

# Measurement of Fluid Flow with Different Velocity Profiles by New Built Ultrasonic Flowmeter

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**Abstract.** The paper describes the development of a non-invasive flowmeter for lower flow rates and its first tests. This gauge is physically based on the interaction of fluid flow with an ultrasonic signal that passes through the fluid from the transmitter to the receiver. Ultrasonic flowmeters are currently relatively commonly used gauges, whose advantages such as non-invasiveness (i.e. zero pressure losses) and the ability to seamlessly measure the flow rates of any (for example opaque) liquids, without contact with the liquid, are widely known. However, there are still parts of the ultrasonic flowmeter measurement chain that are undergoing research and development. It can be signal processing itself (mainly), its design solution, measurement for different flow cases (measurement in a flow field with a uniform velocity profile, in a flow field with an axisymmetric velocity profile, in a flow field with a general velocity profile), validation of the applied signal processing approaches, evaluation of uncertainties. The flowmeter itself, which development is described in the paper, will be used for trouble-free measurement in air engineering, but also serves as a training device for building a more complex ultrasonic gauge. Therefore, this flowmeter contains more signal transmitters and receivers than it is usual and all transmitter-receiver combinations are captured during the measurement. This gauge is called ultrasonic tomograph and its principle is also outlined in the paper. Here, so far, without a reconstructed vector field.

**Keywords:** *experimental methods, mechanics of fluids, ultrasonic flowmeter, ultrasonic tomograph*

## 1 Introduction

This paper deals with the development of two gauges for use in fluid mechanics, an ultrasonic flowmeter and an ultrasonic tomograph. These gauges are based on non-contact measuring principle in which ultrasonic transmitters and receivers are used as sensors, and the sound signal travelling through the flowing medium and the interaction of both of these moving

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entities is considered for measurement. The measured quantity is the time delay of the travelling signal. From this quantity, velocity/ flow rate is evaluated in case of flowmeter. In case of the tomograph, the signal processing is considerably more complex and includes, among other quantities, the determination of the angle of incidence of the signal, while only the same transmitters and receivers are available as for flowmeter.

The very nature of these flowmeters has been known for decades and used with success; there is a whole range of solutions for these gauges, one can purchase meters from indicative to highly accurate, with the possibility of completely non-contact measurement, based on various principles. Their fifty years of history overview is clearly described in paper by Lynnworth, 2006 [1]; together with the article by Furness, 1991 [2], who summarizes all available flowmeters and their areas of application, these two papers form an introduction to the issue of flow measurement. Today, the development of this gauge is directed towards special areas of fluid mechanics, such as cryogenic applications or the area of compressible flow (Otero, 2019 [3]).

A more advanced application of the principle of interaction of the ultrasonic signal and the flowing medium is called the ultrasonic tomograph.

The principle of measuring the 3D velocity field using an ultrasound tomograph has also been known for quite a long time (see Teerawatanachai, 1991 [4], Komiya, 1993 [5]), but its implementation is not very frequent. From the beginning, the limiting factor for complex development was apparently the fact that it was believed that ultrasonic transmitters and receivers needed to be supplemented with yet another gauge (Schlieren technique; Braun and Hauck, 1991 [6], Johnson et al, 1977 [7]) and all the theory remained rather on paper. Nowadays, when, for example, Jovanovic showed in her dissertation in 2008 [8] that she could reconstruct a 3D velocity field from only known velocities and ultrasound signals, the development of new - and thus spatially dimensional - experimental methods in areas of fluid mechanics are probably outside the area of interest of the respective institutions, or beyond their capacity.

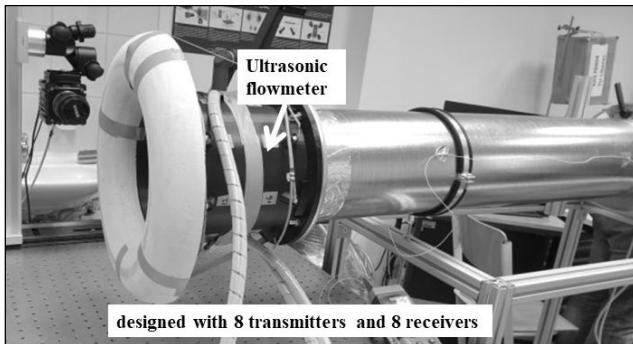
## 1.1 Ultrasonic flowmeter and tomograph development

The ultrasonic gauge development, as it was conceived for the project described in this paper, involved following tasks: A) selecting and testing ultrasonic transmitters and receivers, while several aspects had to be taken into account in the selection, like their design (small dimensions are more suitable for intended applications, but one cannot forget a reach considering), physics (frequency characteristics, directional characteristics and wave range), microelectronics (control and power supply). B) The next step was the construction of gauges (to choose suitable production technology, especially with regard to the exact geometry demanded) and C) building the whole electronics using the simplest and most affordable components.

