Flomeko 2000 - IMEKO TC9 Conference
Salvador, Bahia, BRAZIL
4-8 June, 2000

LDA MEASUREMENTS IN HIGH-PRESSURE GAS PIPELINES

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Abstract: In industrial gas volume measurement, the reliable, precise, and economically efficient determination of the gas quantities by measurement is of utmost importance. Standby meter sections, Z-connection, and permanent series connection of two gas meters of different designs represent the state of the art. The permanent or temporary series connection for the comparison and test sections require expenses for a the establishment of a second complete measuring device. An alternative at present is the dismounting of the gas meter and checking it in an high-pressure test facility. A test according to requirements, using a non-interfering measuring instrument which should be portable, if possible, and usable with other gas meters, can be a bridge between these two options. To prove this, measurements with an LDA system were carried out in a natural gas high-pressure pipeline upstream of a turbine gas meter. After extensive profile and single-point measurements have been made, it can be said that this test using the single-point method is feasible with an uncertainty of ±0.5%, providing that certain prerequisites are met.
Keywords:Laser Doppler Anemometry (LDA), High-Pressure Natural Gas Pipeline, Flow Profile, Single-Point Measurement, Turbine Meter Check

1 INTRODUCTION

The analyses which were carried out aimed at comparing volume flow measurements by using turbine gas meters on the one hand and the laser Doppler method on the other hand in order to be able to answer the questions concerning the conditions, effort and outlay, and accuracy under which tests of turbine gas meters by means of a Laser Doppler Anemometer will be possible under operating conditions at a high-pressure natural gas pipeline.

The following table indicates which minimum requirements must be met by the laser technique with respect to the uncertainty of measurements.

Table 1:

Maximum permissible errors according to DIN 33800 for turbine gas meters [1]		
Flow rate	Error ranges	Maximum permissible errors on testing turbine gas meters as manufactured
$Q_{min} \leq Q < 0.2\ Q_{max}$	±2%	±1.0%
$0.2\ Q_{max} \leq Q \leq Q_{max}$	±1%	±0.5%

The test allowing to ensure that the maximum permissible errors of ±2% and ±1% are met is also required in accordance with prEN 12 261 [2] and OIML R32 [3].

2 MEASURING FACILITY

The high-pressure measurements were carried out with natural gas at a standby meter section (DN 200) of the Kirchheilingen underground storage of the company Verbundnetz Gas AG, Leipzig (cf. Figure 1).

Figure 1. Test-setup at the Kirchheilingen underground storage.

An 8" turbine gas meter of the type ELSTER G 1000 (cf. Figure 1 on the right) was available as a reference instrument. Together with a flow straightener and an inlet pipe (20D), the turbine gas meter has been tested at 50 bar at the high-pressure test facility of Ruhrgas AG at Dorsten and adjusted to an error range of ±0.2%. Upstream of this pre-assembled unit, the pipe-adapting piece was located – equipped with windows which ensure optical accessibility for the LDA flow measurement (cf. Figure 1 on the left). To ensure a uniform flow inside the pipeline, a disturbance-free inlet section of 62.5 D was mounted, which included four planes for the generation of particles (cf. Figure 2).

Figure 2. Pipe configuration

As no scattering particles of the size and concentration required for the LDA method were available in the high-pressure network after filtering /1/, methanol was therefore injected for these tests through type 121 Kreisl mist generators made by the company Schlick[1]. These generators (nozzles with diameters of 0.1 … 0.3 mm) produce an atomizing cone of 60° with droplets ranging from 5 to 150 µm. By arranging two nozzles each vertically and horizontally in a spraying plane as well as their individual or combined use, an optimal seeding was possible (cf. Figure 2)

Special care was given to the construction of the optical windows. They must withstand the maximum permissible pressure of 63 bar, be completely tight, and at the same time sufficiently large to allow scattered light to be transmitted (cf. Figure 3).

