## Global Flow Measurement Workshop
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## Extended Abstract

### Measuring hydrogen and hydrogen enriched natural gas flows with ultrasonic flow meters – experiences and perspectives

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**PREAMBLE**

The flow measurement of natural gas with admixed hydrogen and of pure hydrogen is gaining importance in the context of decarbonization of energy supply.

Ultrasonic flow measurement has set a new standard in terms of reliability, durability, and measurement accuracy over the last two decades in both the natural gas and process gas industries. However, due to its very high speed of sound and low density, hydrogen presents a physical challenge for ultrasonic flow meters. Both the challenges and the necessary adaptations to the device design and signal analysis of the ultrasonic transducers are discussed. It is shown that adapted ultrasonic gas meters are well suited for hydrogen-containing gases as well as for measuring pure hydrogen.

In addition to the primary measurement values and the required high accuracy, ultrasonic meters offer further advantages such as a large flow range, very high flow rates ("energy-equivalent transport of hydrogen"), low pressure drop and diagnostic capabilities. In particular, the precise measurement of speed of sound also provides opportunities for gas composition analysis. For example, the hydrogen content can be determined when the composition of the natural gas is known. This provides a sustainable alternative or complement to hydrogen content measurement.

## 1 INTRODUCTION

In the decarbonization of the energy supply renewable energies, especially those generated from wind, water, or the sun, are playing an increasingly important role. For maintaining a stable and affordable supply of energy natural gas will remain an important energy source for many years to come. In the search for alternatives, hydrogen is coming into focus as an additional energy carrier [1, 2].

But also, energy storage is becoming more important, not only to come closer to the goal of a $CO_2$-neutral energy supply, but also against the background of fluctuating, especially weather-dependent energy generation on the one hand and seasonally fluctuating consumption on the other.

The production of hydrogen from renewable energies and its feeding into existing gas networks will play an important role, as a bridging technology towards a $CO_2$-neutral energy supply [3, 4]. Hydrogen can be generated in places with high availability of renewable energy. It furthermore can be stored and transported as an additional energy carrier via the existing gas grids to the consumer. In the existing natural gas distribution system, hydrogen content of up to 30 vol% can be stored and transported. Networks for pure hydrogen will initially be expanded on a regional basis. These will then gradually grow together to finally be able to form larger networks. Estimates for a Europe-wide hydrogen transport network assume 40,000 km that can be created by 2040 [5].

The change in gas composition creates new metrological challenges for the various meter technologies. In addition to the material-technical issues, these are above all the effectiveness of the measurement principles used with the changed media properties. Against this background, the transfer of the quantity measurement in gases, as currently used, with the same precision also for hydrogen-containing gases and pure hydrogen is of fundamental importance [6].

Ultrasonic meters (USM) are suitable for measuring both hydrogen-containing gas mixtures and pure hydrogen. However, for precise flow measurement of gases with very different medium properties, adjustments are also required for USMs.

## 2 ULTRASONIC FLOW METERS - MEASUREMENT PRINCIPLE

Ultrasonic flow meters operate according to the principle of ultrasonic transit time difference measurement. Signal transit times $t_{AB}$ and $t_{BA}$ are defined by the speed of sound (SOS) and gas velocity (VOG). The transit time in flow direction $t_{AB}$ is given by the SOS of the gas and the part of flow velocity in flow direction. Whilst the transit time against flow direction $t_{BA}$ includes the part of flow velocity against flow direction (Eq.(1)). $L$ represents the distance between the ultrasonic transducers opposite to each other, $\alpha$ specifies the angle to the flow direction (see Figure 1).

Gas velocity $v$ is determined from the difference between the reciprocal signal transit times (Eq. (2)). The volume flow is calculated from the gas velocity and the diameter $D_I$ of the measuring section of the gas meter. SOS $c$ is determined from the sum of the reciprocal signal transit times (Eq. (4)).

$$t_{AB} = \frac{L}{c} + \frac{L}{v\cos\alpha}\ ;\ t_{BA} = \frac{L}{c} - \frac{L}{v\cos\alpha} \quad (1)$$

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

$$Q = \frac{\pi}{4} D_I^2 v \quad (3)$$

$$c = \frac{L}{2}\left(\frac{1}{t_{AB}} + \frac{1}{t_{BA}}\right) \quad (4)$$

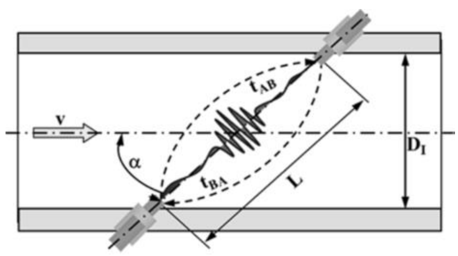

*Figure 1 Measurement principle of ultrasonic flow measurement*

The measuring effect for the flow velocity and thus for the total volume flow results from the difference in the time measurement for the ultrasonic signal in both directions. The SOS results from the total transit time in both directions and is independent of the angle and the flow velocity.

