Index

Paper 3.2

A New Ultrasonic Gas Flow Meter As A Base For A Natural Gas Energy System

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1 INTRODUCTION

Ultrasonic technology has reached a high degree of maturity and is widely accepted throughout the measurement community. But there is still work to be done on technical and economical details until the technology will be as widely used as other technologies, e.g. turbine or orifice meters, and will have reached the predicted market shares [1] .

Additional to the well-known volume flow measuring sites in gas transmission pipelines there is an upcoming need to measure natural gas energy content in remote, arbitrary locations. These are e.g. production fields or gathering lines.

The paper describes an integrated energy measuring system for natural gas. The base is a new ultrasonic meter for fiscal applications. This meter is designed for use in traditional ultrasonic measuring sites as well as in sites, where ultrasonic meters are not applied today. The capability of the whole system to be operated with solar power together with enhanced data transmission and radio communication options make it ideally suited for remote locations. Besides the advantages well known from ultrasonic meters this system provides a real self-diagnostic based on speed of sound check and therefore completes the necessary features for a system operated in distant locations. This will be very important to lower the personnel cost connected with the maintenance of the meter and will provide a better reliability of measuring data.

2 ENERGY METERING SYSTEM UTILIZING ULTRASONIC FLOW METERING TECHNOLOGY

Natural gas is bought and sold in energy units worldwide. No single metering device is currently available which directly measures the energy stream in a natural gas pipeline. Energy metering systems comprised of volumetric gas flow meter, gas-analyzing equipment with automatic samplers and calculator are widely used. The gas flow metering technology applied in such energy metering systems reaches from simple orifice plates, turbine meters to the latest technology ‘ultrasonic gas flow meters’.

The system described here takes advantage of the low energy consumption of its components, which allows the system to be completely powered by batteries charged through solar panels. Alternatively, AC or DC line power can also over each system component.

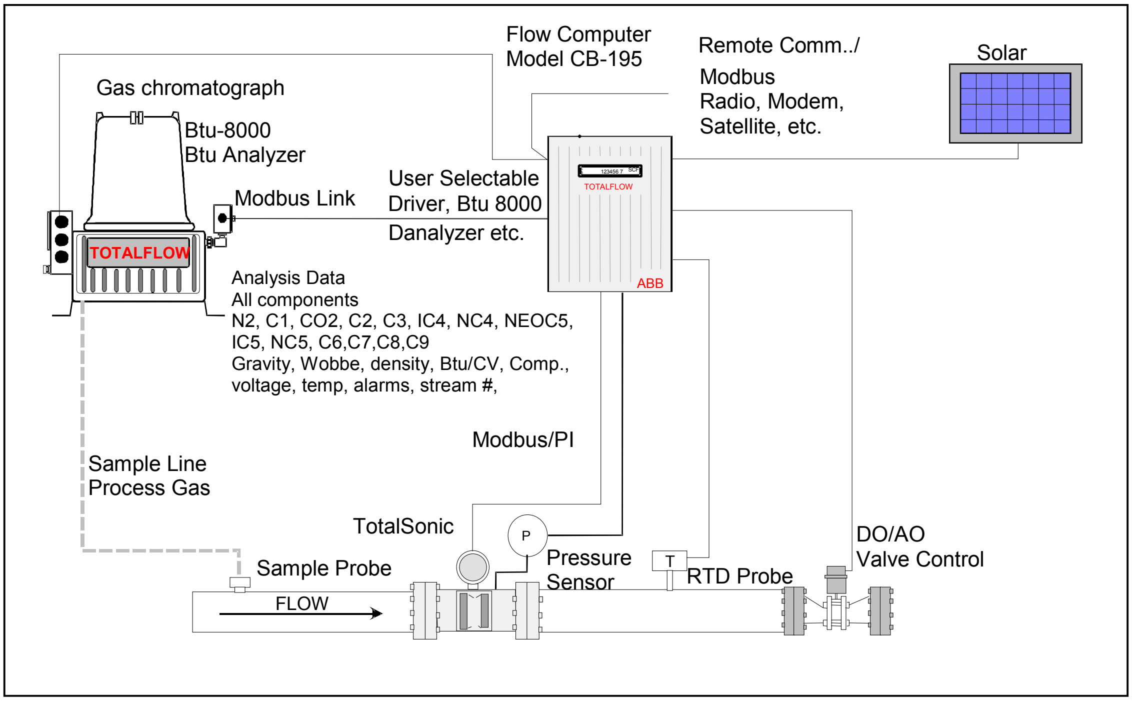

Fig. 1 - Energy metering systems for natural gas

2.1 System Description

The system described in Figure 1 with all its components and instrumentation is required to determine the energy content of natural gas. All major devices are described below.

Volumetric Gas Flow Meter

The energy metering system proposed here utilizes a compact and robust ultrasonic gas flow meter as shown in Figure 2. The sensor technology uses miniaturized ultrasonic transducers with very low pressure and temperature cross-sensitivity. This enables the meter to operate over a wide temperature and pressure range down to ambient pressure.

The volumetric flow rate is determined by integrating the actual flow velocity profile from local gas velocity information received from the ultrasonic paths distributed over the cross-section of the pipe. This information is processed by the onboard computer taking into account the meter's geometry and characteristics. Information about actual measured flow rate, path velocity, speed of sound and counted volume is then passed on to the system flow computer using a digital communication interface.

This compact ultrasonic gas flow meter (Figure 2) has no moving parts and therefore is virtually maintenance free. A wide range of communication options including remote diagnostics reduces the overall required maintenance.

Additional meter information such as path velocities, speed of sound and diagnostic information is available via the serial communication interface.

Fig. 2 - Ultrasonic flow meter TotalSonic

BTU Analyzer

The BTU Analyzer is based on gas chromatograph principle. This device automatically takes gas samples from the gas pipeline and breaks the sample down to determine its molecular composition and heating value with custody transfer accuracy. The resulting information is required to calculate the gas density, super compressibility and its energy content. Using this modern type gas analyzing equipment, information about the gas composition is available within minutes. The on board controller will store the analytical results in registers from which the latest data values can be read by the system computer. These data register are updated whenever a new analysis is completed which is about every 3 minutes.

