100sec moving average of 10sec readings or 300sec moving average of 10sec readings. During the 1500sec time interval the flow conditions were kept as stable as possible.

Measurement series: (1500sec time slices used)	Mean flow velocity [m/s]	Average 10sec 2σ uncertainty	Moving average 100sec 2σ uncertainty	Moving average 300sec 2σ uncertainty
10D, 100 BarG, 2.5% Sonic nozzles.	0.394	0.560%	0.177%	0.102%
10D, 100 BarG, 6.25% Sonic nozzles.	0.986	0.512%	0.123%	0.046%
10D, 100 BarG, 13.75% Sonic nozzles.	2.168	0.281%	0.074%	0.041%
10D, 100 BarG, 27.5% Sonic nozzles.	4.321	0.237%	0.062%	0.034%
10D, 100 BarG, 50% Sonic nozzles.	7.736	0.204%	0.061%	0.023%
10D, 70 BarG, 2.5% Sonic nozzles.	0.394	0.695%	0.178%	0.091%
10D, 70 BarG, 6.25% Sonic nozzles.	0.997	0.447%	0.132%	0.071%
10D, 70 BarG, 13.75% Sonic nozzles.	2.192	0.301%	0.096%	0.048%
10D, 70 BarG, 27.5% Sonic nozzles.	4.355	0.212%	0.068%	0.020%
10D, 70 BarG, 50% Sonic nozzles.	7.811	0.206%	0.070%	0.027%
10D, 55 BarG, 2.5% Sonic nozzles.	0.398	0.571%	0.212%	0.106%
10D, 55 BarG, 6.25% Sonic nozzles.	1.009	0.458%	0.207%	0.074%
10D, 55 BarG, 13.75% Sonic nozzles.	2.216	0.335%	0.107%	0.061%
10D, 55 BarG, 27.5% Sonic nozzles.	4.400	0.218%	0.065%	0.026%
10D, 55 BarG, 50% Sonic nozzles.	7.890	0.186%	0.051%	0.016%
5D, 100 BarG, 2.5% Sonic nozzles.	0.384	0.773%	0.206%	0.102%
5D, 100 BarG, 6.25% Sonic nozzles.	0.981	0.762%	0.234%	0.132%
5D, 100 BarG, 13.75% Sonic nozzles.	2.168	0.597%	0.172%	0.083%
5D, 100 BarG, 27.5% Sonic nozzles.	4.313	0.487%	0.093%	0.043%
5D, 100 BarG, 50% Sonic nozzles.	7.723	0.445%	0.152%	0.101%

1 Accordingly, a comparison of the 2σ-uncertainty between various flow meters is only meaningful if the averaging intervals are similar for the various meters.

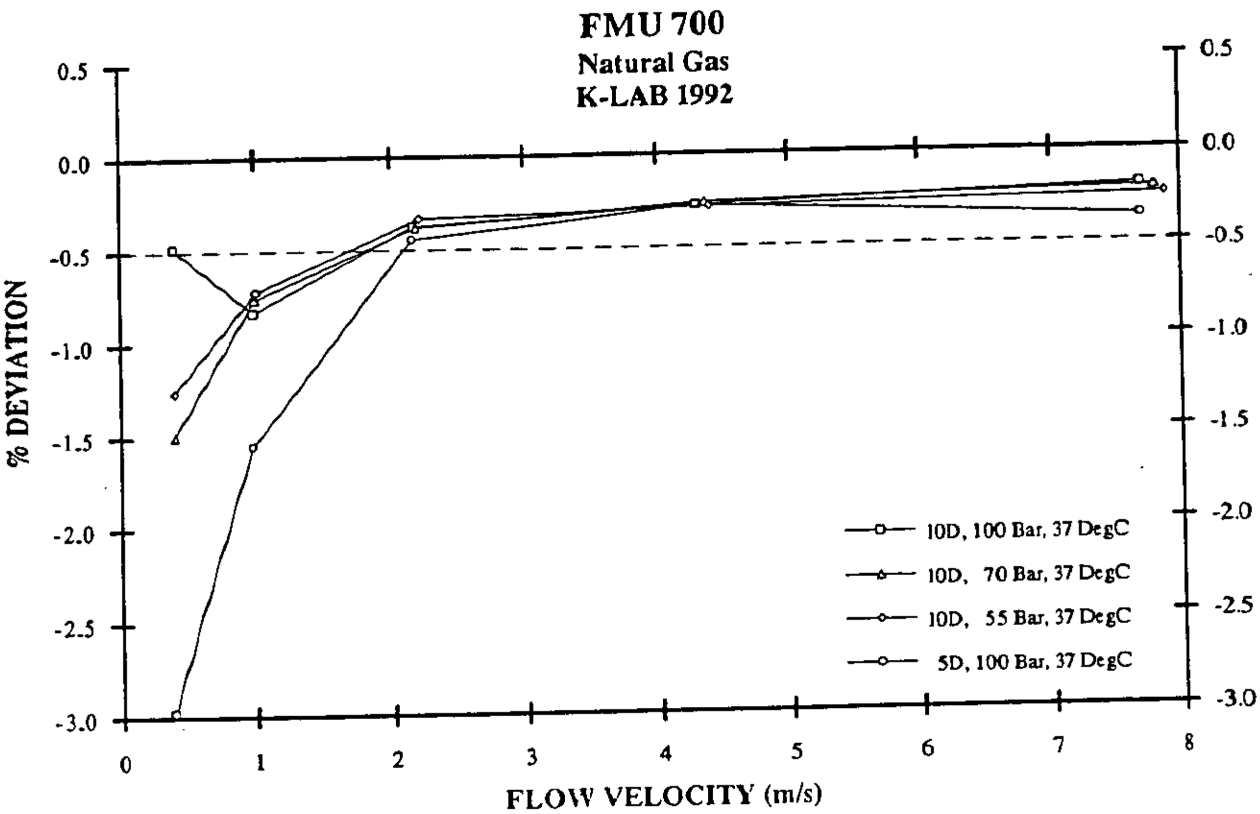

Figure 4 Calibration test results at K-lab for FMU 700. 10D and 5D measurements.