The lower limit of the measuring range for the flow is the temporal resolution, i.e. the transit time difference that can still be measured with sufficient accuracy.

## 3 MEASUREMENT OF GASES WITH INCREASED HYDROGEN CONTENT

Blending hydrogen into natural gas, the SOS is already significantly increased. For 100 vol% hydrogen, it is about 3 times higher than that for natural gas. The graphs in Figure 2 show the SOS for natural gas, a hydrogen mixture of 30 vol% and pure hydrogen.

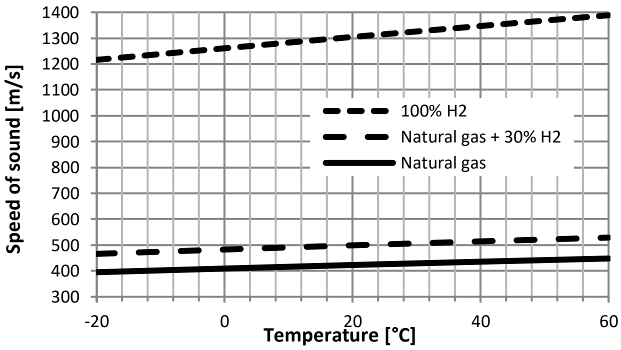


*Figure 2 Speed of sound for a typical natural gas (methane content of 90 vol%) and hydrogen admixtures up to 100%*

This results in several requirements for the design of USMs. Both, the measuring range equivalent to that for natural gas and the required measurement uncertainty must be ensured. This comprises the reduction of the spread of measured values, the reduction of cross-sensitivities to pressure, temperature and media variation, as well as the reduction of fluid mechanical influences.

As the SOS increases, the measuring effect of the transit time difference measurement decreases. In the lower flow range, a relationship proportional to the SOS applies to the measured value variance [3].

$$\sigma^2(v) \sim \sigma^2(\Delta t) \cdot c^2 \qquad (5)$$

For natural gas with hydrogen admixtures of up to 30 vol% this influence can still be compensated. For pure hydrogen other concepts are required such as higher transducer frequencies. Furthermore, due to the reduced density in hydrogen, other transducer concepts have to be chosen to achieve the required electro-acoustic efficiency.

With higher SOS, the acoustic directivity of the ultrasonic transducer changes. This leads to a widening of the radiation pattern. Therefore, reflection effects lead to superimpositions in the received signal, which can provoke additional transit time difference errors.

Also, these dependencies are still manageable for hydrogen admixtures. For pure hydrogen, the directivity of the ultrasonic transducers has to be much narrower, i.e. they have to be specially designed for the high SOS range. For natural gas optimized USMs, outer paths must currently be dispensed with at very high SOSs, which limits the resistance to installation effects and the accuracy that can be achieved.

## Extended Abstract

For precise flow rate measurement in pure hydrogen, the ultrasonic transducers must be designed in such a way that their directivity is so narrow that multipath layouts equivalent to the measurement in natural gas can be used.

USMs represent fluid mechanical components whose flow behavior is determined by the Reynolds number.

$$Re = \rho \cdot v \cdot d / \eta \qquad (6)$$

It describes the fluid mechanical similarity. Accordingly, the device response is determined by the gas velocity $v$, the geometric expansion (characteristic length: inner diameter $d$) and the medium (density $\rho$ and viscosity $\eta$). Reynolds number transferability means that in different media for the same Reynolds number the same flow condition occurs in the meter corresponding to a different pressure or gas velocity.