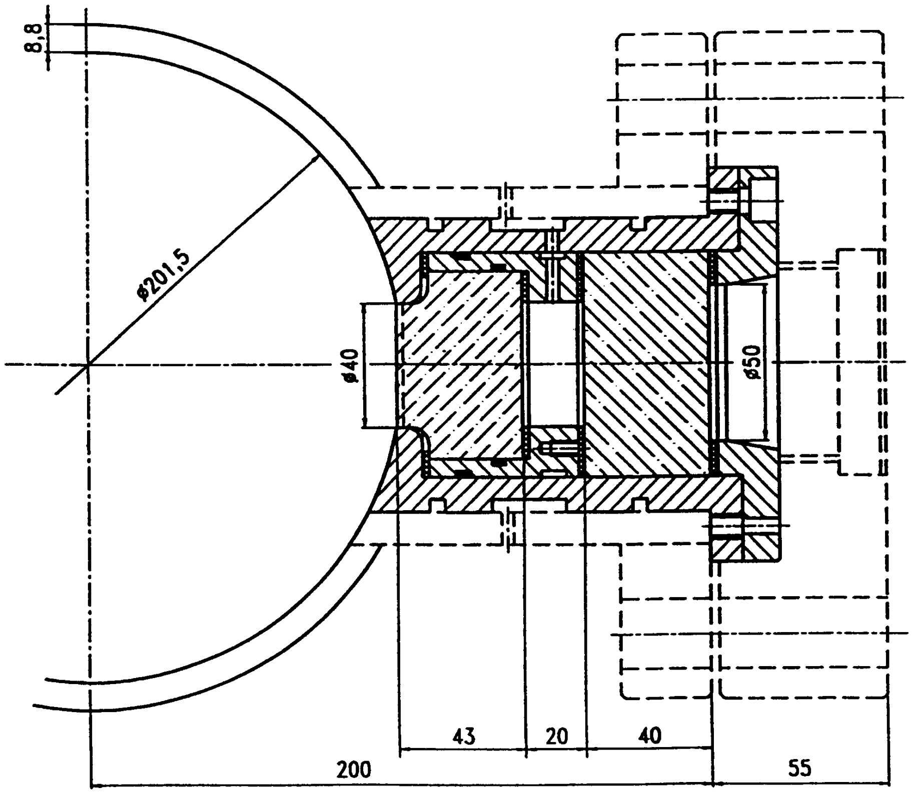

Figure 3. Construction of the optical window.

The selected design, with two glass plates per window, allows the condition to be constantly checked by measuring the pressure in the space between the glass plates. Either plane glass plates or cylindrically ground contour glasses were used for the inner windows.

3 MEASURING TECHNIQUE

The measuring setup that was used is shown in Figure 4. The pipe-adapting piece was manufactured with two windows arranged at an angle or 180° – thus allowing LDA measurements with forward and backward scattering. In addition, small focal distances of the LDA optical system allow to measure a half profile (measurement with backward scattering) from both sides. This was possible in case of these measurements with a focal distance of f = 310 mm. Using the lens system with f = 500 mm, the entire profile could be measured from one side.

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Figure 4. LDA system and optical window.

The measurement of the flow rate was carried out with the LDA probe (LDV 280) and the associated LDA controller (LDE 200) of the company Polytec. The measuring computer (LDA PC) ensures the A/D conversion and the processing of the measured values. The results are transferred to the master computer. For the recording of velocity profiles, the measuring computer triggers, via a control unit, a traversing system for the LDA probe (cf. Figure 5).