One of the main tested attributes of the flowmeter being developed is the invariance to the velocity profile of the measured fluid. At the same time, the whole system is designed as variable as it can be used on pipes of any cross-section (circular, rectangular, general shape) in an effort to build in as little space as possible, i.e. to construct a gauge with the shortest possible length.

At the moment, the development of the flowmeter has completed the structural part and the assembled electronics and also few validation measurements have been provided. (Simultaneously with the construction of the gauge, an experimental line was also built, on which its parameters were and are being verified. The test line is fitted with a standard flowmeter and, as necessary, additional verification measurements are made using other experimental methods.)

The tomograph development is a logical step that other research teams who are building their own ultrasonic flowmeter are also trying to achieve as far as possible. It means to take the data from flow measurements and to reconstruct a 2D vector velocity field using these data. It does not appear to be a complicated problem from a design point of view. If a pipe of circular cross-section and a configuration where two rings of transmitters and receivers are placed around the pipe are taken into account, then the non-axial components of the flow velocity vector in the channel can be obtained by such arranged measurements. For example, this is roughly how the team Liu 2015 [9] proceeded.



**Fig. 1.** Ultrasonic flowmeter designed for testing a 2D tomograph principle.

## 2 Measurement setup

The task of the project, as already mentioned in the introduction, was to build an ultrasonic flowmeter used (and validated) especially for air flows of the order of 1 m<sup>3</sup>/s or lower units of m<sup>3</sup>/s. At the same time, it was necessary to determine the overall accuracy of the gauge for a uniform, axisymmetrically deformed and generally deformed velocity profile.

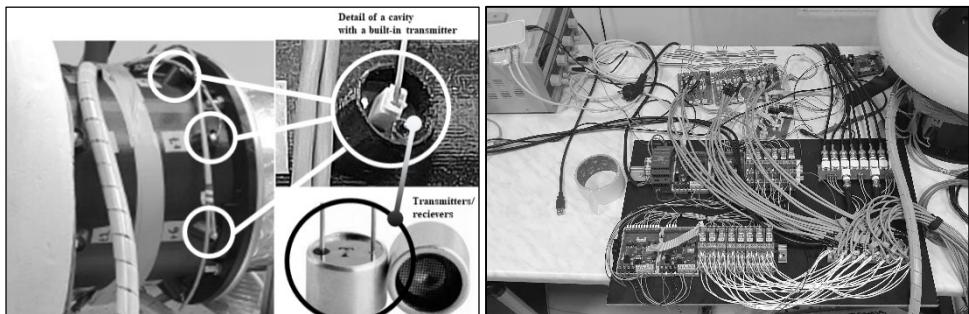
### 2.1 Ultrasonic flowmeter Prototype

The ultrasonic flowmeter will be used mainly for measuring air substances, from the point of view of fluid dynamics in the area of incompressible flow. The temperature of the flowing medium is assumed to be within the range usual for our climate zone. Due to the expected use of the gauge (for example, in air engineering), the main requirement for production was the variability of the geometry; the pipe can have a circular, rectangular or general cross-section. The velocity profile at the point of measurement can be laminar or turbulent, but it can also have a completely general, deformed shape, which usually affects the uncertainty of the measurement. The proposed device is designed as a contact device, i.e. transmitters and receivers will be placed directly in the pipeline as a part of it and come into contact with the flowing medium.

#### 2.1.1 Construction, electronics and data processing proposal

Taking into account the variability of production while maintaining the high accuracy of the geometry, 3D printing was chosen. A circular cross-section test piece was designed with a diameter of 200 mm. The transmitters and receivers are distributed around the perimeter evenly in two concentric circles so that the distance between the centers of the sensors' cavities is 200 mm. The axes of the cavities in the case of this product make an angle of 45 degrees with the axis of the pipe. A fundamental part of the design of microelectronics is the selection of suitable transmitters/receivers. The requirements for sensors for the intended use

(and especially for the proposed test prototype) are contradictory: on the one hand, they should be subtle products with a low supply voltage, on the other hand, ideal transmitters/receivers should work at frequencies higher than 100 kHz, so that the frequency of the sensors moves above the frequency of possible non-stationarities in the flow. Finally, sensors designated MCUST and MCUSR working on frequency 40 kHz, suitably small and having a good noise property (and, also available and expected to be available in the future, which is an aspect that also needs to be taken into account at present) were selected.