In terms of fluid mechanics, there are no special features for hydrogen admixtures or for pure hydrogen [7]. The lower density of hydrogen leads to a lower Reynolds number. For 30 vol% hydrogen the Reynolds number is reduced by a factor of about 1.4, for pure hydrogen by a factor of about 6.7, compared to that of air or natural gas. Accordingly, a calibration in air or natural gas can be transferred to the measurement in hydrogen, provided that the Reynolds number range for hydrogen can be covered. This is usually achieved by calibrating at a lower pressure.

Since existing USMs are designed for the SOS range in natural gas, the mentioned effects currently lead to restrictions in hydrogen applications. This affects possible nominal sizes and usable path layout and restricts flow ranges.

In future, calibratable measurement of hydrogen admixture and pure hydrogen the same specifications and requirements are to be expected as for the measurement in natural gas. Accordingly, the USMs must be adapted to the new measurement task. Additionally, a new design must be made regarding material compatibility and explosion protection. Moreover, due to the low density, the flow rate of hydrogen can be significantly higher than that of natural gas. On the other hand, dedicated hydrogen transport pipelines will not differ significantly from natural gas pipelines [1]. For flow meters for hydrogen, this results in comparable requirements in terms of pressure and nominal size. The requirements roughly correspond to those for current natural gas meters. For an energy-equivalent transport capacity, either larger nominal sizes or higher flow rates in transport systems are required. USMs specially designed for hydrogen will therefore have to allow higher maximum gas velocities.

Since all the requirements can be met very well, USMs are ideal for fiscal flow measurement in future transport and distribution networks, regardless of whether for hydrogen admixtures or pure hydrogen.

The advantages of flow measurement with USMs for increased hydrogen percentages are:

- Wide range of nominal diameters (DN50 to DN1400)
- High measuring span of ≥ 1:100
- Blockage-free, no pressure loss
- No mechanical moving parts, no pulsation

- Higher flow rates in hydrogen
- Transferability of the calibration with other media

In addition to the classification regarding the hydrogen content, USMs also can be distinguished by their use in process gas applications, in transport networks and in distribution networks.

A. Process gas measurement

For many years, USMs have been used in a wide variety of process gas installations to measure gases with different hydrogen percentages. These differ from standard meters designed for custody transfer measurements due to the restrictions for measurements in gases with increased hydrogen content. This affects the path layout, the achievable measurement uncertainty and limitations of the flow and pressure range. With the development of new ultrasonic sensors for use in pure hydrogen the current restrictions compared to standard meters are expected to be omitted also for these applications.

B. Measurement of hydrogen-containing gases in transport networks

In transport networks, large quantities of gas are transported in pipelines with nominal diameters from DN400 at high pressures. New gas meters such as the FLOWSIC600-XT can also measure gases with hydrogen contents of up to 30 vol% and are suitable for volume measurement under calibration law [8]. The prerequisite for this is that the reliability and quality of the measurement results are not influenced by changes in density, flow velocity and SOS, or are only influenced to an insignificant degree.

For installed flow meters an assessment for the operation with hydrogen admixture is available in the market, e.g. by SICK, where it is evaluated whether and which conversions are necessary in order to be able to measure higher hydrogen contents.

C. Measurement of hydrogen-containing gases in distribution networks

USMs in distribution networks differ in terms of their design pressure (typically <20 bar) and their nominal size (≤ DN150). The FLOWSIC500 meter is specially designed for use in natural gas distribution. It has been qualified for the measurement of up to 30 vol% of hydrogen in the entire specification range by adapting the signal evaluation and expanding the measurable SOS range.

## 4 HYDROGEN CONTENT DETERMINATION BY SPEED OF SOUND MEASUREMENT

An USM always records the current SOS of the measure gas with the transit time measurement (Eq. (4)) in addition to the volume flow. In contrast to the volume flow, which is determined from the transit time difference, the SOS is determined from the total transit time, independently of the gas velocity. Since measurement uncertainties in the time measurement have a significantly lower effect on the total running time, the SOS can be measured with a much better accuracy, typically <0.1%.

Based on changes in the SOS, information on changes in the gas quality can be derived. The implementation of a "Gas Quality Indicator" (GQI) in the USMs offers the opportunity of detecting changes in the gas composition via the SOS. Changes in the hydrogen content can be recorded very sensitively due to the extremely high SOS of hydrogen. Moreover, if the reference gas composition or its SOS (without hydrogen) is known, the hydrogen content can be determined very precisely. The device compares the measured SOS with the reference SOS. Assuming that this is exclusively due to an admixture of hydrogen, the hydrogen content can be determined directly. The approximation is made using an empirical formula that is implemented in the USMs firmware.