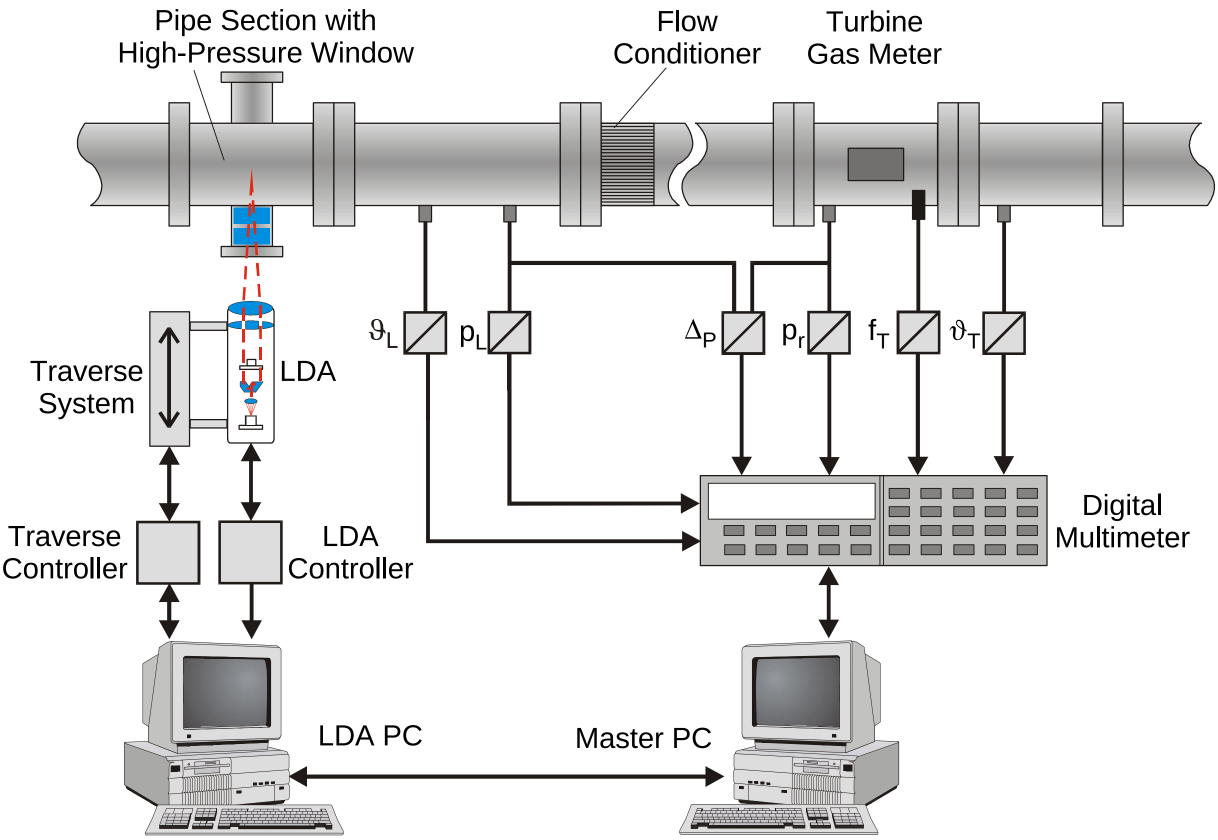

Figure 5. Test setup.

Behind the pipe-adapting section, there are the measuring points, to be assigned to the LDA plane, for the temperature t_L (0 … 60 °C) and the pressure p_L (0 … 63 bar) of the gas. To reduce the influence of the errors resulting from the pressure measurement in the requested comparison of the measuring instruments, a differential pressure transducer p (0 … 2 bar).

The comparison of the two measuring methods can only be made in accordance with the continuity equation for compressible media, on the basis of the mass flow rate or the standard volume flow rate, in the two measurement planes for Laser (L) and turbine gas meter (T).

A highly constant and stationary flow is an important prerequisite. This prerequisite could be met for this facility for a number of hours when gas was fed into the natural gas storage reservoir.

4 AUTOMATED MEASUREMENTS

The object-oriented software TestPoint for MS Windows was installed on the master PC. Using this software, the program LDAMess was developed which takes over the automation of the entire measurement process. The program communicates with the lower-level LDA PC via a serial interface, and issues commands to this PC in order to move the traversing carriage, to select certain measuring points, to initiate a measurement, to configure the LDA measuring software, and to terminate the program. The LDA PC provides the measured velocity and other relevant parameters.

The user can enter, into LDAMess, the initial parameters for the measurements, use the program to traverse the laser probe with high precision, and trigger the measurements after selecting or defining the measuring points along the radius. He/she may choose between a semi-automatic and a fully automatic mode. In the semi-automatic mode, he/she can decide whether the measurement is to be repeated at the previous radius or is to continued with the next one. In the fully automatic mode, the profile is traversed without any intermediate stops. Some of the values which are measured and computed by means of the LDAMess program are visualized and allow a clear picture of the measurements while these are carried out. During the profile measurements, the values are taken over by the multimeter which is connected with the master PC via a GPIB interface. The two instruments communicate with each other by means of the SCPI command set.

The Keithley multimeter of the type DMM 2000 serves as a digital measuring instrument for the collection and processing of the signals for the state variables pressure p and temperature ϑ and of the frequency f_T of the turbine gas meter. The multimeter can be programmed and operated either directly or through the PC. An internal multiplexer board of the multimeter provides 10 measuring points. A data memory allows to record several measured values and execute computations.

At the end of a profile measurement, the initial parameters, the profile values including the file names for the values measured at one traversing point and stored in the LDA PC, as well as the final results are output into a file of the master PC. They will thus be available also at a later date.