Standard serial communication links (RS232, RS 422 and RS 485) using Modbus protocol allow easy access to the latest analytical gas data by flow computers, supervisory systems and computers running Man-Machine Interfaces (MMI). Available are 3 remote and one local communication port. Supported communication protocols range from remote/local MMI, engineering interface to printers/consoles, ASCII (HCIA) host computer interface, Modbus, DSFG and PTB printouts.

An overall modular design reduces the mean-time-to-repair from weeks to as short as hours. The required time between calibrations has been extended to months using state of the art digital technology.

System Flow Computer:

It is the metering system's central processing unit that requests the latest analytical information from the gas analyzer, receives the flow rate information from the flow meter as well as pressure and temperature information. Applying certified and by local metrology authorities approved (i.e.: AGA, PTB, NMI, etc.) calculation methods the energy stream in natural gas is calculated.

The capabilities of the flow computer include the trending and archiving of critical data over a user selectable time interval. All stored data can be accessed remotely using the communication option of the flow computer. Available communication options are standard phone line via modem, radio, satellite, etc.

A wide range of software running on stationary and mobile PC's is available to communicate, monitor, access data and diagnose the flow computer remotely or on site (**TF.NET**.; **WINCCU)**

2.2 Communication Interfaces And Data Transmission

The system flow computer communicates serially with the system gas analyzer. Modbus protocols for the Totalflow Btu 8000 gas analyzer and most other industry standard gas chromatographs and analyzing equipment are available. The flow computer is requesting the required information from the data register of the system gas analyzer. If an on-line gas analyzer is not available the required information can be entered into the flow computer and updated whenever new values are available.

Using a state of the art ultrasonic flow meter it is best to use the serial communication interface to the flow computer. Modbus protocols to the TotalSonic and a number of ultrasonic flow meters used in the gas measurement industry are available. Also, frequency and analog flow metering interfaces to other type of gas flow meters are offered.

All process relevant data are stored in the none-volatile memory of the flow computer averaged over a user selectable time interval. This information including trending files and the system monitoring data from the audit trail can be accessed through local and remote communication interfaces using modem, radio, satellite, etc. as shown in Figure 3.

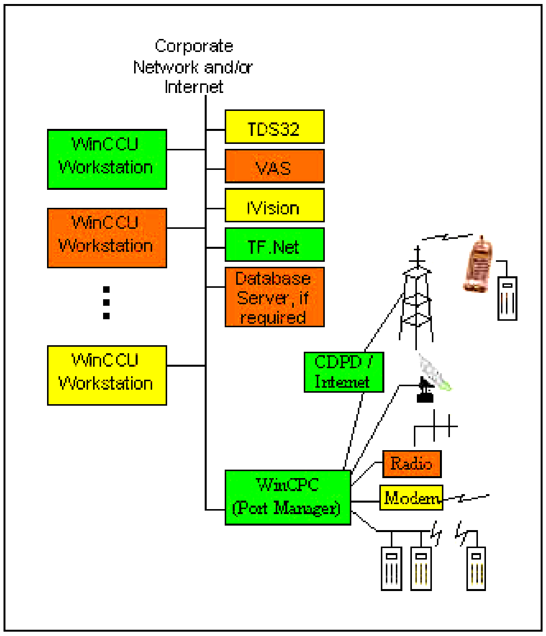

Fig. 3 - Communication with corporate network and/or Internet

2.3 System Health Check

To assure proper system operation and high data quality each component of the system needs to function within set specifications. Therefore each measuring device constantly performs a number of operational and status checks. If problems or maintenance situations occur it is communicated to the system's central commuter, logged and made available to supervisory and/or monitoring systems. Each system component can be accessed with local and/or remote diagnostic software to determine operational status and to analyze problems.

A simple and powerful way to monitor system performance is by comparing the speed of sound information available from the TotalSonic ultrasonic gas flow meter to speed of sound for natural gas calculated from the gas composition analysis available from the gas analyzer. In order to perform this calculation a commercially available software package can be used or the method described in AGA 10 [2] can be licensed and programmed. Such calculations and comparisons will be performed in scheduled time intervals or continuously and customer set deviations and limits will trigger alarms and indicate system performance problems.

3 DESCRIPTION OF ULTRASONIC METER “TotalSonic”

3.1 Operation Principle

The TotalSonic meter uses the well-known principle of transit time measurement. In the meter body ultrasonic sensors are installed to define a measuring path with an angle of 60° to the gas flow (Figure 4).

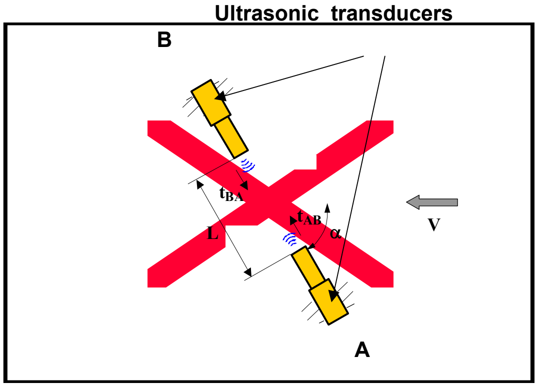

Fig. 4 – Principle of the transit time measurement

Both transducer work as transmitter and receiver. Intermittently they transmit ultrasonic pulses through the gas; once in the direction of flow from transducer A to transducer B, once against the direction of flow from transducer B to transducer A. The pulses sent in the flow direction are accelerated; the pulses in the opposite direction are delayed. The velocity along the measuring path is calculated from the two measured time values and the geometrical constants

$$v_p = \frac{L}{2 \cdot \cos\alpha} \cdot \left(\frac{1}{t_{AB}} - \frac{1}{t_{BA}} \right) \quad (1)$$

v_p - mean path velocity
t_{AB} - Transit time upstream
t_{BA} - Transit time downstream
L - Measuring path length
α - Installation angle

To get a high accuracy at different installation conditions a multipath measurement is applied and the volume flow is calculated as the weighted sum of the path velocities:

$$Q_{ia} = \pi R^2 \sum_i w_i v_{pi} \quad (2)$$

v_{pi} - mean path velocity of path no. “i”
w_i - weight factor for path no. “i”
Q_{ia} - volume flow in actual conditions
R - inside radius

3.2 Path Layout

Path layout has an important influence on the meter performance. Much has been published about different path layouts using typically 3 to 6 paths and applying direct propagation or bounced path technology.

