

# Ultrasonic Flowmeter for flow rates below 100 l/h

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## Abstract

The paper describes an ultrasonic flow meter with an axial measuring path, which uses acoustic plane waves propagating through pipes with a sufficiently small diameter. The propagation of plane waves in a circular pipe depends on the pipe diameter and the wavelength of the acoustic signal. Therefore, the design of the meter has to consider the speed of sound for the gases intended to use, e.g. nitrogen, methane, hydrogen and any mixture of these. In order to measure low flow rates with small uncertainties, a great acoustic path length, i.e. a pipe with long length is advantageous. On the other hand, the signal attenuation increases proportionally with the length of the measuring pipe. The paper provides information about the basic conditions to reach plane waves in a pipe with small diameters.

The investigated prototype uses an inner pipe diameter of 4 mm and a path length of 320 mm. The ultrasonic transducers and the electronics are taken from a commercially available ultrasonic meter with two paths and a working frequency of 135 kHz. In this configuration, the signal quality is already very good with nitrogen under atmospheric conditions, but due to the acoustic attenuation, methane is only measurable with more than 2 bar absolute pressure. The results for nitrogen and methane show nearly linear behaviour over a flow range from 10 to 1,000 l/h. At the lower flow range of the meter the zero flow uncertainty is the limiting influence value. The prototype has shown stabilities of lower than  $q_z = 0.1$  l/h.

The meter may be used for quality assurance of test rigs such as checking small nozzles and as transfer standard for intercomparisons.

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## 1. Introduction

For determining flow rates in pipes, various measurement principles are on the market. For flowrates below 100 l/h, the available kinds of meters are limited though. Laminar flow meters and thermal mass flow meter are usable, but both principles are sensitive to the composition of the gas. Diaphragm gas meters are used in very large numbers for such flow rate ranges, however, the long term stability and reproducibility is influenced by mechanical stress and purity of the gas. A rotary meter, which was developed for low flows, show a severe slope of the error curve at flow rates below  $Q = 100$  l/h already because of internal leakages and friction losses of the mechanics. Wet-test gas meters are not influenced by the type of gas if the solubility of the gas in the sealing liquid is negligible. Wet-test gas meters are able to provide uncertainties below  $U = 0.2$  %, but the handling is relative difficult.

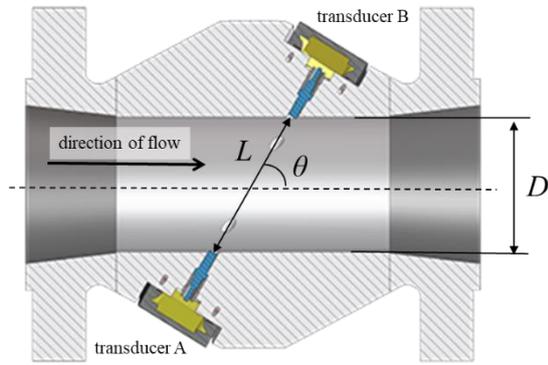
Flow measurement in pipes based on the travel time of ultrasound signals by ultrasonic flow meters (USM) is mature technology for accurate and robust measurement

of gas quantities. Along with the high repeatability and high accuracy, ultrasonic technology has inherent features like negligible pressure loss and high rangeability. In addition, the measured speed of sound may be compared with the speed of sound calculated from pressure, temperature, and gas composition to check the mutual consistency of the four instruments involved. Further, the signal quality may be supervised during application.

## 2. Design of an USM for very small flow rates

### 2.1 Basic principle of an USM

Figure 1 illustrates the basic principle of an USM. Typically, at least two ultrasonic transducers, marked (A) and (B), are arranged in an angle  $\theta$  to the pipe axis. Hence, the direct line between the two transducers defines the measuring path of the length  $L$ . A signal pulse transmitted from a transducer travels with the speed of sound  $c$  of the fluid to the transducer located opposite.