The work of the operator carrying out the measurements is limited to the start of the software, the input of the initial parameters, the measuring points and the file names as well as the operation of buttons in the LDAMess program. This ensures the automation of the measuring process and the analysis of the measured values.

4 PRELIMINARY LDA TESTS

4.1 Plane Glass Plates or Contour Glasses?

During the first high-pressure tests, weak LDA signals were detected for measurements in the center of the pipeline when contour glasses were used. Therefore the signal quality was examined for both types of glasses as a function of the distance y of the measuring volume from the exit face of the inner window.

To generate signals, a glass fiber was pasted on the circumference of a rotating test disk. The speed of the driving motor was electronically controlled and kept at a constant level. For the plane glass window, very good constancy of the Doppler frequency (s = ±0.006%) resulted in an almost constant and high signal-to-noise ratio (SNR) over the entire path of 160 mm available inside the pipe. A completely different result was obtained in an equivalent test using a contour glass window. Under ideal laboratory conditions, the constancy of the Doppler frequency (s = ±0.07%) is still acceptable. However, the signal-to-noise ratio decreases by about 30 dB from the pipe wall to the center of the pipe (cf. Figure 6).

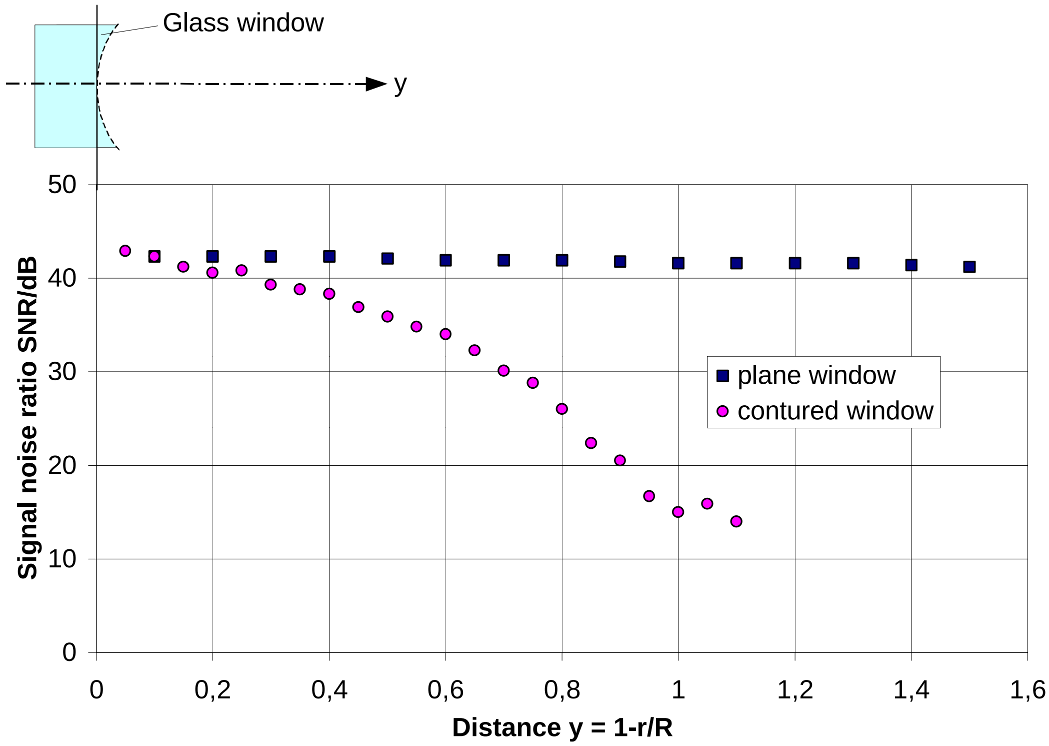

Figure 6. Signal-to-noise ratio SNR for plane and contour glasses.

This was one of the reasons why the subsequent high-pressure tests were carried out by exclusively using plane glass plates.

4.2 Measurement of Large and Small Particles

At a wavelength of = 820 nm and a focal distance of f = 310 mm, the laser probe which was used produced an interference fringe spacing of 4.25 µm. This would also be the desired size of the particles. When single-substance nozzles are used, droplet diameters of up to 100 µm are to be expected according to the manufacturer's specifications. Therefore an additional test was carried out with a wire of 5 µm in diameter and another wire of 100 µm in diameter, both arranged on the test disk and offset by 180° . The amplification was set to such a level that both signals could be acquired. However, the scatter for both velocities which were measured simultaneously remains almost the same, about ±0.07%. Hence it can be assumed that signals of different intensity and droplets of different sizes can be measured without any adjustment of the amplification or a correction of the trigger level. /2/

5 HIGH-PRESSURE MEASUREMENTS

With the symmetry of the flow proved and considering the low burst rate of maximally 5/sec at the LDA and the associated long measuring times for 2 x 512 single values per radius step, the half-profile measurement was selected. Figure 7 shows a typical result.