For the TotalSonic meter (Figure 5) it was chosen to use the simplest 4-path layout which is very similar to that proposed by Whyler [3].

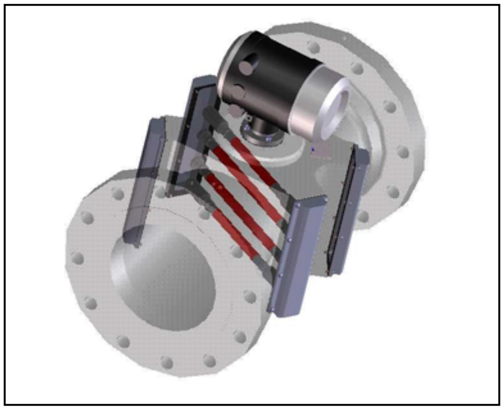

Fig. 5 – TotalSonic path layout

Several reasons support the decision to use a non-bounce multi-path layout:

1. The increased time measuring accuracy of the transducer technology developed by SICK (see below) does not need the extension of the path length. The uncertainty of the measurement contributes to less then 10% for the total uncertainty – even less at large diameter.
2. Not applying bounced path technology removes the reflector place inside the pipe, which can change its characteristics due to contamination or change in wall roughness and therefore lead to an additional uncertainty. The mechanical preparation of the meter body is simplified and reduces the manufacturing costs.
3. A avoiding a reflection saves acoustic energy which can be used to reduce the electrical power input (Intrinsically safe operation Ex ia) and allows to operate even large meters at all operating conditions including atmospheric pressure and gases of low density (H_2) or high acoustic attenuation (CO_2).
4. This special path layout compensates (but does not measure it) very well for measurement deviations due to swirls, which has been proven through numerous tests at high and ambient pressure facilities.
5. Using 4 paths and using a path layout that compensates for swirl instead of 6 paths and measuring the swirl component separately saves cost and helps to bring the cost of the ultrasonic technology closer to that of mechanical technologies.

3.3 Transducer Technology

It is well known that the transducers are the heart and decisive part of the technology. Most commonly used transducers apply so-called acoustic matching layers to match the impedance of the gas and the solid body.

SICK/ABB's transducer technology is based on a full metal design that does not use any of these matching layers (Figure 6). The impedance matching is realized with specially designed acoustic-transformers fully made out of titanium. The driving force is generated as in most commercial systems – piecoceramics.

The design process is based on two strongholds:

1. More than 20 years of transducer design experience that has been used in the field of hot combustion gas flow metering for emission control.
2. Strong theoretical background– all transducers are theoretically modeled using methods of FEM and electromechanical conversion.

Fig. 6 - Transducer

This special transducer design results in the following improvements:

1. Transducer miniaturization makes the above described path layout also useful for small diameters (3 & 4 inch). It allows a compact meter construction.
2. The excellent time measurement precision allows an installation angle of 60° – this reduces the turbulences caused by the transducer port or the parts of the transducers that protrude into the flow.
3. The use of metal acoustic transformers allow a high efficiency – leading to the capability to operate the meter at ambient as well as at high pressures up to 100 bar with one type of transducer.
4. The theoretical model allows an effective control of the design parameters. This results in a negligible pressure or temperature dependency of the transducer performance and no compensation for such effects is required.
5. The lack of a matching layer and temperature sensitive glue allows operating the system at higher temperatures up to 200° C.
6. A high mechanical reproducibility in the manufacturing of the transducer provides very reproducible travel time measurement. This is a precondition for a transducer exchange without changing the meters baseline.
7. High signal strength together with a wide beam allows the measuring at very high gas velocities (depending on meter size up to 40 ... 80 m/sec).
8. High frequencies are applied to avoid problems with interfering noise from installed equipment, i.e. valves.

There are several tools available to design the transducers and to check the results. As an example a method of interferometry is described in [4].

3.4 Speed Of Sound Measurement

The measured flow velocity is proportional to the difference between both transit times. From the sum of both transit times, the speed of sound is derived.

(3) $$c = \frac{L}{2}\left(\frac{1}{t_{AB}} + \frac{1}{t_{BA}}\right)$$

c - actual speed of sound

The speed of sound is a very valuable means of self-diagnostic on a system level. Since the speed of sound is dependant on temperature and (very little) on pressure these values have to be known. Together with the gas composition, which is known in an energy metering system, the speed of sound can be calculated using known models (AGA 10 Draft [2] / SONICWare [5]). The comparison of the calculated and measured speed of sound gives a very strong indication about the health and accuracy of the measuring system including the TotalSonic meter. If the difference is outside a limit of e.g. 0.3% an alarm is generated. The source of error or uncertainty cannot be detected as easily, but the statement system OK can be made with high certainty.

A second, independent, self-diagnostic is made on the meter level, not using the gas composition data. Based on the assumption, that there is no temperature distribution inside the pipe, the speed of sound of all paths should be within a limit of e.g. 0,1 %.