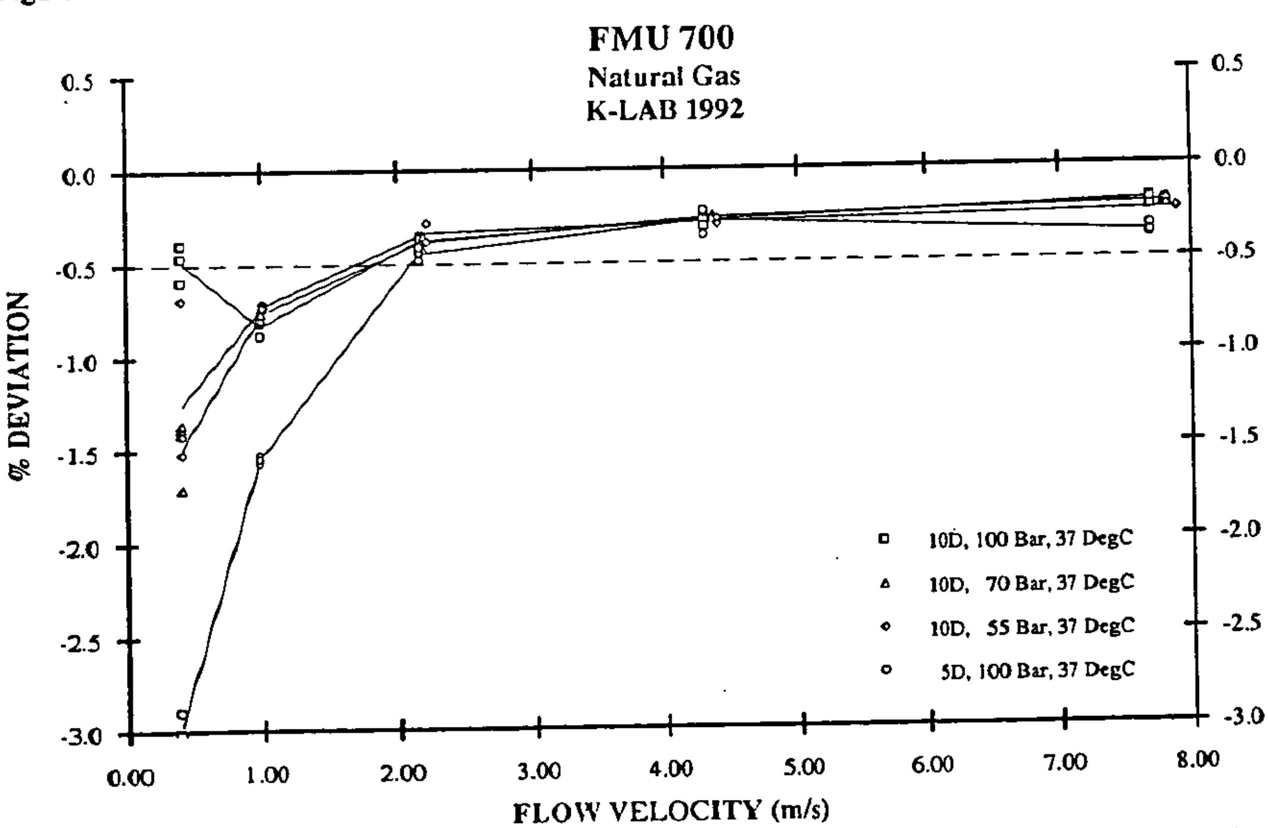

Figure 5 Calibration test results at K-lab for FMU 700. 10D and 5D measurements which indicate the good repeatability of the meter.

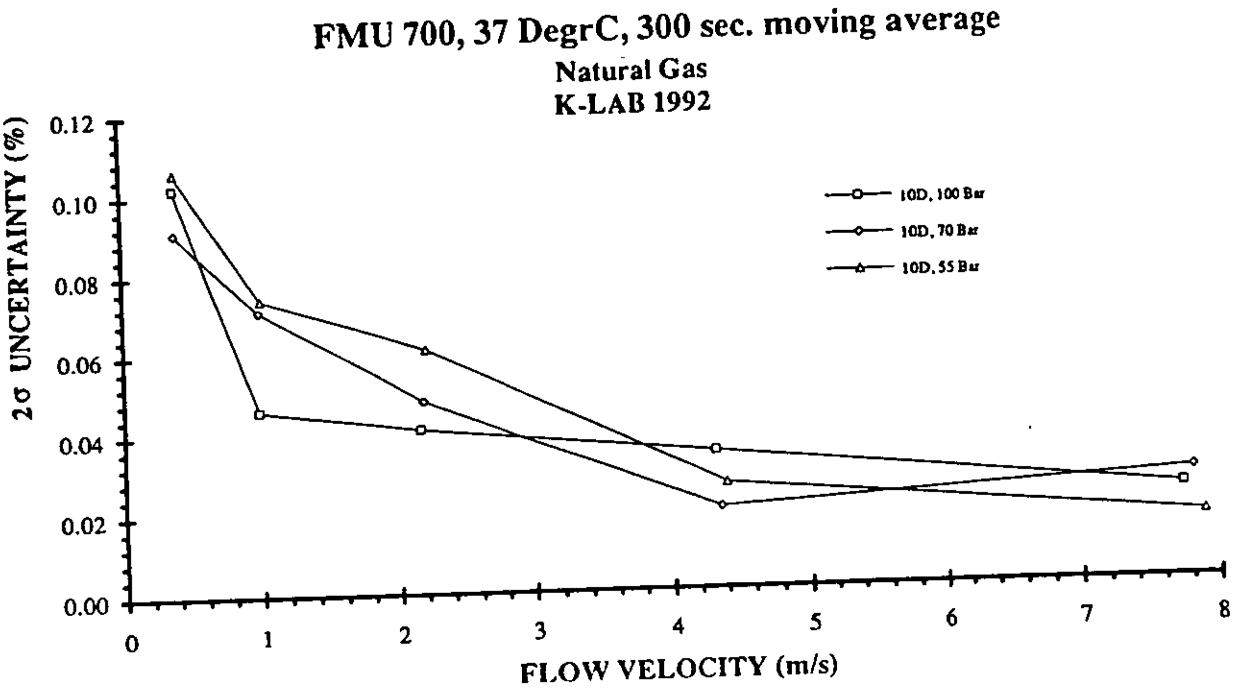

Figure 6 Estimates of the 2σ-uncertainty of the FMU 700 during the tests at K-lab. The 2σ-uncertainty displayed here is based on a 300sec moving average of the 10sec average flow meter readings. At K-Lab each comparison between the FMU 700 and the reference nozzles was based on an average reading over 300sec.

Conclusion, K-Lab test

The results show that it is quite feasible to build a very compact and light metering station compared to conventional solutions and at the same time comply with the requirements set to fiscal metering stations.