**Fig. 2.** A) Detail of the installation of transmitters/receivers of the gauge. B) Control and switching unit of the gauge.

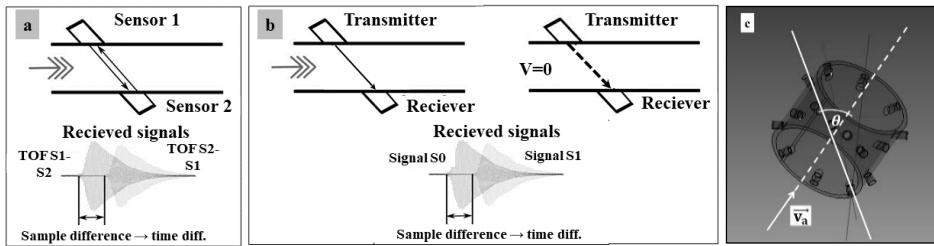
For the construction of the control unit, emphasis was once again placed on the simplest possible instrumentation, composed of easily available, common and possibly replaceable components. The control unit provides the operation of excitation and reception of ultrasonic signals, high-speed sampling of these signals, their temporary buffering into the buffer and transmission for further processing.

Conceptually, there are three different approaches to ultrasonic flowmeter measurement and signal processing: Doppler shift, direct time-of-flight measurement, and cross-correlation. For applications under consideration for Prototype flowmeter, only time-of-flight measurements and cross-correlation are considered (and appropriate). Determining the exact time-of-flight directly is quite a difficult task. Fig. 3 shows an example of a raw outgoing/incoming signal from the testing measurement of the gauge Prototype. A crucial problem of this task can be seen there: to accurately find out the origin of either the transmitting or the received signal is necessary (in general, this is a separate topic for research on its own; the exact determination of the origin of the reception of an ultrasound signal is solved, for example, by Fang et al., 2017 [10]). In addition to determine the beginning of the signal on the receiver side, it is also necessary to find the exact moment of excitation on the transmitter side, which exact outset is apparently emerged in noise.

For the reasons mentioned above, the method of mutual comparison of signals was finally chosen, therefore the cross-correlation method. Again, the application of this method may vary: the cross-correlation can be performed either in a frequency domain (Sullivan and Wright, 2002 [11] have shown the flow velocity-dependent frequency shift for the receivers working on the frequency reaching 1Mhz) or a time domain ([12]).

For the Prototype, the time domain was selected.

Basic schema for measurement is depicted in Fig. 3.



**Fig. 3.** Measurement setup schema and geometry: a) usual type, b) cross-correlation proceeds in a manner that only one signal is taken under flow condition and is correlated with no-flow measurement. C) Geometry of the gauge included in the velocity and flow rate calculation.

During the testing of the Prototype, one change was made in the usual cross-correlation procedure against the scheme in Fig. 3a., where the signals measured up the stream and down are correlated; this arrangement was replaced (apparently temporarily) by the correlation of a single signal measured with flow and a signal without flow in the pipe. This is a conceptually less convenient setup, since it is not always possible to immediately measure the regime with zero flow velocity in the pipe. However, the first tests of the Prototype showed that the signals measured downstream and upstream are every now and then difficult to correlate. Fig. 3b shows the diagram that is used in the measurement of the Prototype.

The time-of-flight of the signal between the transmitter and the receiver is expressed by a curve integral:

$$\tau = \int_{\Gamma} \frac{1}{\mathbf{u}_g} d\mathbf{s} = \int_{\Gamma} \frac{1}{(\mathbf{c}\mathbf{n} + \mathbf{v}) \cdot \mathbf{s}} d\mathbf{s} \quad (1)$$

where “.” denotes the scalar product,  $\tau$  is time-of flight,  $\Gamma$  is sonic ray trajectory,  $\mathbf{u}_g$  is the sonic wave group velocity,  $\mathbf{s}$  is vector tangent to the  $\Gamma$  trajectory,  $\mathbf{c}$  is speed of sound,  $\mathbf{n}$  is vector normal to the wave front,  $\mathbf{v}$  is the flow velocity.