3.5 Meter Construction

It is the overall design goal of the meter (patent pending), that the construction allows the ultrasonic technology to be used more widespread than currently. Such considerations include:

- Simplicity of use, including calibration
- Same footprint and interfacing as other metering technologies (e.g. turbine meter)
- Rugged construction, no external transducer cabling
- Manufacturing technologies that allow price reduction potential without loss of accuracy

The meter body is made using steel casting, resulting in reduced manufacturing and test costs. Precise machining serves for high reproducibility. Shrinking, warpage and the lack of roundness often in conjunction with welding produces, are completely avoided. The meter body is constructed in a way, that it totally encloses all transducers and cabling (Figure 7).

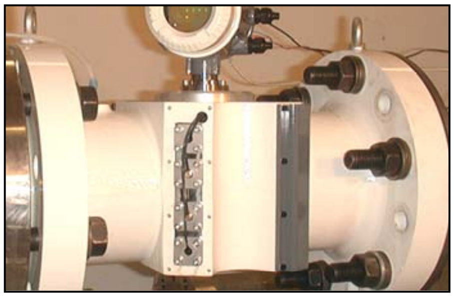

Fig. 7 – A side of 4 transducers and cables without cover

This is important to protect the transducers from environmental influences and it protects the cables from damages caused during transport, installation and maintenance.

The footprint for all meter body sizes is 3 D down to 4” pipe diameter. This is compatible with e.g. turbine meters, therefore the meter can be used in the same installations or even replacing metering equipment, where turbine meters had been before.

All electronics necessary for operating 4 paths, signal calculation and interfacing to the meter are in a small Ex-d housing on top. The interface is compatible with turbine meters on one side (dual pulse outputs) and with modern systems as described above on the other side (Modbus Interlink for the system describe above).

The meter supplies the following values:

- 2 independent volumes counters for both directions, 2 error volume counters
- Volume flow under actual conditions
- Path velocities, speed of sound,
- status (serial Interlink only).

All electronic is made in low power design, allowing a solar panel supply. Control circuitry for the solar panel adaptation is included.

The meter has Ex Certificates according ATEX and CSA and is compliant with the European PED (Pressure equipment directive) and the U.S. DOT part 102 regulations. Custody transfer approvals for several European countries have been applied for, verification tests for North America have been done at SWRI.

3.6 Calibration

Most meters are shipped with a flow calibration with air at ambient pressure today. For fiscal applications a costly high-pressure calibration – sometimes including the complete meter run - is often required.

The TotalSonic meter offers the capability to be calibrated under ambient pressure conditions (if accepted by the customer) as the standard calibration at the moment. Using a Reynolds number correction the baseline for the operating pressure range can be computed and stored into the system file. This results in substantial cost savings.

A procedure as described in AGA 9 [6] is not a real calibration, but an adjustment of all parameters that are influencing the accuracy of the meter to their actual values.

Using new and enhanced manufacturing technologies as described above for all components relevant for the performance of the meter, a real “Dry calibration” procedure could be established in the near future. If we succeed to duplicate an existing primary meter in all components – that is time measuring components like transducer and electronics as well as components defining geometrical dimensions like transducers and the spool piece – the second instrument should have identical performance in a special installation condition compared to the primary meter. That means reproducibility in manufacturing of components and reproducibility of system assembly will result in reproducibility of performance and in foreknown (predictable) accuracy. Additionally calibration costs are saved.

Obviously there are some additional obstacles on this way. Of course “zero” manufacturing tolerances are unrealistic from a technical and economical point of view. Therefore sufficient tolerances have to be established and the resulting scattering of the measurement performance has to be measured on a statistically significant number of manufactured pieces. Since the number of produced meters so far is within the lower hundreds – indeed a significant number in this stage of development – higher quantities are required to support assumptions and theoretical calculation with sound practical data.

4 TEST RESULTS

Several meters (sizes from 4 to 16 inches) were produced in the past to proof the meter performance and manufacturing concept stability. All meters have a 4 path layout, except the 4”-meter. Meters of this size use a 3-path layout. Most of these meters are investigated on ambient and high-pressure test facilities. Different pressures, temperatures and gases (air, natural gases) were used. Due to the ability of the new meter to measure also at ambient pressure conditions, all meters up to a size of 10 inches are at least tested on SICK's own ambient pressure test rig. The test of the initial prototypes and later the pre-production units where carried out between March 2000 and June 2002 in several test series in Groningen (test rig Gasunie, NL) and San Antonio (South West Research Institute, USA).

During that period the performance of the meters and a wide variety of installation effects where tested. Additionally, the insensitivity to valve noise and the over range performance (up to 83m/s in a 4” pipe) was tested. The systematic investigation of the collected data shows a Reynolds number dependency. A correction for this effect is now implemented in the software.

The data presented here are examples of these measurements, which show some interesting aspects regarding the behavior of these meters. Initially, the measurements where made without Reynolds number correction, this correction was applied afterwards to the raw data. To proof the right implementation of the correction in the firmware of the meters the last test series in June 2002, which covered especially low flow aspects, was done with implemented

Reynolds number correction. The results showed, that the implementation improves especially the low flow performance and works without problems (see low flow verification).

With 3 small size meters of 4, 6 and 8 inches each, a test campaign using the low-pressure-loop of the GRI test facility in San Antonio was carried out. The low-pressure-loop provides the ability to set up long, undisturbed inlet piping (up to 100D) as well as typical disturbed flow situation (see Figure 8). Also one of each meter size was double checked on the "Gas Unie Research" test facility in Groningen.

Fig. 8 - Test setup SWRI

Fig. 9 – Testmeter (3x4" and 3x6"meter)

The main focus of these tests was:

- determination of measurement accuracy
- checking the reverse flow performance
- the meter response to flow conditioners
- the meter response to disturbed flow situations
- determination of the "dry calibration" uncertainty

To check the meter's stability regarding pressure, temperature and gas compositions, further investigations will be done.