4.2 Flow analysis

The flexibility of the flow meter may be utilized by e.g. calibration laboratories to monitor the flow conditions as shown in the following. In view of the good repeatability of the flow meter, it should also be fully possible to use it as a reference flow meter in calibration loops.

During continuous metering, measured data can be stored in a file by giving an appropriate command. Similarly, the system can be set to measure only a single path, for test, trouble shooting or calibration purposes. Stored data can be used to examine earlier series of measurements by fetching data from file and displaying them on the screen. This enables the operator to scan rapidly through the data to interesting areas of the measurement series.

Figure 7 is an example of such a stored time series from the tests at K-lab, where an interesting part has been plotted showing mean flow velocity and velocities along each of the five acoustic paths around an abrupt change of the flow velocity. In Figure 8 the same incident is shown for the speed of sound along each of the five acoustic paths. The mean flow velocity and the speed of sound along one of the acoustic paths are plotted on top of one another in Figure 9 to show the simultaneous change in both measured values. This event also illustrates the flow meter response the ability to resolve rapid changes of the flow rate.

In Figure 10 another part of the time series is plotted showing the turbulent fluctuation in mean flow velocity and velocities along each of the five acoustic paths at a constant flow rate. Notice how the flow velocities along the acoustic paths closest to the pipe wall, 0-9 and 4-5, display the highest turbulent fluctuation and how the fluctuations appear to inversely correlate. The same is the case for the mid-paths, 1-8 and 3-6, but with less turbulent fluctuation. The center path is less influenced by turbulence while the calculated mean flow velocity is almost constant. Another interesting observation is that the turbulent fluctuation along two paths on the same side of the center path, f. ex. 0-9 and 1-8, also inversely correlate while the turbulent fluctuation along two asymmetric paths on different sides of the center path, e.g. paths 0-9 and 3-6, correlate. This correlation and inverse correlation effect between the turbulent fluctuations along different acoustic paths is easier seen in Figure 11. It shows an extract of the time series from Figure 10, with the flow velocity along the five paths plotted as a profile, with time as parameter.

In Figure 12 the same part of the time series as in Figure 10 is plotted showing the fluctuation of the speed of sound along each of the five acoustic paths. No rapid fluctuations of the speed of sound are observed. The slow overall fluctuation of the speed of sound is probably due to the regulation system on the centrifugal compressor circulating the gas around the loop at K-lab.

During test metering, the received ultrasonic pulse representations can be stored in file. Due to the large amount of data that a single ultrasonic pulse represents, only short time series can be stored. The stored ultrasonic pulses can be examined later by a separate program which e.g. can produce various plots of single pulses as shown in Fig. 13 and time series of computed times-of-flight as shown in Fig. 14. Individual pulses and transit times can also be valuable tools for analyzing various flow phenomena.

Analyses as described above can provide information on the meter performance and the flow conditions.

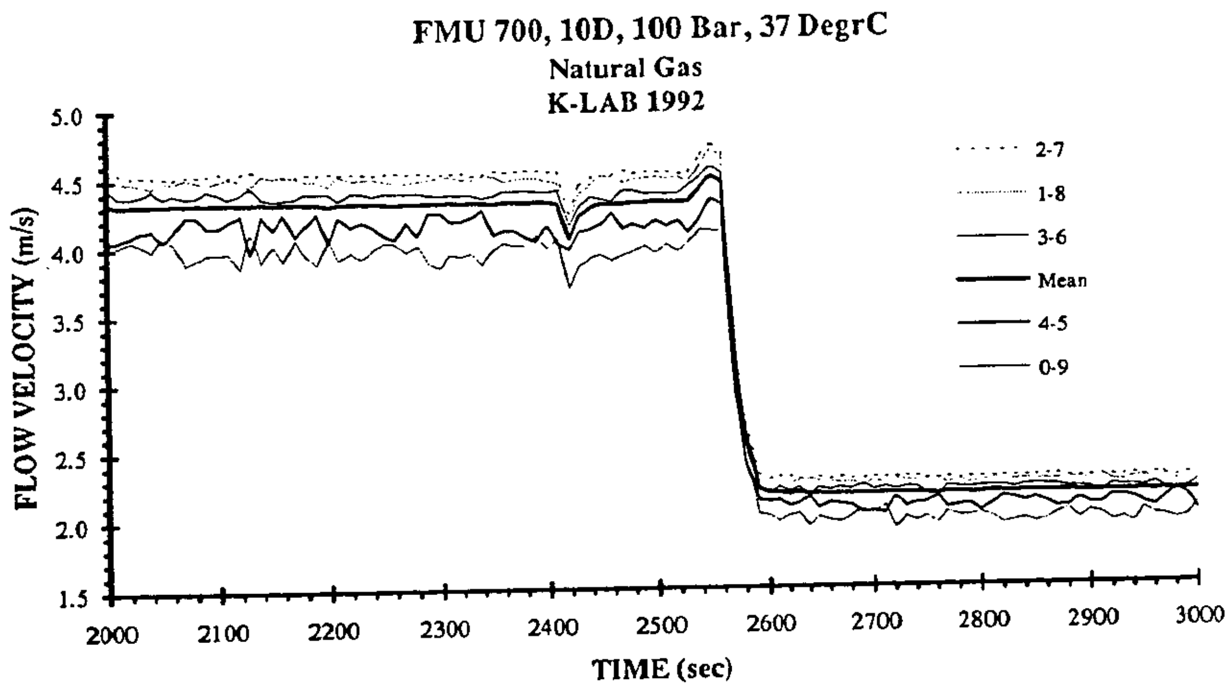

Figure 7 Tests at K-lab. Showing mean flow velocity and velocities along each of the five acoustic paths around an abrupt change in flow velocity.