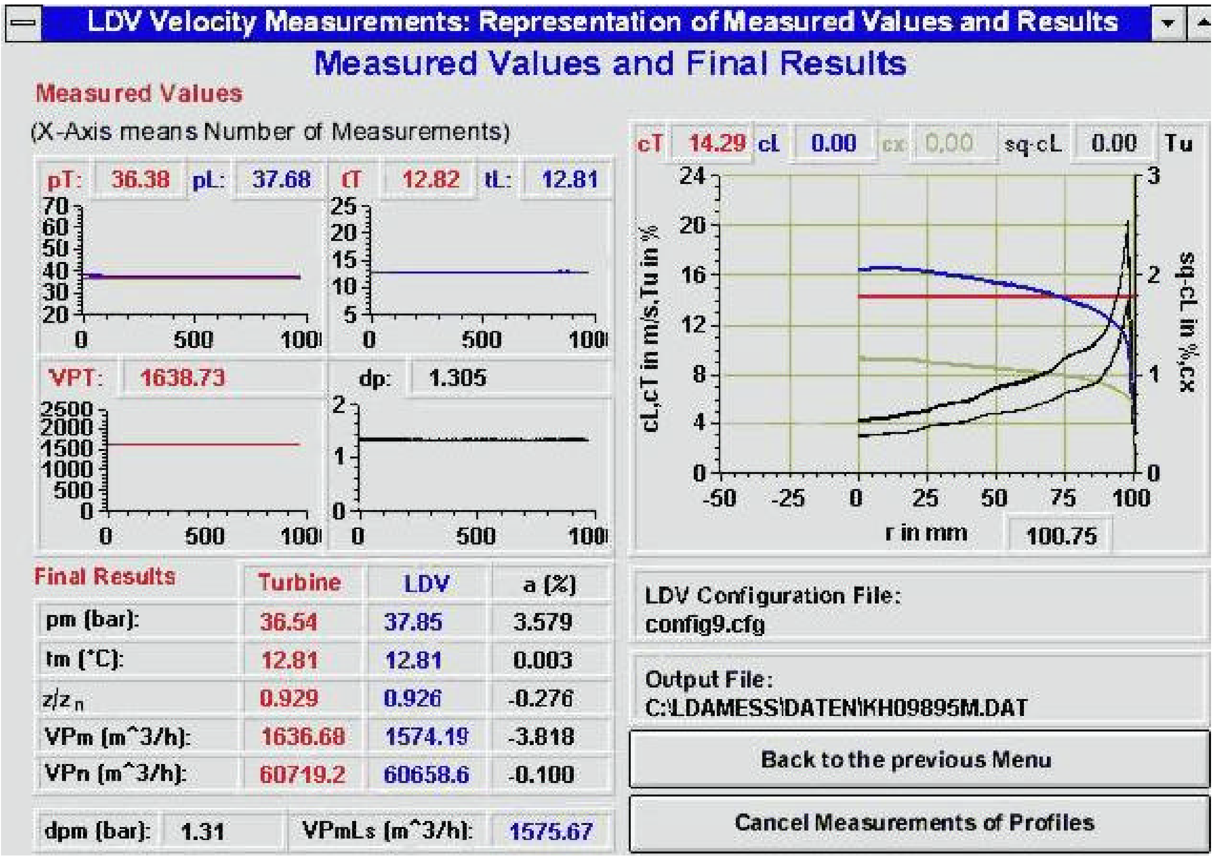

Figure 7. Screen shot during measurement.

This screen display is set up, point by point, on the master PC and allows the operating state and the function of the measuring device to be constantly checked during the measurement. The measured values (instantaneous values) are taken over from the multimeter in accordance with the adjusted cycle time (approx. 2 sec), plotted, and displayed in the relevant window. The profile diagram is updated after each radius step with the latest numerical values appearing in the upper windows. The last point at R includes the condition for aborting the measurement. According to the adherence condition, the quantities flow rate c_L, standardized flow rate c_x, standard deviation s (S = 95%) of the mean value at the measuring point, and the degree of turbulence Tu are set to zero. The value for the mean flow velocity c_T in the Turbine meter plane is displayed. The final results appear after the complete profile has been scanned and evaluated. The final file comprises all measurement data including the names of the files covering the measurements with LDA, which are stored in the LDA PC. The file name indicates the place, the date, and an ID for the measurement series.

