Germany's new Optical Primary National Standard for Natural Gas of high pressure at pigsar™

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Abstract

During the past decade a research test facility for the measurement of gas flow rates with a relative uncertainty of 0,1 % has been set up based on the laser Doppler technique. This facility has been used as an optical primary standard for gas under atmospheric pressure and flow rates up to 6500 m^3/h. To measure flow rates for gas under high pressure directly and in a single step without staggered arrangements of several flow meters the laser Doppler technique has been applied to set up a new optical primary single-step standard for natural gas under high pressure.

Keywords: Primary standard, flow rate, laser Doppler velocimetry, high pressure natural gas

Inhalt

1.0 Introduction

The German National Laboratory "pigsar™" which realizes the primary flow rate standard for natural gas under high pressure up to 50 bar is located in Dorsten. "Pigsar™" is operated by E.ON Ruhrgas company under the metrological supervision of PTB. The new optical flow rate standard based on laser Doppler velocimetry has been integrated into this facility and constitutes an extension of the piston prover used up to now as the primary standard on a volumetric working principle.

2.0 Principle of the optical primary standard

2.1. Flow rate measurement

In the new optical primary standard the volume flow rate is obtained by integrating the flow velocity across a well defined nozzle outlet surface *F*:

$$q_V = \int_F u\,dF \qquad (1)$$

(u: velocity perpendicular to the nozzle outlet surface).

If the velocity field is rotationally axisymmetric, it is sufficient to measure the profile along a radius *r* and to calculate the volume flow rate according to:

$$q_V = 2\pi \int_{T-0}^{R_{max}} u(r) r\,dr \qquad (2)$$

where $r = 0$ represents the axis of the nozzle and $r = R$ the nozzle wall. Figure 1 shows a normalized top hat shaped velocity profile, typical for the nozzle used.

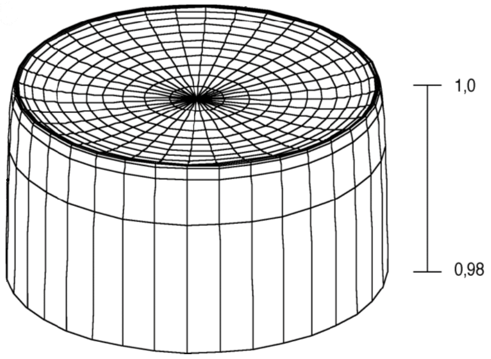


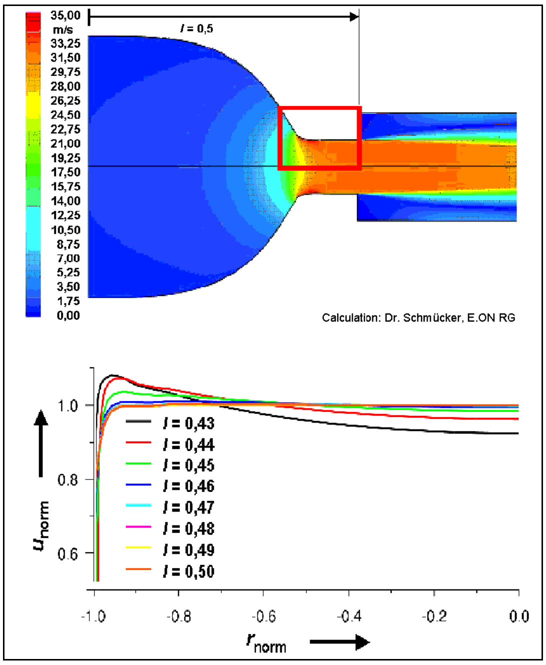
Fig. 1 Rectangular velocity profile across the LDA nozzle

The flow rate measurement based upon the measurement of velocity profiles at the nozzle exit plane is directly traced back to the SI units of length and time.

The velocity measurement is carried out by a properly calibrated laser Doppler anemometer considering the optical access to the nozzle outlet in the high pressure assembly. Additional measurements of temperature, pressure allow to obtain the mass flow rate.

2.2. LDA nozzle design

The calculus uses a singularity model. The walls have been replaced by vortex layers, at the inlet is a source disk and the outlet of the nozzle a sink disk. The wall friction was taken into account by boundary layer calculations using the method of Bradshaw et al. (Bradshaw, P.; Ferriss, D.H.; Atwell, N.P.: Calculation of boundary-layer development using the turbulent energy equation. In: J. Fluid Mech.; Cambridge U.K. 1967, Vol. 28, part 3, p. 593-616). A profile has been regarded as optimised, when in the exit of the nozzle there is a plane velocity distribution and when in the boundary layers of the contour the friction coefficients are larger than 0,002 to suppress flow separation. The computation of a large amount of nozzle shapes results in a set of profile parameters for different Reynolds numbers and contraction ratios [2] that have been adapted to the LDA nozzle. Figure 2 shows the calculated velocity distribution in the LDA nozzle for the applied nozzle contour.