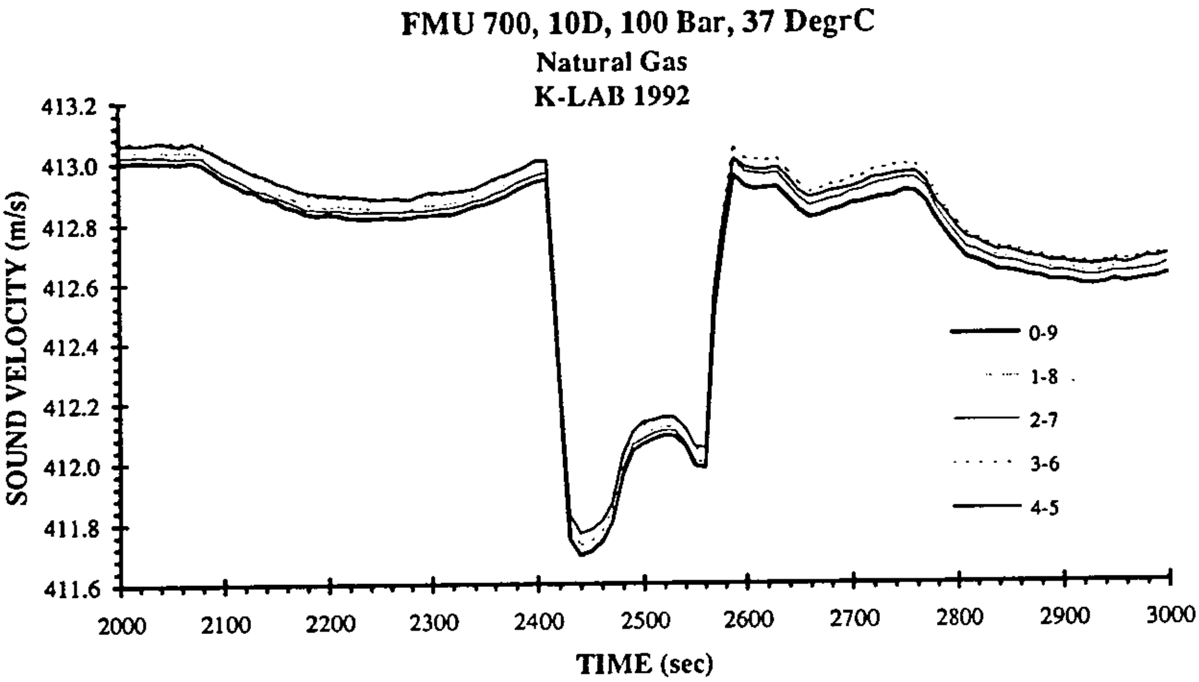

Figure 8 Tests at K-lab. Showing speed of sound along each of the five acoustic paths around the abrupt change of the flow velocity displayed in Fig.7.

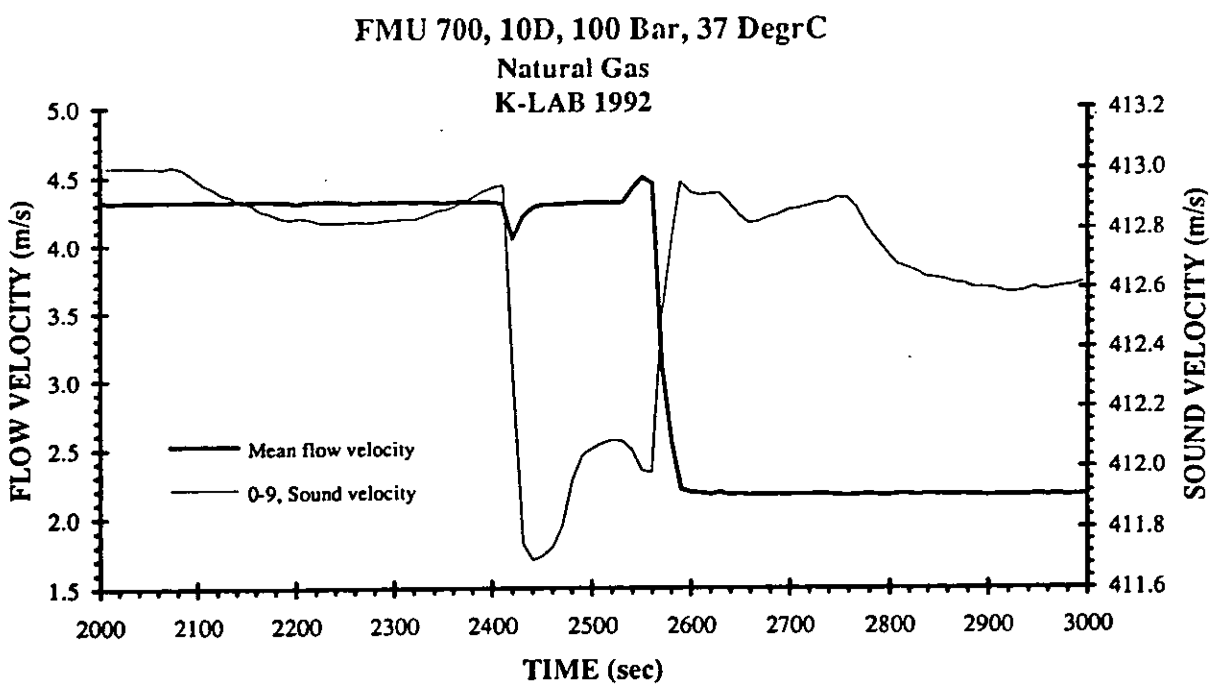

Figure 9 Tests at K-lab. The mean flow velocity and the speed of sound along one of the acoustic paths are plotted on top of one another to show the simultaneous change of both measured values.