4.1 "Dry Calibration" Results

To check the "Dry calibration" accuracy every meter was installed in an near "ideal" flow situation. This means the longest possible straight pipe length in the testrig upstream of the meter. The flow profile can be considered as nearly fully developed velocity profile. All nine tested meters performed very well (Figure 10). Every presented data point is the mean value of 6 repetitive measurements over 100 seconds each. The loop was running with natural gas and stabilized at 13bar pressure and 20°C temperature. The meter error was always below the A.G.A. No.9 [6] error limit specification of +/- 1% for a small size meter. In addition, all tested meters reached the +/-0.7% limit specification of a large size meter. The flow-weighted mean error (FWME) over the tested flow range was calculated and then the derived calibration factor applied for each meter. Therefore the results in the next sections show always the deviation of the meter from its ideal flow baseline calibration.

Table: 1 Summery Of The Applied Adjust Factors

Calibration Factor	*4" meter*	*6" meter*	*8" meter*
	0,9966	0,9990	1,0018
	1,0015	1,0030	0,9992
	1,0064	0,9978	0,9988
average	1,0015	0,9999	0,9999
$2*S_x$	0,69%	0,39%	0,23%

The Table 1 shows the calculated calibration factors, their mean and the estimated standard deviations for a 95% confidence level (S_x).

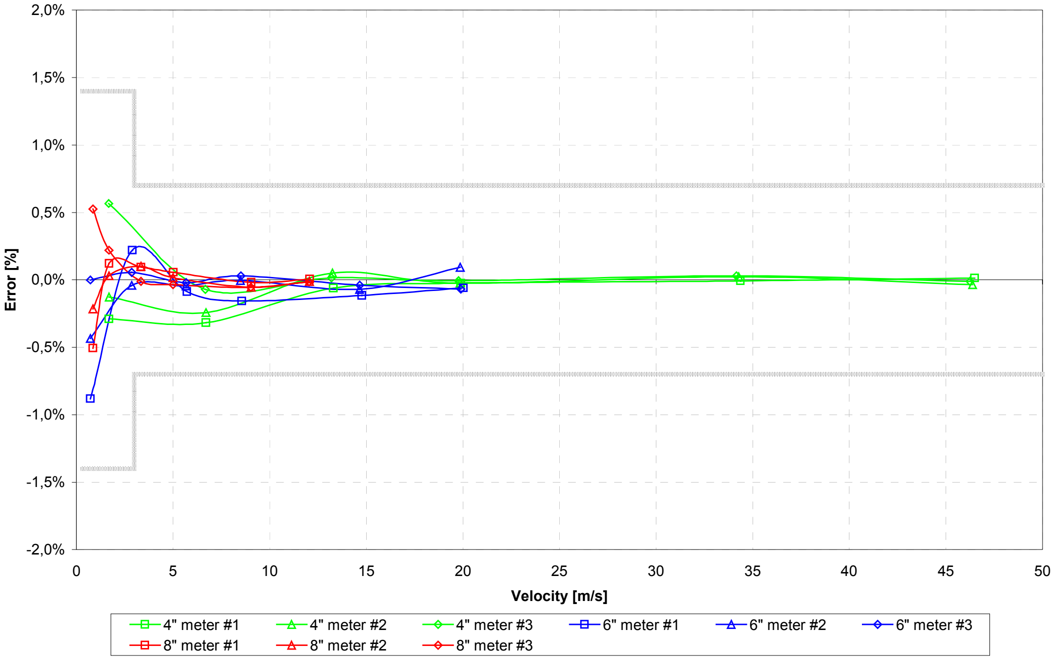

Fig. 10 – Adjusted meter performance for all meters

Most of the other tests were carried out only with one meter of every size due to the limited time and cost frame.

4.2 Reverse Flow

The tests have shown different calibration factors for forward and reverse flows, although the meters were designed symmetrically. This effect tends to get smaller with increasing meter size.

Table 2: Adjust Factors For The Reverse Flow Tested Meters

Calibration Factor	*4" meter*		*6" meter*		*8" meter*	
	forward	*reverse*	*forward*	*reverse*	*forward*	*reverse*
	0,9966	1,0081	0,9990		1,0018	
	1,0015	1,0040	1,0030		0,9992	
	1,0064	0,9974	0,9978	1,0008	0,9988	0,9991
average	1,0015	1,0032	0,9999		0,9999	
$2*S_x$	0,69%	0,76%	0,39%		0,23%	

Also the results of these tests where always within the error limit specifications of A.G.A. No.9. [6] The scatter of the reverse flow adjust factors is in the same order as the results for the forward flow tests (see Figure 11).

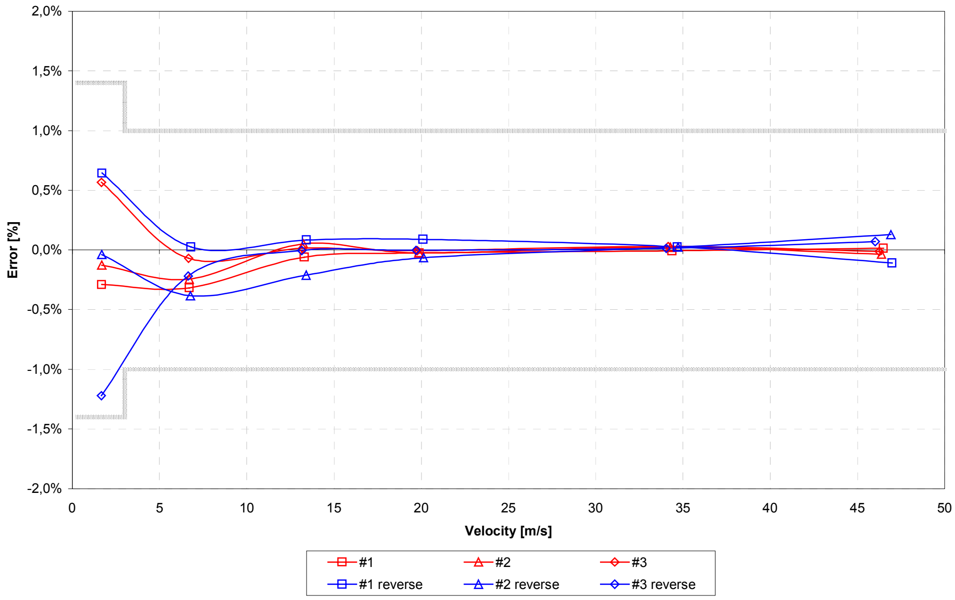

Fig. 11 – Adjust meter performance forward and reverse flow, size 4

4.3 Influence Of Flow Conditioners

Induced in published test results of other ultrasonic meter path layouts, the response of the meter to flow conditioners was investigated. The tests were carried out with the commonly used 19-tube bundle design (Figure 12) and with the CPA 50E plate (Figure 13), as an example for the perforated plate design.