**Figure 1:** Basic arrangement of an ultrasonic measuring path

The signal pulse additionally accelerates when travelling with and decelerates when travelling against the flow. Thus, the flow measurement is derived from the measured signal travel time  $t_{AB}$  between the two transducers with the flow and  $t_{BA}$  against the flow.

$$t_{AB} = \frac{L}{c + v \cos \theta} \quad (1)$$

$$t_{BA} = \frac{L}{c - v \cos \theta} \quad (2)$$

Here, the time difference is a direct measure of the average flow velocity  $v_{path}$ , whereas the sum is a measure of the speed of sound along the acoustic path.

$$v_{path} = \frac{L}{2 \cos \theta} \left( \frac{1}{t_{AB}} - \frac{1}{t_{BA}} \right) \quad (3)$$

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

To increase the accuracy for an arrangement shown in Figure 1, more than one measuring path is arranged over the cross-sectional area  $A$  of the pipe. Several of these multi-path layouts may be found e.g. in [1]. These layouts provide different path velocity information of different regions of the cross sectional area. The individual path velocity measurements are combined by a mathematical function, e.g. a weighted average, to yield an estimation of the average velocity  $v$  in the pipe. The volumetric flowrate  $q_v$  is obtained by multiplying the cross-sectional area  $A$  with the estimate of the average velocity  $v$ .

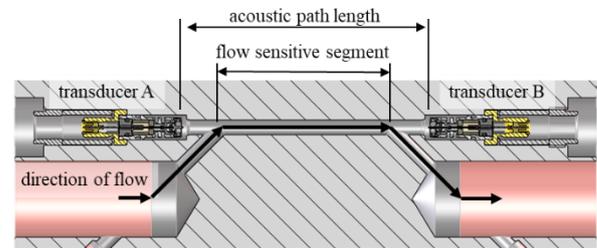
$$q_v = A \cdot v = 0.25 \cdot \pi \cdot D \cdot v \quad (5)$$

### 2.2 Design constraints for very small pipe diameters

Considering a flow velocity of approximately 30 m/s in the pipe at the maximum flowrate of e.g. 1,000 l/h results

in some millimeters pipe diameter only. On the other hand, the size of the ultrasonic transducer relates to its working frequency and cannot be scaled down proportionally to the pipe diameter. Obviously, the conventional USM design as shown in Figure 1 is not applicable here due to the space needed for the transducers in the pipe wall. Furthermore, the signal travel time will be excessively short for an accurate time measurement.

To cope with these challenges, the transducers A and B are aligned with the axis of the pipe, as Figure 2 shows. Thus, the diameter will no longer be a limiting factor for the path length.



**Figure 2:** Axially arranged ultrasonic measuring path

The fluid flow is guided through the measuring path e.g. as Figure 2 shows or flows directly around the transducers before entering respective leaving the meter. The acoustic signal shall propagate along the pipe axis only, and the sound field shall cover the complete cross-sectional area without interference of the signal by reflected signals. In a cylindrical pipe, the fundamental wave mode, respective a plane wave fulfils these requirements. The front of a plane wave propagates equal to the speed of sound  $c$ . If higher wave modes are present as well, the propagation speed of the acoustic signal pulse will become slower than the speed of sound [2].

For a circular flow channel with the diameter  $D$  and a flow velocity  $v$ , the higher wave modes can propagate if the signal frequency is higher than the cut-on frequency of the respective wave mode [3]. For the 1<sup>st</sup>-order wave mode this cut-on frequency is given with Equation (6) below.

$$f_{cut-on} = \frac{1.84118}{\pi D} c \sqrt{1 - \left(\frac{v}{c}\right)^2} \quad (6)$$

### 2.2 Design of an USM for very low flow rates

For the presented prototype of an USM with an axial path, the transducers and electronics of a commercially available flow meter with two measuring paths and a working frequency of 135 kHz was used. The meter shall measure different gases at pressures up to 50 bar and a maximum flow rate of 1,500 l/h under measuring

conditions. Considering the different speed of sound for the different gases intended to use, with Equation (6), we can calculate the cut-on frequencies of the 1<sup>st</sup>-order mode in our meter as shown in Table 1 below.