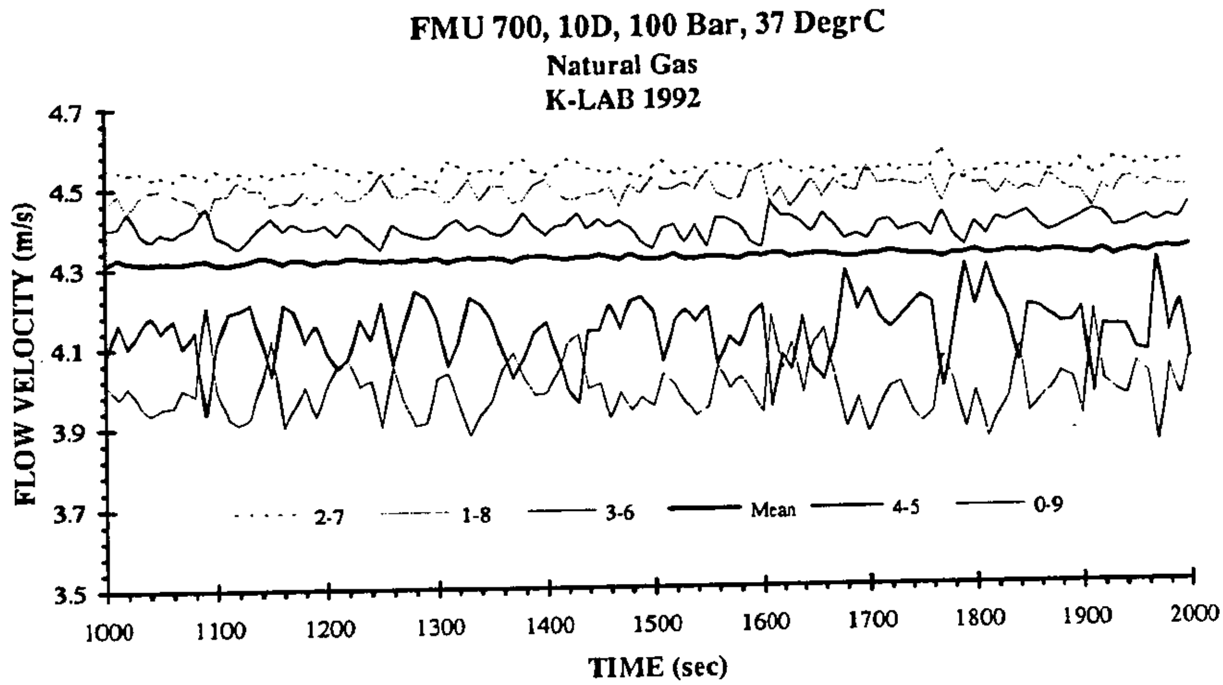

Figure 10 Tests at K-lab. Showing the turbulent fluctuation in mean flow velocity and velocities along each of the five acoustic paths at a constant flow rate. Notice the correlation and inverse correlation effect between the turbulent fluctuations along different acoustic paths.

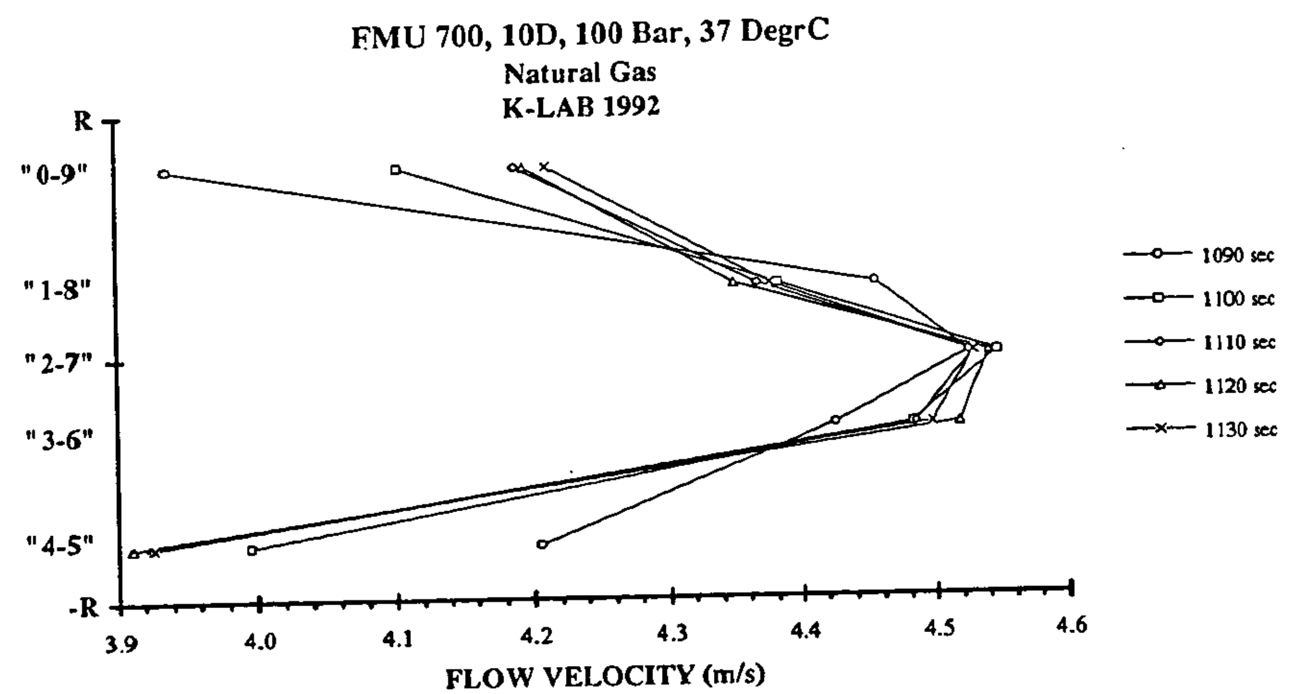

Figure 11 Tests at K-lab. Showing an extract of the time series from Figure 10, with the flow velocity along the five paths plotted as a profile, with time as parameter. Notice the correlation and inverse correlation effect between the turbulent fluctuations along different acoustic paths.

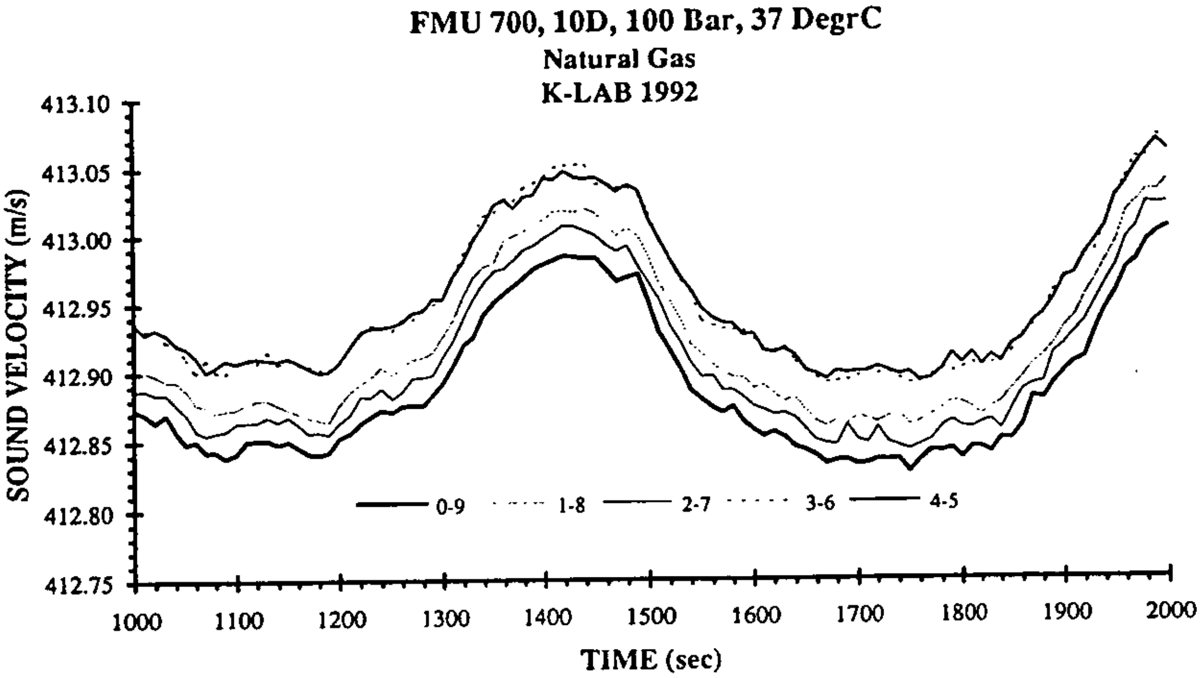

Figure 12 Tests at K-lab. Showing the fluctuations of the speed of sound along each of the five acoustic paths.