As an example, Figure 3 shows a FLOWSIC500 USM in the mixing station of the pilot project "Hydrogen in the gas network" [9, 10]. As part of the joint project, hydrogen admixtures of up to 20 vol% are added to the natural gas distribution network. The meter is used to measure the quantity of the natural gas-hydrogen mixture. At the same time, the hydrogen content in the natural gas is recorded with the help of the GQI.

*Figure 3 FLOWSIC500 in the mixing station of the avacon pilot project "Hydrogen in the gas network"*

Figure 4 shows the recorded total volume flow over a 12 days period. The daily cycle of consumption shows a maximum in the morning and in the afternoon. Consumption is lowest at midnight. Figure 5 displays the measured SOS for the same period. Figure 6 gives the hydrogen content determined using the GQI, which is equivalent to the SOS.

Figure 7 shows the actual hydrogen content as it results from the separately measured volume flows. Hydrogen was not fed in continuously. On the third day of the period shown, the admixture of hydrogen switched from about 10 vol% to 15 vol%. A very good agreement can be established both for the absolute value of the hydrogen content and for the measuring dynamics. Nevertheless, there are minor changes in the SOS, which the GQI outputs as a hydrogen proportion, especially in times without hydrogen being fed in. The measurement took place over the entire period with a one-time parameterized reference gas composition, since the natural gas provided retains a stable, almost constant gas composition.

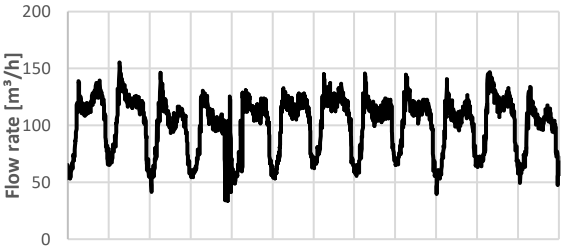


*Figure 4 FLOWSIC500 measurement of the volume flow of the natural gas-hydrogen mixture in the H2 injection system over a period of 12 days*

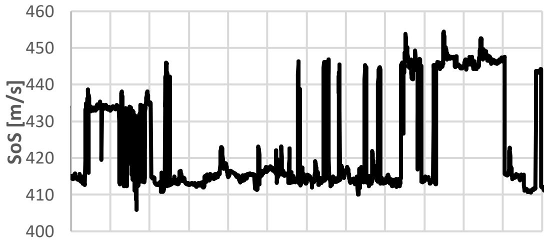


*Figure 5 FLOWSIC500 measurement of the speed of sound of the natural gas-hydrogen mixture in the H2 injection system over a period of 12 days*

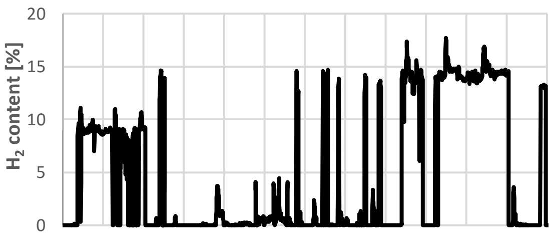


*Figure 6 FLOWSIC500 measurement of the hydrogen content by means of the GQI over a period of 12 days*

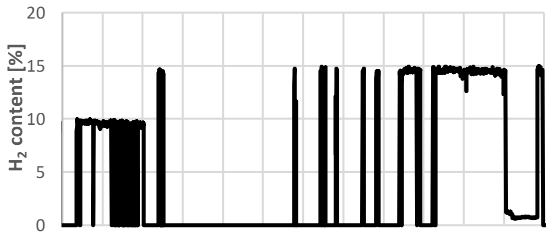


*Figure 7 Determination of the hydrogen content from the ratio of the hydrogen volume flow to the total volume flow over a period of 12 days*

So far it is not clear whether the small SOS changes are caused by lower hydrogen admixtures or are a reaction to changes in the natural gas composition, such as irregular admixture from a nearby biogas plant. However, it shows how sensitively the SOS reacts to gas changes.

If the SOS of the natural gas could also be measured before mixing, then any variation in the composition of the natural gas as observed can be eliminated. This would allow the hydrogen content in the mixed gas to be determined with very high precision. Moreover, the readings are output instantaneously, since updated every second. This can offer the prerequisite for using the GQI output to control the feed.