Fig. 12 - 4” 19-tube bundle flow conditioner

Fig. 13 - 4” ANSI CL150 CPA 50E plate [7]

Once again the “ideal” flow situation piping was used. The 19-tube bundle was installed 5D upstream and the CPA 50E plate 8D upstream (manufacturer recommendation).

The influence on the meter performance is shown as to be less then ±0,2% and therefore negligible (Figure 14).

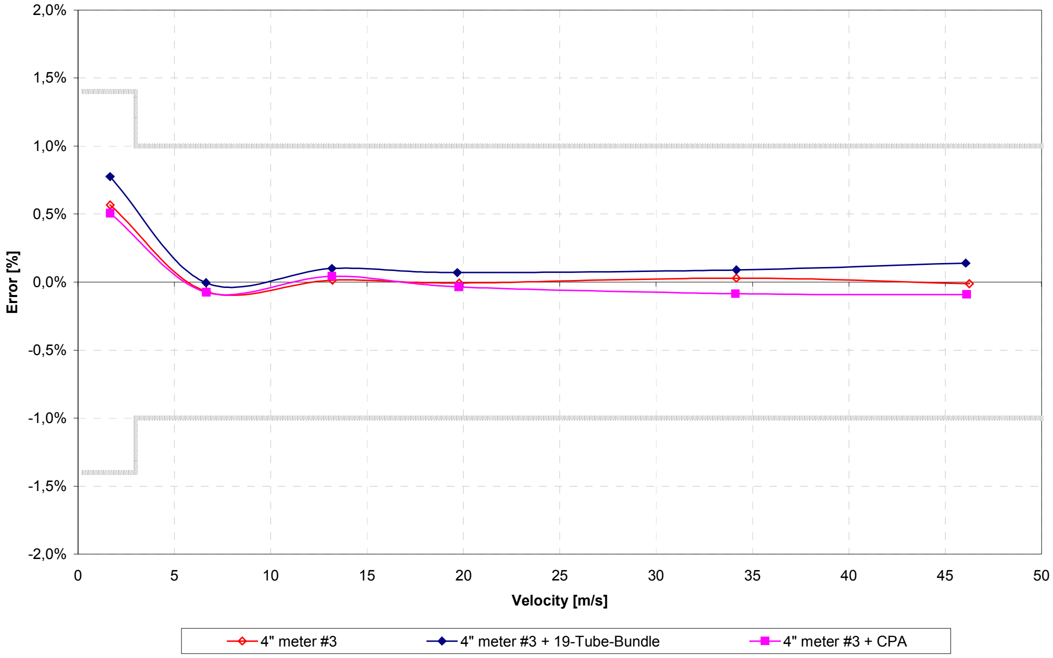

Fig. 14 – Response to flow conditioner, 4” Size

4.4 Disturbed Flow Situation

Commonly an “ideal” flow situation is not possible in practical installations. Often the meter has to deal with limited space and therefore limited straight upstream pipe length, valves and elbows. The chosen disturbed flow situation under test was a configuration with a double elbow out of plane and a distance of 13D to the meter (Figure 15). The 13D was split in 8D and 5D. So it was possible to install a flow profiler between the disturbance and the meter.

Fig. 15 – A tested 6”-meter installed 13D behind a double elbow out of plane

The result shows that the 4-path layout is insensitive to these typical practical flow disturbances and does not need a flow profiler.