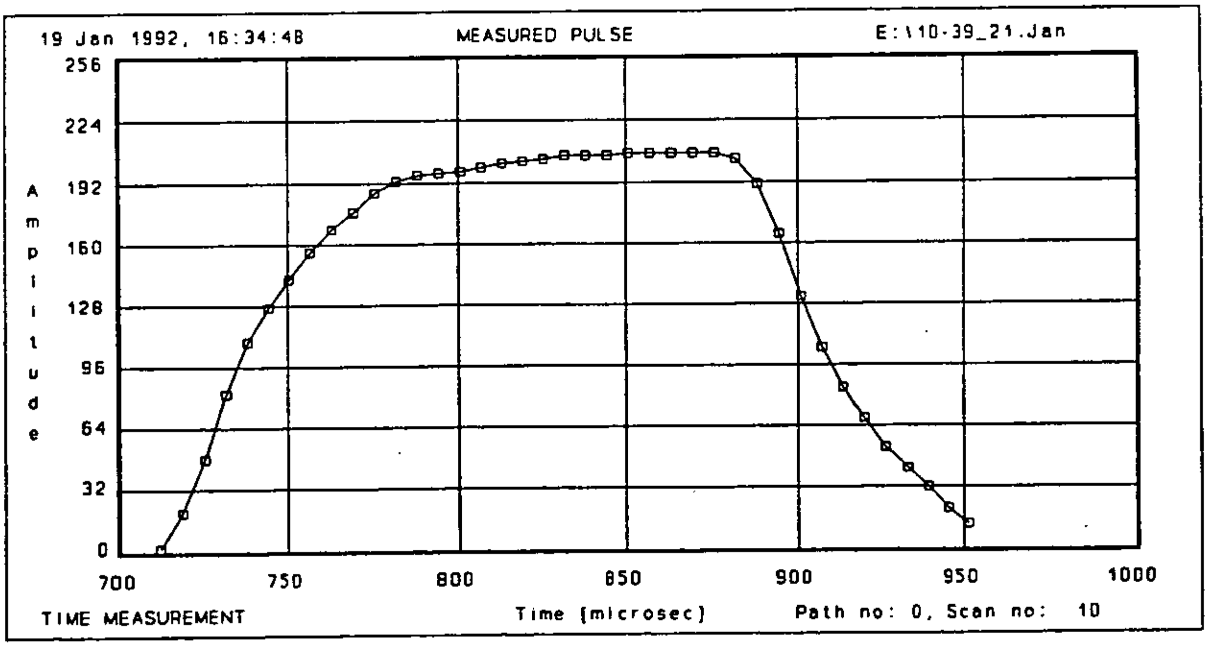

Figure 13 Tests at K-lab. Received ultrasonic pulse representation showing peak amplitude and negative going zero-crossing time for each period of the received pulse.

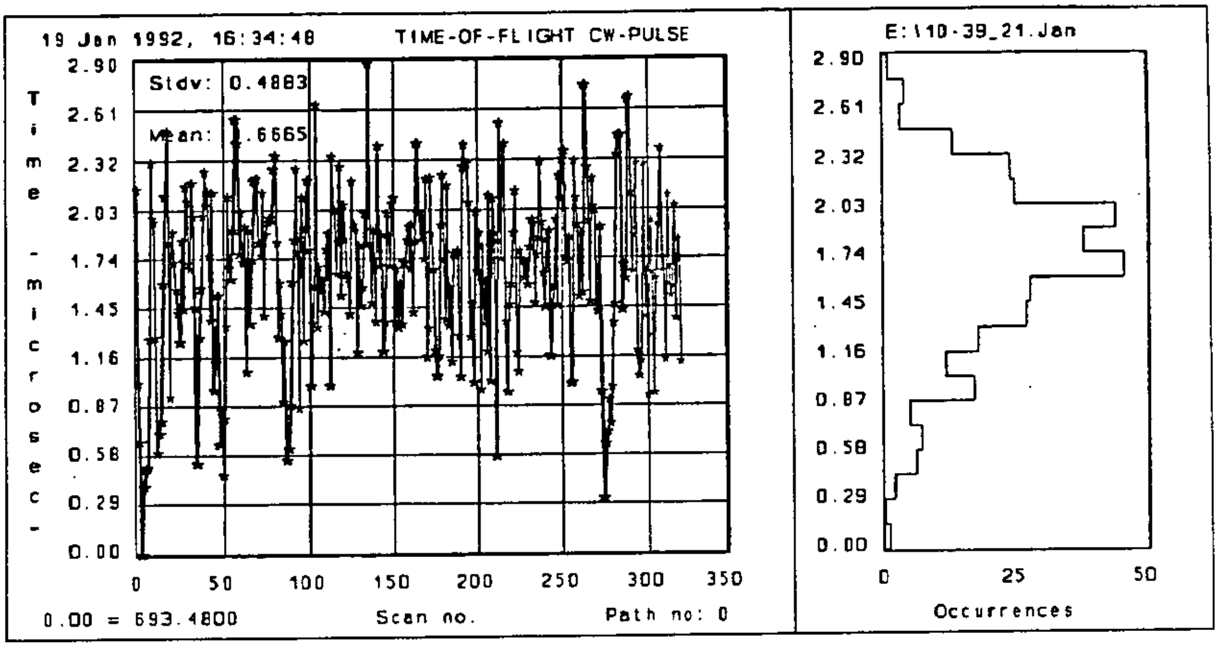

Figure 14 Tests at K-lab. Time series and distribution of computed times-of-flight for a single path at 8 m/s.

5 SPECIAL FEATURES

In the following we will highlight some of the technical achievements which are of particular importance to the users. Particularly the FMU 700 features :

Titanium housed ultrasonic transducers which eliminates the risk of gas penetration into the transducer and subsequent transducer failure.