A requirement for an exact determination of the hydrogen content is precise knowledge of the residual gas composition or its SOS, in each case without hydrogen. The SOS is normalized internally for pressure and temperature. Hence, an exact temperature measurement is also required for high precision.

In order to be able to use the SOS measurement to determine the hydrogen content, various strategies can be used. The simultaneous SOS measurement of the residual gas can be used as well as the one-off entry of the reference gas composition, in particular for a stable gas composition that is constant over time. A regular determination of the gas composition (without hydrogen) would be also applicable, e.g. by means of process gas chromatography measurement, which can be done once a week, daily or hourly.

## 5 HYDROGEN PURITY DETERMINATION WITH USMs

Recent experiments, performed together with the *Physikalisch-Technische Bundesanstalt* (PTB) and *Open Grid Europe* (OGE) at SICK, show that USMs are excellently suited for determining the purity of hydrogen in addition to flow measurement. The smallest impurities in the hydrogen can be measured by changing the SOS.

For example, in an experimental setup, a USM was sparged with hydrogen of purity class 6.0 to 20 bar over five purge cycles until a theoretical purity of 5.8 was achieved in the meter. At the hydrogen purity of 99.999%, the measured SOS deviates from the theoretical one by only 0.044% (Figure 8). In principle, this small deviation allows precise determination of the purity of the hydrogen for the typical pipeline temperature ranges

| | | SOS | SOS theor. | relative dev. |
|---|---|---|---|---|
| **air** | | 344.34 m/s | adjusted | |
| **He (4.6)** | | 1012.45 m/s | adjusted | |
| **Measured $H_2$ (>99.999%)** | 20.3 bar(a) 23.52°C | 1329.07 m/s | 1328.49 m/s | 0.044% |
| **Measured $H_2$ (>99.999%)** | 9.97 bar(a) 25.66°C | 1324.15 m/s | 1323.59 m/s | 0.044% |

*Figure 8 SOS adjustment with air and helium*

The controlled successive addition of nitrogen changes the purity of the hydrogen in the instrument, which immediately reflects the change in the SOS. (Figure 9).

| set/estimated purity | conditions | SOS | SOS theor. | relative dev. |
|---|---|---|---|---|
| **99.999%** | 20.11 bar(a) 23.6°C | 1329.06 m/s | 1328.41 m/s | 0.05% |
| **99.960%** | 20.07 bar(a) 23.9°C | 1326.38 m/s | 1325.80 m/s | 0.04% |
| **99.910%** | 20.08 bar(a) 24.0°C | 1322.70 m/s | 1321.80 m/s | 0.07% |
| **99.750%** | 20.14 bar(a) 24.3°C | 1311.25 m/s | 1311.00 m/s | 0.02% |
| **99.060%** | 20.28 bar(a) 24.4°C | 1261.95 m/s | 1265.00 m/s | -0.24% |

*Figure 9 SOS change caused by nitrogen blending*

The detailed test setup, as well as further results, will be presented in a separate paper.

## 6 SUMMARY

USMs have been used successfully for measuring the gas quantity in a wide range of applications for more than 20 years now. This also includes applications for gases with different hydrogen contents. The devices used in these applications, as well as others in the SICK FLOWSIC family are already adapted and approved for fiscal measurement of natural gases with a hydrogen content of up to 30 vol%.

The measurement of pure hydrogen will be of further importance in the future. For this purpose, the device behavior must be fundamentally adjusted, especially with respect to the new media properties. Appropriately adapted USMs will be able to measure pure hydrogen with similar specifications as the previous natural gas measurement.

Furthermore, USMs offer various diagnostic capabilities that can verify the quality of the quantity measurement. The precise measurement of the SOS opens up new possibilities for determining the hydrogen content. The advantages of determining the hydrogen content by means of an inline SOS measurement are the high measurement dynamics and high precision, which are not truly independent of pressure and temperature, but rather much less dependent than variation yielding from composition variations. This not only provides a supplementary analysis method for hydrogen. Complex analysis techniques for hydrogen determination such as extractive gas chromatography might be substituted in several applications.

In addition to determining and monitoring the hydrogen content in the gas, this is basically also possible for any other gas components such as methane or carbon dioxide.

The simultaneous measurement of the volume flow and the speed of sound in one device represents a complementary combination for monitoring gas applications up to entire gas networks with increased hydrogen content or even monitor the purity of hydrogen in real time.

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