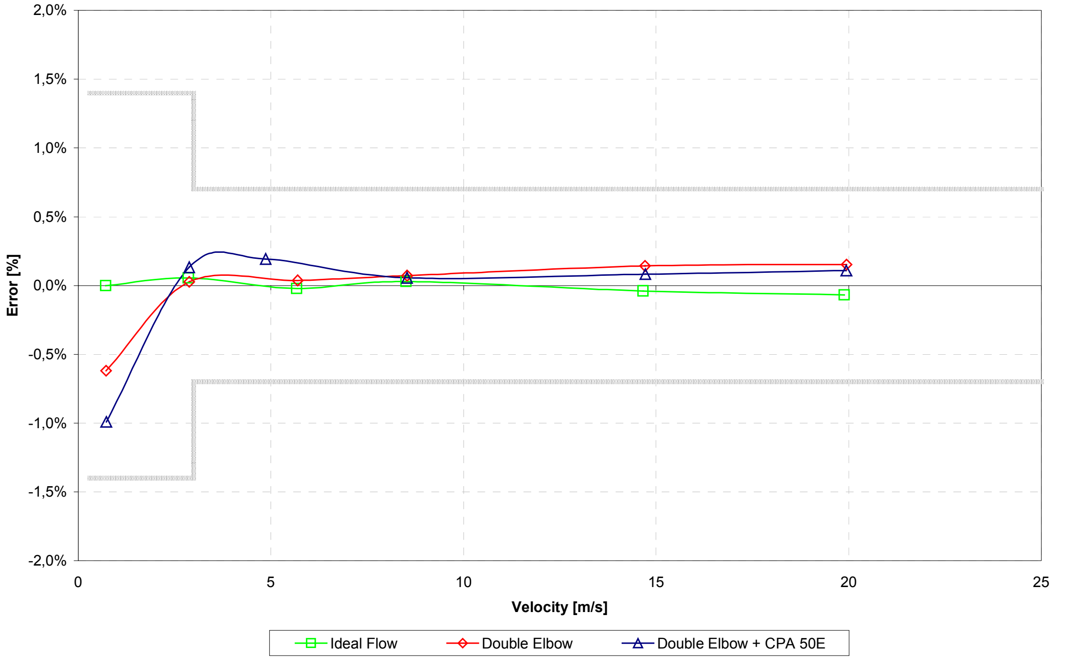

Fig. 16 – Disturbed flow situation, 6" meter

4.5 Low Flow Test

As mentioned above there was a need to improve the systematic error curve at the low flow end taking into account the Reynolds number (see Figure 17). Therefore an additional test was carried out to proof the implemented correction. Figure 18 shows the good performance down to velocities of 0,3m/s. It should be mentioned that, caused by ambient temperature changes between 30...40°C during these tests, it was difficult to stabilize the gas temperature. The result is a data scattering of several percent at very low flows. Longer averaging times and double data points were used to calculate the mean values.

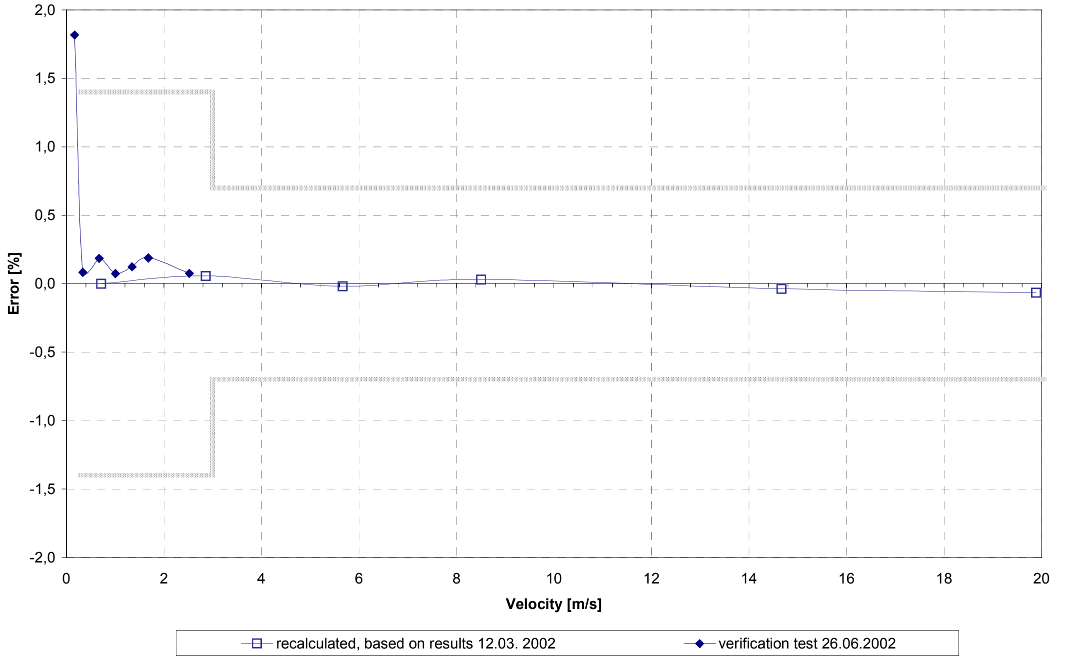

Fig. 17 – Low flow performance, 6" meter

5 FIELD INSTALLATION

Meter installations on the “Verbundnetz Gas AG” underground storage facility in Kirchheilingen, Germany (Figure 18) were used to gain more experience on field installation effects during the whole development period of the meter. This application provides a wide variety of flow and pressure situations. Varying pressures (between 20 and 52 bar), periods with a wide range of different flow rates and also periods with no gas flow. The first prototype meter was installed in Spring 2000. This 8”, 3-path meter was in stable service for more then 2 years.

Fig. 18 - Picture of the installed 8”-meter in Kirchheilingen

Starting in August 2001 a 6”- and an 8”-meter are installed and in operation (Figure 19). Both meters are referred to an Elster reference turbine meter. This meter run was recently complemented with an ABB flow computer. All meters are connected over frequency outputs to the flow computer. Additionally, the ultrasonic meters are linked by RS485 MODBUS interface to the flow computer. The flow computer provides data collecting and averaging of all three meters. Every 100 seconds a normalized flow value of each meter is stored. Also the deviation for every ultrasonic meter to the turbine meter is calculated and stored. The ultrasonic meter provides via the MODBUS interface diagnosis information such as velocity, speed of sound, gain level and signal-to-noise-ratio on each path. By a remote communication connection to the flow computer (a radio communication setup is planned) a health check can be performed very easily from remotely.