The simplified equation (1) applied to the flowmeter Prototype leads to a determining the axial velocity as:

$$\mathbf{v}_a = \frac{\mathbf{c} - \frac{L}{\Delta\tau + \frac{L}{\mathbf{c}}}}{\cos \theta} \quad (2)$$

where  $\mathbf{v}_a$  is the axial velocity,  $L$  is the distance between transmitter and receiver,  $\theta$  is the tilt angle of transmitters/receivers (the angle between their axis and the pipe axis) and  $\Delta\tau = \tau_1 - \tau_0$  the time difference between Prototype downstream and no-flow downstream soundwave “time-of-flight”.

As it was mentioned, the cross-correlation of the signals is proceeded in the time domain. Time delay of two signals is determined as the maximum of the correlation function (eq. 3) of these signals, computed with help of Fourier transform (eq. 4):

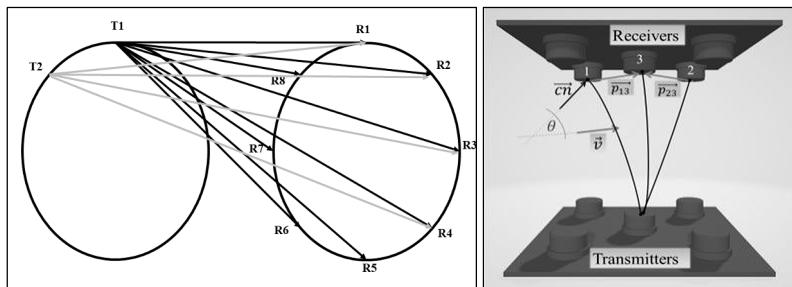
$$w(t) = u(t) \otimes v(t) \quad (3)$$

$$w(t) = F^{-1}(F(u(t))F^*(v(t))) \quad (4)$$

The result of the cross-correlation is number of samples converted to the time, and together with the geometry of the gauge and the speed of sound (evaluated from the temperature) this quantity fully determines the flow rate.

## 2.2 Ultrasonic tomograph proposal

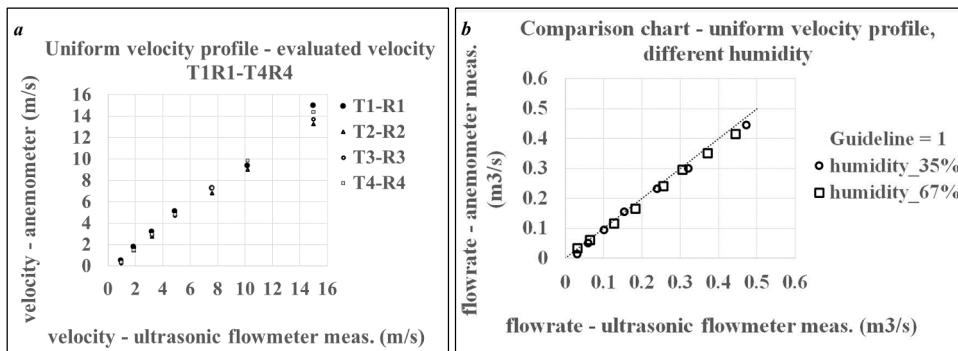
The ultrasonic flowmeter was designed with emphasis on the invariance to the measured velocity profile. One of the design aspects that helped this feature is the fact that the flowmeter can work as 8 independent flowmeters. At the same time, this design allows the flowmeter to be used as a tomograph, where the non-axial components of the velocity vector are evaluated. The principle of this tomograph is based – again – on the time delay measurement. It requires the assembly of tripoles – see diagram in Fig. 4 – and determining the time delay between transmitter and receivers R0, R1 and R2, which corresponds to the angle between the velocity vector and the normal of the incident sound wave vector. From the known distance between the sensors, from the detected time-of-flight in the triole configuration, their differences, and from the detected TOF between T0-R0, the velocity field can be reconstructed via inverse problem.