As had been expected for Re numbers between 10^6 and 10^7, the same shape resulted for the standardized velocity profiles for 19 measurement series which were carried out on different days during a complete feed-in period, after repeated modification of the setup, including re-adjustment of the probe, and at different loading points.

The lowest uncertainty of measurement $u = 2*s/(N^{1/2})$ due to the degree of turbulence was determined in the center of the pipe with ±0.25% and, for r/R = 0.75, with ±0.35% (N = number of individual values for each traversing point).

The clear assignment of the local flow velocity to the average flow velocity allows a gas meter to be tested by means of a single-point measurement in the pipe center or at another suitable point (at up to 80% of the radius).

Major fluctuations and deviations resulted from the comparison of the standardized volume flows for the profile measurement. These are primarily caused by the increasing degree of turbulence towards the wall of the pipe. In addition, there is a systematic error due to the finite extension of the measuring volume. The local LDA measured values are larger than the values for the edge flow through the extrapolation of the computed velocities (cf. Figure 8). Under practical conditions, however, measurements were only possible up to r = 98 mm (at a radius of the pipe of R = 100.75 mm). In case of a simple numerical integration, the values of the LDA profile measurement then are always smaller than the values with the turbine gas meter.

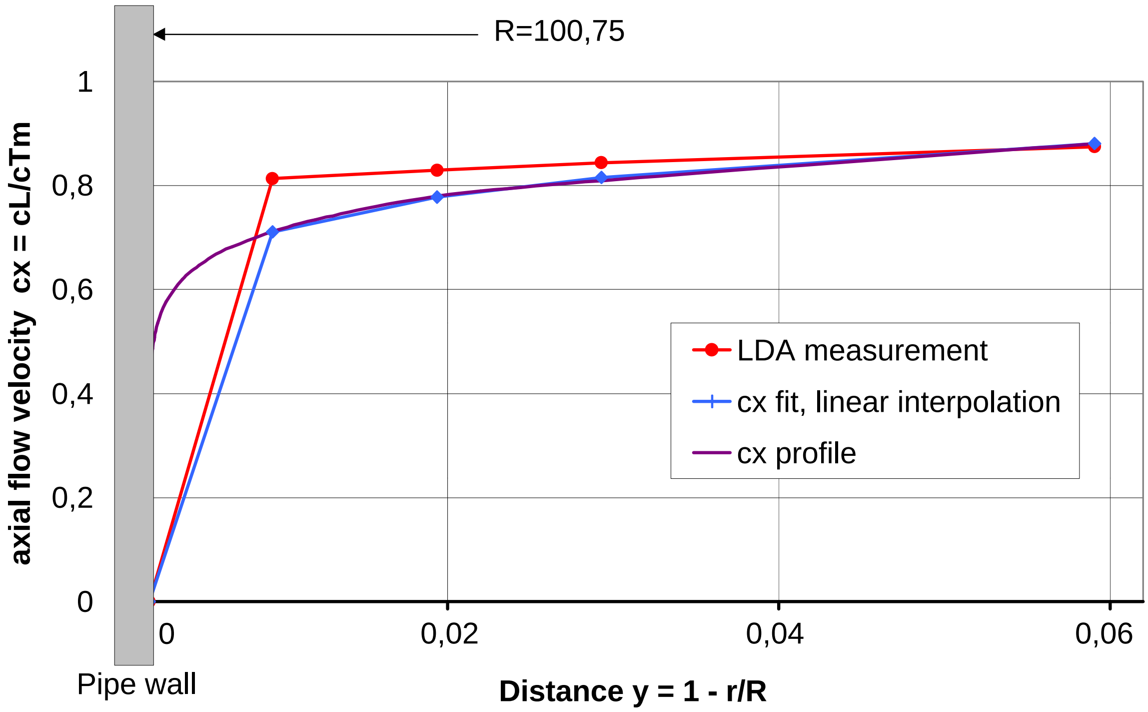

Figure 8. Axial low velocity near the pipe wall

The automated measurements in the high-pressure network were complicated by the fact that the particle size and concentration is obviously dependent on the volume flow or the flow rate. Since settings of the laser system – such as amplification, trigger level, and filter – were not modified during these measurements, this can be seen from the recorded periods of the analyzed laser bursts. This led to a further complication when measurements were carried out nearby the pipe wall. One of the options of increasing the particle concentration consisted in varying the dose of seeding and, in case of small gas flows, in shifting the spraying location towards the measuring plane. Obviously the evaporation of the methanol is mainly dependent on the retention time of the droplets in the gas flow (cf. Figure 9).