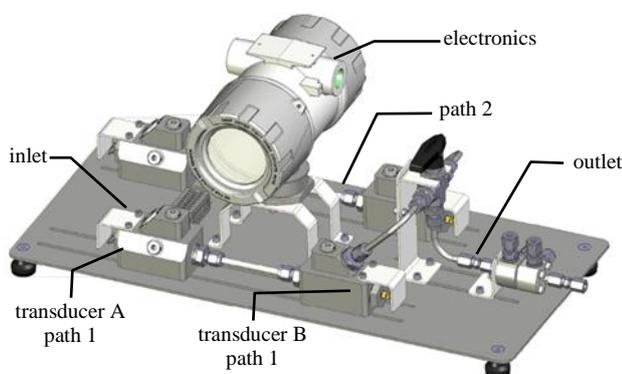
**Table 1:**

	Nitrogen	Methan	Hydrogen
Speed of sound [m/s] @ 101kPa, 20°C	349,1	445,0	1304,1
f_cut-on [kHz], Di 4mm	51,1	65,2	191,1
Dmax_f(1,1) [mm]	1,5	1,9	5,7
qV <sub>max</sub> [l/h] @ 33m/s	214	348	2991

According to Equation (6), the propagation of higher wave modes may be prevented by reducing the pipe diameter and / or the signal frequency. Due to the fact that the available ultrasonic sensors and electronics define the signal frequency, only the pipe diameter might change. The dilemma here is the dramatically reduced maximum flow capacity when we will reduce the pipe diameter. With a pipe diameter of 1.5 mm, the maximum flow rate at 33 m/s velocity will be 214 l/h only. A higher flow velocity might be applicable if on one side the increasing pressure drop and on the other hand, the increasing flow induced acoustic noise will not limit the measurement setup.

Due to the various gases to measure and the possible maximum flowrate limitations, a compromise with a pipe diameter of 4 mm and a length of 322 mm for the acoustic path was chosen. Unfortunately, do we have to expect the propagation of higher wave modes for gases with lower speed of sound values than at Hydrogen.

Both measuring paths of the electronics were used with the option of getting two independent measuring channels. Hence, this offers the possibility to choose different path lengths and/or pipe diameters in a later phase of the project.



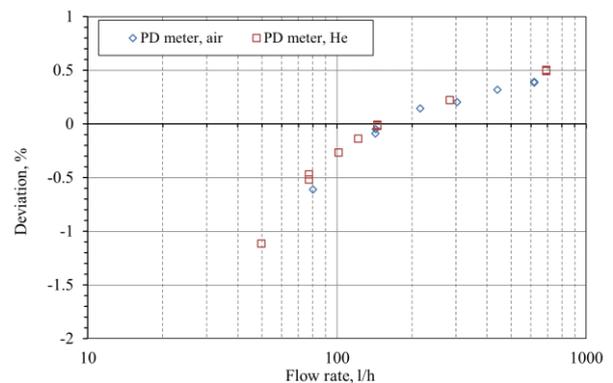
**Figure 3:** Flow meter with axially arranged ultrasonic measuring paths

Each transducer is mounted in a metal block with the gas in- / outlet, and a connection for the measuring channel. The measuring channel is made from a standard 6 mm stainless steel pipe with a wall thickness of 1 mm, resulting in the 4 mm diameter of the acoustic channel. Furthermore, each of the four mounting blocks provides connection ports for measuring the gas temperature and pressure.

### 3. Results of the USM with different gases

#### 3.2 Test setups

For investigating the capillary USM, a positive displacement meter (PD meter) and a mercury sealed piston prover (PP meter) were used. Figure 4 shows the error curve of the DP meter