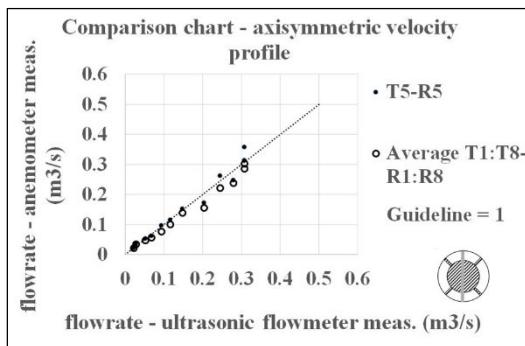
**Fig. 4.** Scheme of the system of transmitting and receiving the ultrasonic signal in the tomograph.

## 3 Measurement results

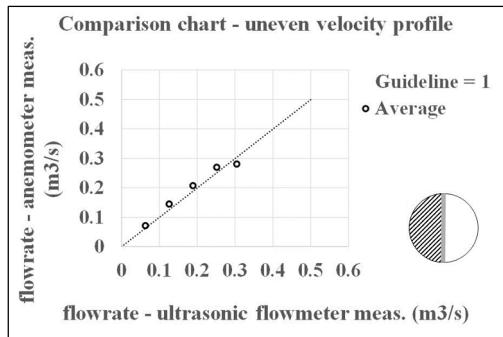
Measurements have been performed and evaluated so far for a uniform, an axisymmetric and an uneven velocity profile, plus for different humidity values in the laboratory. These configurations were achieved by inserting elements to deform the velocity profile at the beginning of the gauge, just after the lead. Their sketch for an axisymmetric and non-uniform velocity profile is marked in the corresponding graph. The following graphs in Figs. 5, 6 & 7 show and compare the most important data: calculated velocity for different velocity profiles and calculated flow rates from anemometer and from ultrasonic flowmeter measurements in the comparison (ideally, the corresponding values should meet on the  $y=x$  line). For the ultrasonic flowmeter, one sample value is taken from one transmitter and receiver for two cases (in the configuration in which the gauge is designed, it actually works as 8 independent flowmeters, since theoretically only 1 transmitter and 1 receiver are sufficient). Other values are calculated as averages from all 8 transmitter-receiver pairs.



**Fig. 5.** (a) Ultrasonic velocity measurement in comparison with the reference measurement from the anemometer, uniform velocity profile. (b) Evaluated flow rate in comparison with the reference measurement, ultrasonic gauge used in different humidity.

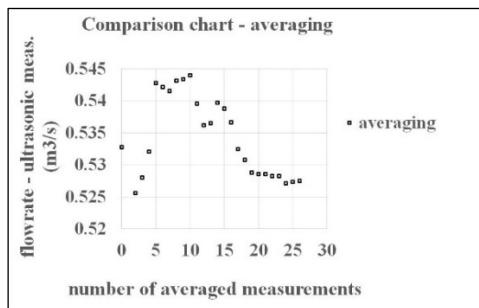


**Fig. 6.** Ultrasonic flow rate measurement in comparison with the reference measurement from the anemometer, axisymmetric velocity profile.



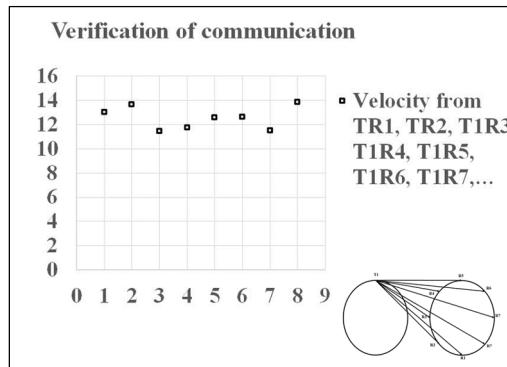
**Fig. 7.** Ultrasonic flow rate measurement in comparison with the reference measurement from the anemometer, uneven velocity profile.

As an almost perfect match for the measured values from the anemometer and from the ultrasonic gauge was expected (and was not achieved), more detailed statistics was evaluated as well. For future experiments, more than 20 signals from one transmitter-receiver pair are to be taken to get more accurate results. The course of the calculated values of the velocity (and flow rate) for an increasing number of measurements can be seen in Fig. 8. For a number of measurements higher than 20, the average value changes only in the order of tenths of a percent.



**Fig. 8.** Ultrasonic flow rate measurement – averaging of T1-R1 signal, uniform velocity profile.

For 2D ultrasonic tomograph, the first results were provided so far; their results were supposed to show, whether the positions of the sensors are appropriate or not; especially those where the transmitter-receiver pair is located next to each other. Whether the receiver could hear the corresponding transmitter. The results are depicted in the Fig. 9.