Automatic gain control keeping the amplitude of the received ultrasonic pulses at a constant level. This makes it possible for the flow meter to operate over a wide temperature, pressure and flow velocity range without any manual adjustment of the electronics. If automatic gain control is lacking, the flow meter will cease to operate if e.g. the pressure changes.

On-line measurement of transit time delay in cables and electronics is implemented and accounted for in the transit time measurement. In most ultrasonic flow meters fixed values for these time delays must be implemented in the flow computer and drift in the transit time delay will not be accounted for.

Software pulse detection eliminating electronics for pulse detection and making it possible to implement a signal processing technique which is able to recognize pulses modulated by turbulence effects, pressure and temperature changes. Accordingly the flow meter reliability is improved.

The geometrical arrangement of the ultrasonic transducers and the corresponding integration technique, see Eq. (5), was developed as result of extensive numerical simulations where various methods were investigated. Based on set of 34 flow profiles an adaptive and robust integration method was developed particularly designed to integrate asymmetric flow profiles.

The flow computer concept, based on an industrial PC, has several advantages since this solution results in :

A less complex flow meter electronics,
Easy access to flow meter raw data which makes service and testing simple,
Simple procedures for upgrading flow computer software, e.g. diagnostic software,
Use of standard equipment which is under continuous technological improvement,
A computer environment most operators are familiar with.

The technical solutions implemented in the FMU 700 flow meter, thus represent a general improvement of the ultrasonic flow meter technology and will help to improve the flow meter reliability.

6 PROVING

An important aspect of the introduction of multi-path ultrasonic flow meters for fiscal or allocation measurement of gas, is the proving procedure for the meter. In the following we will discuss some possibilities and propose a practical solution as to how proving can be carried out.

The following procedure is suggested for proving of a multi-path meter in a fiscal metering station :

1. Zero calibration of flow meter when delivered from manufacturer.
2. Flow calibration prior to installation in the metering station.
3. Use of the flow meter's self diagnostic properties to indicate if and when zero calibration should be repeated.
4. On-site zero calibration of individual transducer pairs which are removed from the pipe line and installed in a zero calibration cell.

In addition to the above items it is fully possible to increase the redundancy by installing two meters in series. Since the flow meters are non intrusive they can be installed close to each other, potentially "flange to flange".

In the following we will describe the proposed procedure with reference to the experimental experience gained during the testing of the FMU 700.

6.1 Zero calibration

The basic measured parameter is the acoustic transit time in the flowing gas, see Eq.(2). However, the measured transit times also contain the transit times in the acoustic transducers and the accompanying electronics. Thus, the measured transit time must be corrected for these time delays. It is of particular importance to ensure that the flow meter reading is zero when the gas it at rest, i.e. the transit times in the gas in each direction along the same path must be identical at zero flow. It is easy to measure the transit time difference accurately. But, the absolute time delay is more difficult to measure. Accordingly the transit time difference at zero flow is measured precisely and the less accurate measurement of the absolute time delays are adjusted to secure zero measured flow in a gas at rest.

When the time delays and the transit time differences have been measured they are stored in the flow computer. During flow meter operation, the measured transit times are corrected prior to calculation of the flow velocity by Eq.(2).

The FMU 700 was zero calibrated by pressurizing the spool piece using nitrogen. Before pressurizing the spool piece, the distances between the acoustic transducers were measured with an uncertainty of 0.04mm. To ensure stable conditions, i.e. no thermal flows, the pressurized spool piece was kept in a temperature bath during calibration. The transit times were then measured over the pressure and temperature range in question. Based on the transit times, the transit time difference corrections were calculated. Using the measured transducer distances, corrected for thermal expansion, the time delays and the speed of sound in the gas were calculated. For control purposes the measured speed of sound was compared to calculated values using the IUPAC-tables[5]. The deviations between the measured and the calculated values were less than 0.5 m/s, i.e. 0.15%. The measured "zero calibration times" were subsequently stored in the configuration file of the flow computer.

At present we are working on a new method for zero calibration which may represent a significant improvement and simplification of the above procedure. The new method will soon to be tested at CMR.

6.2 Flow calibration

The zero calibration ensures that the inherent offset in the measured transit times can be accounted for when calculating the velocity using Eq.(2). This offset is independent of the flow velocity. Due to the simple relationship between the flow velocity and the transit times given by Eq.(2), where calibration constants are not required, it should not be necessary to carry out a flow calibration. When the transit times are measured correctly, Eq.(2) will provide the flow velocity without the use of additional calibration constants.

As described above the FMU 700 was zero calibrated on nitrogen prior to transportation and installation at K-Lab. The acoustic transducers were not removed from the spool piece after zero calibration. The meter was zero calibrated at 37 °C (normal operating temperature at K-Lab) and then transported to K-Lab. During the transportation the meter was exposed to temperatures around 0 °C and then installed at K-Lab and warmed up to 37 °C again. During the test period the meter was exposed to temperature cycling between normal operating temperature and ambient temperature (0 °C) on several occasions. The observed deviations shown i Fig. 4 were obtained without any adjustment of the flow meter after zero calibration at CMR. The meter was simply installed and the tests begun. It is of considerable practical importance to notice that the zero calibration was carried out without the long signal cables (approx. 130m) which were used at K-Lab. This is possible because the FMU 700 features on-line measurement of the transit time delay in signal cables, safe area electronics and parts of the intrinsically safe electronics.

During the test period we did not observe any detectable drift in the zero calibration. This verifies that it is not necessary to carry out a flow calibration if the meter is properly zero calibrated.

However, for fiscal purposes it is likely to assume that a flow calibration will be required.

6.3 Self diagnostics

Ultrasonic flow meters offer the possibility to monitor the flow meter performance to a certain extent. This can be utilized both as an indicator of when proving is necessary and to reduce the work load connected to inspection and maintenance. If an abnormal situation occurs a message will be written to the system log in the flow computer and/or a warning can be given to the operator depending on the nature of the detected error.

In the FMU 700 meter the following meter performance parameters can be monitored continuously :

- Comparisons of the measured speed of sound along the five acoustic paths,
- Transducer failure,
- Transit time error,
- Frequency modulation of pulse,
- Failure to recognize received pulse,
- Measured versus calculated speed of sound,
- Standard deviation of the speed of sound measurements,
- Standard deviation of the flow measurement.

Based on the above diagnostic parameters ultrasonic flow meters can detect meter malfunctioning and give the operator a warning in contrast to e.g. an orifice meter where it is nearly impossible to detect a change in the meter performance.