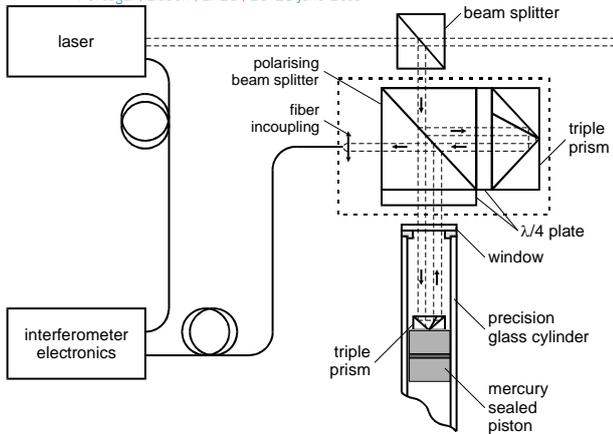


**Figure 4:** Error curve of the PD meter with nitrogen and helium at atmospheric conditions

The PD meter provides similar results for nitrogen and helium. For flows below 100 l/h, the reproducibility of the results decreases. As mentioned in chapter 1, this is because of increasing influences by friction and inner leakage.

In order to investigate the USM prototype for flow rates below 100 l/h at metering conditions  $p_{USM}$ , the mercury sealed piston provers (PP) of the flow laboratory at PTB were used.

Figure 5 shows the arrangement of the interferometer for determining the speed of the piston. The inner diameter of the glass cylinder is traceable by length and was calibrated by a coordinate measurement machine. The PP is not sensitive to the kind of gas as long as the mercury seal does not react with the gas. For inert gases this is the case.

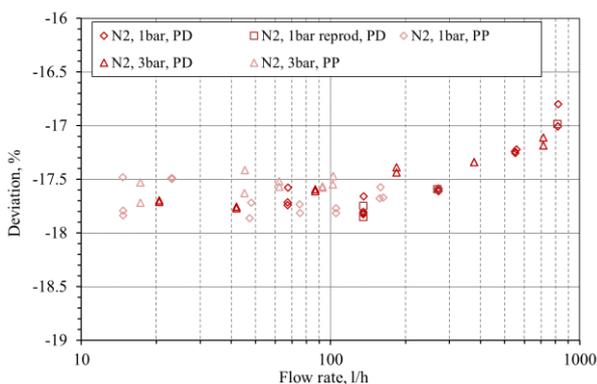


**Figure 5:** Interferometer system of the mercury sealed piston prover for gas independent flow determinations

### 3.1 Flow test results

The capillary USM was investigated with nitrogen and methane. As mentioned above, the methane measurements were carried out at a measuring pressure of  $p_{abs,USM} = 3$  bar only. For determining the measuring pressure, the port at the inlet was used. As long as the pressure drop is low in comparison to the measuring pressure, the results are independent of the port (inlet or outlet) used. The flow standards were always used at atmospheric conditions, that means for the 3 bar measurements downstream to the USM prototype, a needle valve was used for depressurisation of the gas.

The results with nitrogen at measuring pressure of 1 bar (atmospheric pressure) and 3 bar are plotted in Figure 6.

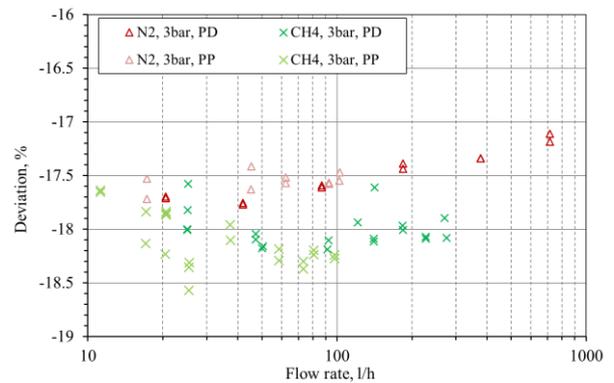


**Figure 6:** Results with nitrogen with  $p_{USM} \approx 1$  bar and  $p_{USM} \approx 3$  bar

The error curves measured by the two different flow standards are overlapping quite well. At higher flows the errors shift to plus.

The large bias of roughly  $E = -18\%$  is caused by the pipe sections near to the transducers which are flow dead zones. Nevertheless, these pipe sections contribute to the measured signal travel times.

Figure 7 shows the results with nitrogen and methane for a measuring pressure of 3 bar. The results of the two gases differ in average by approximately 0.5 %, but the error curves are quite constant for the whole flow rate range.