**Fig. 9.** Tomograph first tests.

## 4 The uncertainty analysis

The uncertainty analysis of the axial velocity in the pipe is based on default equation (2).

The speed of sound uncertainty is calculated as a standard deviation of a uniform distribution of a temperature gauge. The determination of the temperature by the reference thermometer is with an error of  $\pm 0.5$  °C, which makes the width of the interval, i.e. the variance will appear within the limit  $\Delta = 1^\circ$ .

The uncertainties of measuring the geometry of the flowmeter were estimated resulting from the meters and their capabilities; values are quantified in Table 1.

The uncertainty of  $\Delta\tau$  was determined as the uncertainty of type A of repeated measurements and combined with autocorrelator uncertainty of B-type. In the autocorrelator, an error uniform over an interval of  $\pm 10$  samples was assumed.

For the overall determination of the velocity uncertainty, the partial derivation of Eq. 2 according to all quantities and the uncertainties  $u_B$  and  $u_B$  is used.

**Table 1.** Overview of uncertainties.

Quantity	Uncertainty calculated as		Value
Speed of sound	$u_B(c) = \sqrt{\left(\frac{\partial f_c}{\partial T}\right)^2 \cdot (u_B(T))^2} = \sqrt{\left(\frac{8.3}{\sqrt{T}}\right)^2 \cdot \frac{\Delta}{\sqrt{12}}}$		$0.04 \frac{m}{s}$
Geometry	angle	$u_B(L) = \frac{\Delta}{\sqrt{12}}$	0.14 mm
	dimensions	$u_B(\Theta) = \frac{\Delta}{\sqrt{12}}$	0.29 °
Time	autocorrelator	$u_B(\Delta\tau) = \frac{\Delta}{\sqrt{12}} = \frac{20}{100 \cdot 10^6 \cdot \sqrt{12}}$	57 ns

	from repeated measurement, uncert. of A type evaluated	$u_A(\Delta\tau) = \sqrt{\frac{\sum(x_i - \bar{x})^2}{N \cdot (N - 1)}}$	45 ns
	combined – C uncertainty	$u_c(\Delta\tau) = \sqrt{u_A(\Delta\tau)^2 + u_B^2(\Delta\tau)}$	72.6 ns
Velocity (calculated for velocity 7,6 $\frac{m}{s}$ )	Combined – C uncertainty evaluated for uniform velocity profile, for velocity 7,6 m/s	$u_c(v_a) =$ $= \sqrt{\left(\frac{\partial f_{va}}{\partial c}\right)^2 \cdot [u_B(c)]^2 + \dots + \left(\frac{\partial f_{va}}{\partial \Delta\tau}\right)^2 \cdot [u_B(\Delta\tau)]^2} =$ $= \sqrt{\left\{ \frac{1}{\cos \Theta} \cdot \left( 1 - \frac{L \cdot (\Delta\tau \cdot c + L) - L + c}{(\Delta\tau \cdot c + L)^2} \right) \right\}^2 \cdot [u_B(c)]^2}$ $+ \dots + \frac{-L \cdot c}{\cos \Theta \cdot \left( \Delta\tau + \frac{L}{c} \right)^2}$	0.076 $\frac{m}{s}$

## 5 Conclusions

This paper introduced the development and testing of the ultrasonic flowmeter and the further aiming of the project to the ultrasonic tomograph. The flowmeter was conceived as the invariant to the flow field measured, geometrically variable, available in terms of electronic components, designed for lower flow rates and non-compressible flow. Together with the gauge Prototype the experimental line was built. The components for changing the flow velocity profile, turbulence rate, humidity were designed and the measurements with changing all these parameters were provided. The paper contains the first test results for the ultrasonic flowmeter for different velocity profiles. For the uniform velocity profile, the reference anemometer and the Prototype differed about maximum 6 %. For the axisymmetric velocity profile, above a speed of 4 m/s, the reference and Prototype showed an acceptable agreement with a difference of max. 6 %, for lower flows the difference was close to 10 %. The measurement with the uneven velocity profile ended up with the similar result. The dependence of the measurement on humidity was not proven. Unfortunately, the results from measurements with a high degree of turbulence are still confusing. On the contrary, measurements to determine the suitability of the construction geometry proved that the tomograph might be operated in this configuration. The next logical step will be to model what resolution and what uncertainty of vector field determination can be achieved with a given number of transmitters and receivers.

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