Comparisons of sound speeds

If the properties of the acoustic transducers or the electronics change with time this may lead to a drift in the zero calibration, and the flow meter uncertainty is likely to increase. It is particularly important to avoid drift in the measured transit time difference in Eq.(2). Drift in the absolute transit times is far less important.

In a multi-path meter the speed of sound in the gas is measured for each path. If the pipeline is properly insulated, the temperature difference between the area close to the pipe wall and the central portion of the pipe will be very small (if any). Consequently the speed of sound will be constant across the pipe section and the measured speed of sound along the paths should be equal. For very low flow velocities and large temperature difference between the gas and the surroundings, a small temperature gradient may be present. This was in fact observed at K-Lab.

During the K-Lab tests, the difference between the maximum and the minimum values of the measured speed of sounds were typically less than 0.07 m/s, (0.01%), even during abrupt changes of the flow velocity, see Figs. 8 and 12. This difference is due to the measurement uncertainty of the transit times (not the transit time differences) or inhomogeneities in the flow.

If this difference exceeds 0.1m/s, i.e. a change of 0.04m/s, this may represent a drift in the transit time difference measurement of 100ns. At 5m/s a 100ns drift corresponds to a shift in the calibration of the meter of around 1%. Thus, there is a potential for detecting a change in the calibration of the meter by continuously monitoring the difference of the measured sound speeds.

However, the speed of sound is proportional to the sum of the transit times and not the transit time difference. Accordingly, changes in the measured speed of sound can also occur even if the transit time difference is unaffected. At CMR more work will be undertaken to establish a procedure for using the speed of sound difference as a diagnostic parameter.

Measured speed of sound versus calculated

Based on measured temperature and pressure and a specified gas composition, the speed of sound can be calculated. Comparing the measured and calculated speed of sound, can be used as a rough, but independent, check of the transit time measurements.

Transducer failure

If one of the acoustic transducers fail and is unable to emit or receive an acoustic pulse, this will be detected immediately and a proper warning will be given. If a transducer pair drops out, the flow meter is still able to measure the flow by using the transducer pairs in operation to estimate the velocity along the path which has dropped out.

Nonphysical transit times

Nonphysical transit times, i.e. transit times which cannot occur based on the known distance between the acoustic transducers and known upper and lower limits for the speed of sound, will never be measured due to the time gating system incorporated in the flow meter.

Pulse recognition

The percentage of pulses recognized by the flow computer is monitored continuously and will be stored in the system log. Normally 100 % of the pulses are recognized by the flow computer. During transducer malfunctioning, heavy turbulence, electric or acoustic noise, the percentage of pulses accepted may be low and a warning will be given.

Pulse frequency check

Every accepted pulse is checked for "period error", i.e. if for some reason a pulse period is missing. If a "period error" is found the pulse is rejected.

The frequency content of every recognized pulse is checked and strict limits are set for the allowed variation of the pulse frequency around the known frequency of the emitted pulse in order to ensure a high-quality transit time measurement. If these limits are violated the pulse is rejected and the number of rejected pulses is monitored and will be stored in the system log. If the number of rejected pulses is high, a proper warning will be given.

Filtering

When the transit times have been computed a filtering algorithm checks the measured set of transit times for outliers. This filtering is based on the measured transit time distributions. Transit times lying outside the allowed spreading are discarded from the data set which is used when calculating the flow velocity.

Standard deviation

The standard deviation of the measured flow velocity and the measured speed of sound are calculated for each path, see Figure 6. The standard deviation can be used as a meter performance parameter as well as an indicator of the stability of the flow.

6.4 On-site zero calibration

Ideally, it should be possible to carry out zero-calibration of the flow meter on-line, i.e. when the meter is installed in the pipe line. This implies that the flow must be bypassed and it must be possible to keep the gas in the spool piece at absolute rest at a constant temperature. In a practical measurement situation this is not easily obtained. However, "in-line" zero calibration may be a future possibility.

On-site zero calibration can e.g. be carried by:

By removing the meter from the pipe line and installing the spool in a zero calibration facility. This requires the flow to be bypassed in addition to the mechanical work needed to remove the meter spool.

By removing a single transducer pair and the corresponding electronics and carry out zero calibration of only one transducer pair at a time in a special zero calibration facility. In this case it is not necessary to bypass the flow and the meter will be able to operate at a slightly reduced uncertainty.

The latter method is by far the best method from an operational point of view. The acoustic transducers can be removed from the pressurized pipe line either by installing permanent ball valves at each transducer port or by using an extractor tool which can be moved from one transducer port to another. Both techniques are being considered for the FMU 700.

The zero calibration facility will be a pressure cell which should be immersed in a temperature bath and pressurized with nitrogen. Ideally the cell should resemblance the meter spool as much as possible. This is important in order to ensure that the sound diffraction effects in the flow meter and in the calibration cell are as similar as possible. This may be of importance for the measurement of the transit time delay. After zero calibration the transducers and the electronics are reinstalled, and the transit time delays in the flow computer are changed if necessary.

In order for such a procedure to work it is important that the distance between the transducers is unaffected by the dismounting and reinstallation of the transducers. At CMR the distance between the transducers was measured before the sensors were removed and after they had been reinstalled. The distance did not change more than 0.03mm , and this is well below the acceptable limit, i.e. 0.1mm.

Since the FMU 700 measures transit time delay in signal cables, safe area electronics and the intrinsically safe electronics on-line, this zero calibration method is particularly attractive for this meter.

7 CONCLUSIONS

A new multi-path ultrasonic flow meter for gas has been developed and tested on natural gas.

The development has contributed to major technical achievements within the ultrasonic gas flow meter technology such as titanium housed ultrasonic transducers, automatic gain control, software pulse detection and on-line measurement of transit time delay in electronics and signal cables. These achievements represent a significant improvement of the flow meter reliability.

The test results show that it is quite feasible to build a very compact and light metering station compared to conventional solutions and at the same time comply with the requirements set to fiscal metering stations.

8 ACKNOWLEDGEMENTS

The authors would like to express their thanks to Statoil and Fluenta for the opportunity to publish the project results and for making the FMU-project feasible by providing the necessary financial support.

The authors acknowledge the high-quality work carried out by the rest of the CMR-project team consisting of Reidar Bø, Per Lunde, Atle Johannessen, Magne Vestrheim, Gunnar Wedvich, Hans Ingebrigtsen, Stig Heggstad and Roald Toftevaag.

Further we would like to thank Framo Services and Framo Engineering for doing an excellent job on both design and fabrication of the spool piece and Kongsberg Offshore for providing the secondary instrumentation.

Finally we appreciated the service and the enthusiasm shown by the K-Lab staff during the test period.

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