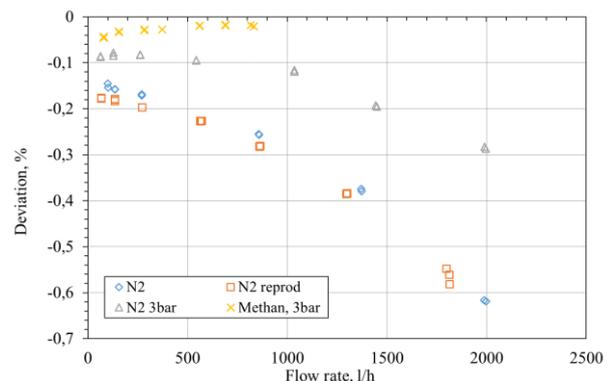


**Figure 6:** Results with nitrogen and methane ( $p_{USM} \approx 3$  bar)

During the measurements it was observed that the deviation of the meter in case of changing the kind of gas drifts over longer times (up to 30 min). This also concerns the measured speed of sound. The reason is the time needed to exchange the gas in the flow dead zones of the prototype. By changing the pressure in the meter, for instance by several 3bar / 1bar cycles, the exchange time may be reduced severely.

### 3.2 Speed of sound test results

Gas qualities of N5.0, respective 99.999% purity was used for the flow tests. The theoretical speed of sound of the gas at the actual conditions of pressure and temperature was calculated by means of the GERG-2008 [4] algorithm. Figure 8 shows the deviation of the measure speed of sound to the calculated theoretical value from gas type, pressure and temperature.



**Figure 8:** Speed of sound deviation from theoretical value

Surprisingly, the speed of sound has shown a strong flow rate dependency. The first attempt to correct this

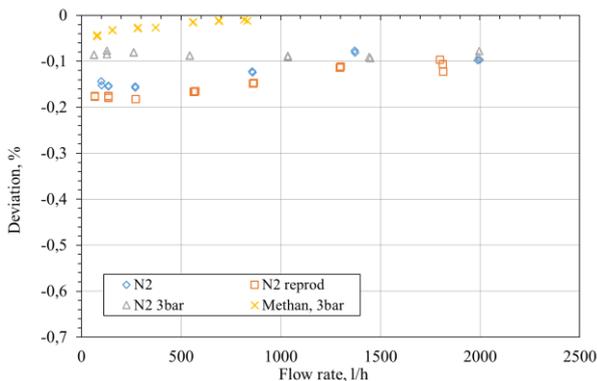
dependency by taking into account the pressure drop over the length of measuring path turned out to be insufficient.

Much better results were achieved by considering the Mach-number and applying Equation (7) as correction factor.

$$c' = \frac{c}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \quad (7)$$

After correction by the Mach-number, the speed of sound deviation is better than 0.05% over the tested flow range (see Figure 9). Nevertheless, a difference between nitrogen and methane was observed, which might be caused by the expected propagation of higher acoustic wave modes in the measuring pipe.

Further tests with hydrogen are planned to investigate how the speed of sound measurement is influenced by the acoustic signal propagation on higher wave modes.



**Figure 9:** Speed of sound deviation from the theoretical value with correction factor applied

## 7. Conclusion

The investigated prototype has shown the applicability of a capillary USM for flow rate measurements. By an inner diameter of the used capillary of 4 mm and an acoustic frequency of the transducers of 135 kHz, a flow rate range down to 10 l/h was reached with different gases. The reproducibility of the meter deviation was mostly inside a range of 0.2 %. The results show a relatively small dependency of the error curve from the kind of gas in case of nitrogen and methane. The reasons for this dependency need to be investigated further. The flow velocity influenced severely the speed of sound detected by the USM, but a compensation based on the Mach-number led to deviations between measured and calculated SOS of lower than 0.05%.

It is planned to use the meter for inter comparisons and for the measurement of speed of sound for changing gas compositions.

## References

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- [4] ISO 20765-2, *Natural gas -- Calculation of thermodynamic properties -- Part 2: Single-phase properties (gas, liquid, and dense fluid) for extended ranges of application*, 2015