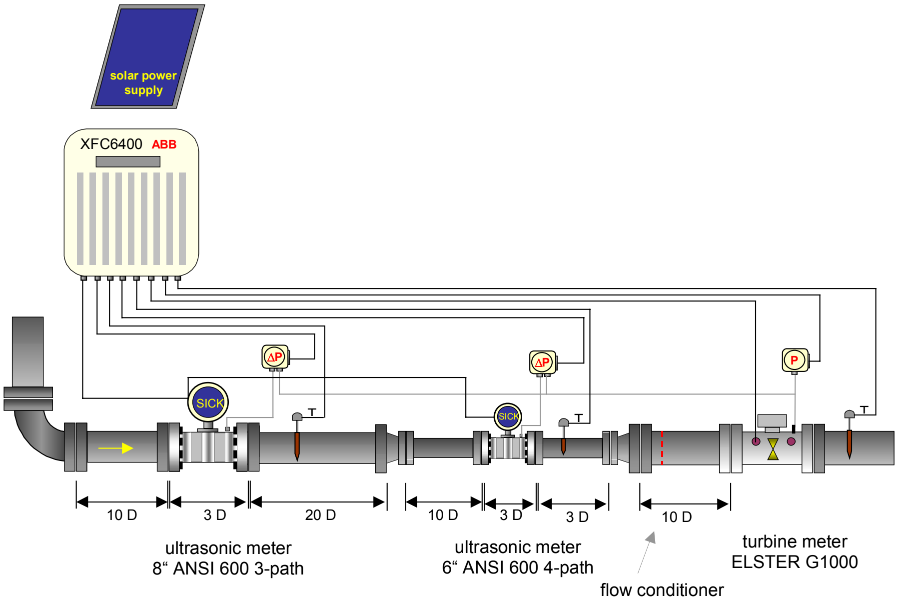

Fig. 19 – System configuration

A "repeatability" test was carried out several times during the last months. The flow was varied between the possible min. and max. values. As shown in Figure 20 and 21 for the 8"- and the 6"-meter the long-term repeatability is always better then ±0,4%. Periodically visual transducer inspections show contamination on the transducer membranes. Normal higher hydrocarbon waxes caused the contamination and very small carbon particles from upstream installed filters. Also fluids, which were used as tracer particles during flow profile measurements with a Laser-Doppler-Anemometer where found on the membranes. Obviously this contamination produces no performance shift.

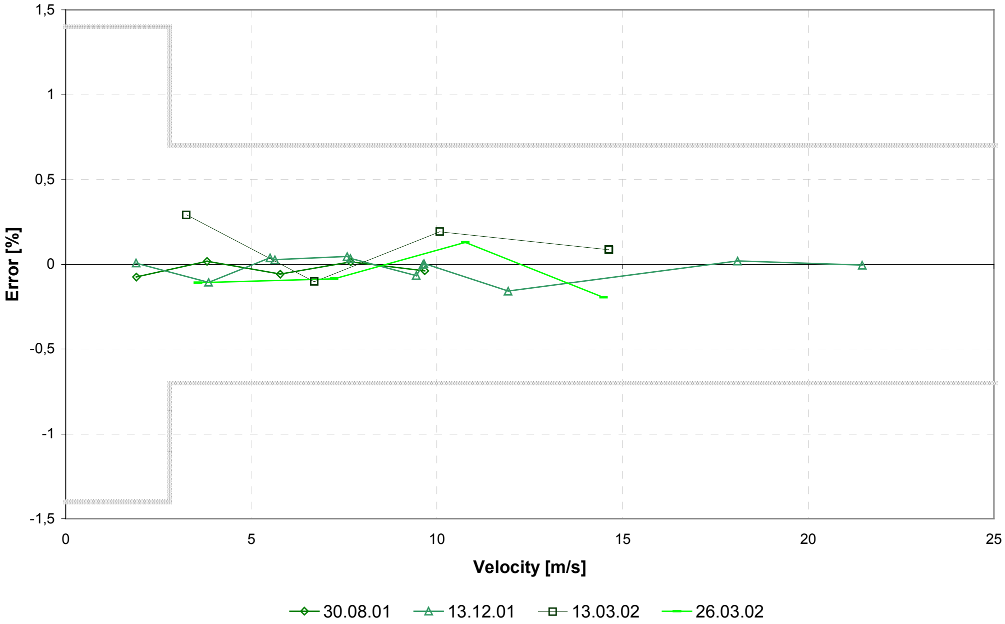

Fig. 20 – Field installation 6" meter, Kirchheilingen,

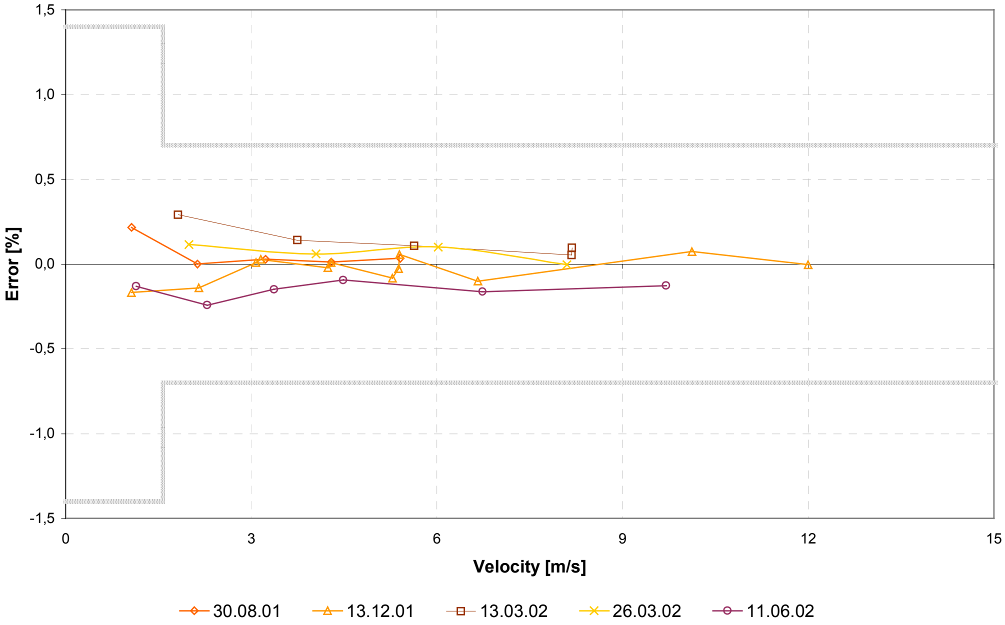

Fig. 21 – Field installation 8" meter, Kirchheilingen

6 SUMMARY

The new energy measuring system presented is based on well-known ultrasonic technology but offers a number of innovations. It shows not only a very compact meter for field use but also demonstrates the tight integration of the measuring system including solar power and radio communication to enable an use in remote locations.

We believe the system will contribute to create further impetus to the ultrasonic technology.

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