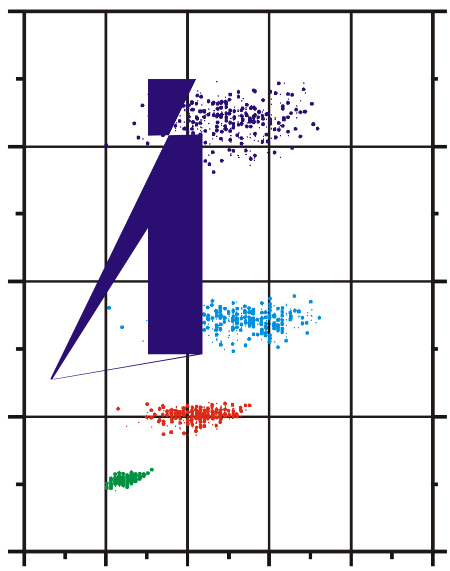

Figure 9. Number of periods per burst for different flow rates

6 COMPARISON OF PROFILE AND SINGLE-POINT MEASUREMENT WITH LDA

The results of the theoretical and experimental laboratory and high-pressure tests are summarized in the following table 2. The uncertainty of measurement of ±0.25% results, for the single-point measurement in the center of the pipe, from the measured degree of turbulence of 4%. It is possible to reduce this uncertainty down to ±0.1% by increasing the number of measured values to 6,400. Meanwhile such an increase can be effected due to the use of faster computers with data rates of 1 kHz and measuring times of less than 10 seconds. Table 2 also shows that, for the single-point measurement, a positioning accuracy of ±1% of the pipe radius also leads to an error of only ±0.1%. The particularly difficult registration of the boundary layer is eliminated, and the traversing facility is no longer required.

Table 2. Measurement uncertainties.

Evaluation of the uncertainty of measurement of the LDA method following tests performed on a high-pressure pipeline			
Evaluation criterion for the measurement of volume flow rates	***Individual values***	***Profile measurement***	***Single-point measurement, pipe center***
Measurement uncertainty from degree of turbulence measured	512 1,024	±0.75% ±0.55%	±0.35% ±0.25%
Dependence on volume flow rate		±1.0%	±0.5% correctable
Registration of boundary layer		large impact	no impact
Error of reference position ±1% of R		±1.3%	±0.1%
Required measuring times			
Duration of measurement at a data rate of 5/sec.	512 1,024	40 – 60 min 80 – 120 min	2 min 4 min
Duration of measurement at a data rate of 50/sec (possible in future)	512 1,024	6 min 12 min	10 sec 20 sec

The use of simpler plane glass plates, which is possible without noticeable effect, improves the signal quality and leads to reduced manufacturing costs.

From these results, it follows that the single-point measurement has considerable advantages as regards uncertainty of measurement, scope of measurement, and measuring time.

7 SUMMARY AND CONCLUSIONS

The selected measuring facility and the test setup allowed extensive, reproducible comparison measurements to be carried out. These measurements show that built-in gas meters can be tested with an overall uncertainty of < ±0.5%.

For facilities in which the flow inside the pipeline is similarly uniform and the degree of turbulence low, it can be assumed that a boundary value of ±0.2 … 0.3% can be achieved, provided the technical improvements of the instruments which are still possible, including a special high-pressure particle generator, are made full use of.

This test method does not require that the evaporation and slipping of particles are exactly known as these features have been taken into consideration in the first comparison measurement by means of the calibration. However, it must be guaranteed that these conditions can be exactly reproduced in subsequent tests.

The construction and the feed of the particles have proved themselves. In the near future, this setup is used for extended experiments under high-pressure conditions./3/

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ACKNOWLEDGEMENT
This work was performed in cooperation with Verbundnetz Gas AG, Böhlitz-Ehrenberg and Ruhrgas AG, Essen. The authors wish to thank all participants for their support and for sponsoring the work.