Calculation: Dr. Schmücker, E.ON RG

Fig.2 Calculated velocity profile depending on the distance l from the LDA nozzle inlet (Börger shaped nozzle contour)

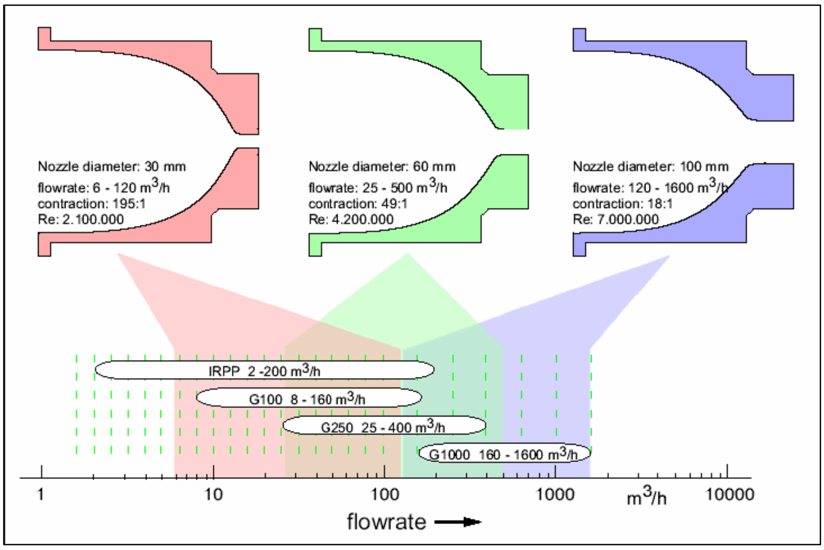


Fig.3 Realized nozzles to cover the flow rate range from 6 m^3/h up to 1600 m^3/h in such a way that the maximum flow velocity at the LDA nozzle outlet does not exceed 40 m/s, IRPP describes the flow rate range of the primary piston prover flow rate standard at "pigsarTM" (IRPP: Instromet Rotary Piston Prover)

Three nozzles have been designed (see fig. 3) to cover the flow rate range of the transfer standards used at "pigsarTM" in such a way that the velocity at the nozzle outlet does not exceed approximately 50 m/s in order to ensure optimal conditions for the LDA signal processing. The nozzles have been constructed as three compatible inserts of the LDA nozzle module, in which two high pressure glass windows provide the optical access for LDA velocity measurements at the nozzle outlet surface (see. fig. 4).

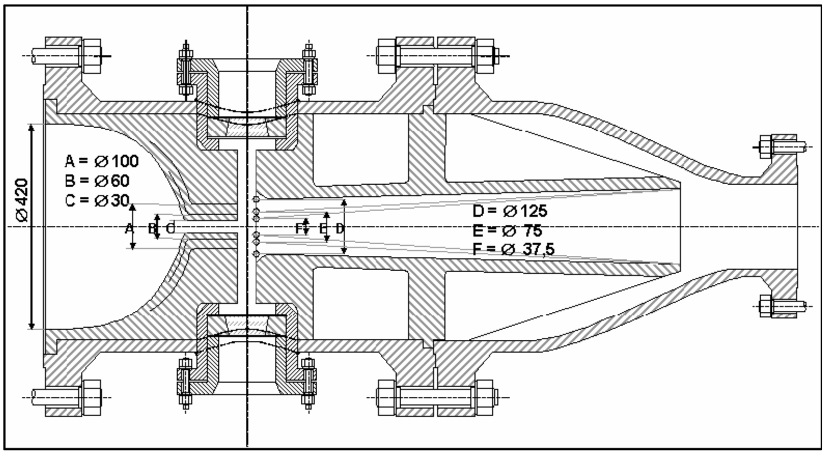


Fig. 4 LDA nozzle module of the new optical primary standard. Three different LDA nozzles (exchangeable) are available.

2.3. Set-up of the optical primary standard

The optical primary standard mainly consists of three sections: the inlet configuration, the LDA nozzle module, and the Laval nozzle stage (see fig. 5). The inlet configuration has a length of approximately 20 m, starting with a seeding section (D 200, 1 m length) connected with a specially developed particle generator for pressures up to 100 bar, a diffusor section (D 200 to D 500, 1 m length) and a long pipe (inlet section) (D 500, 18 m length) for flow conditioning upstream of the LDA nozzle.

The LDA nozzle module (see fig. 4) comprises the LDA nozzle, two glass windows facing each other as optical access to the LDA measuring chamber and a diffusor section with a D 200 output flange to connect the LDA nozzle module to the Laval nozzle bank.

The Laval nozzle bank ensures a stable flow rate during the LDA measurement time and additionally serves as transfer standard between the two primary standards, the piston prover and the new optical standard.

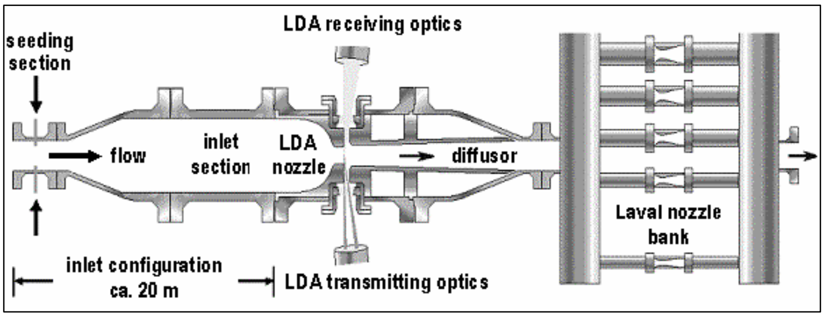


Fig.5 Set-up of the new optical primary standard

2.4. Seeding generator for high pressure

As usual in gas measurement facilities at the inlet of "pigsarTM" a filter system is installed. The purpose is to clean the gas from any kind of dust, oil, particles etc, which may effect the controls, valves and instruments of the facility. By filtering the gas especially contamination inside the standards or the meter under test are avoided which may effect the metrological behaviour like the long-term stability.

In order to apply optical methods for the velocity measurement a sufficient seeding of the gas flow with particles of known size distribution by a particle generator is necessary.

Seeding generators applicable for high pressure applications are commercially not available. The PTB developed a seeding generator in close co-operation with the Technical University of Dresden. The generator atomises DEHS, an often used liquid for seeding purposes.

The atomisation is carried out by a gap nozzle known as Laskin nozzle.

The particle generator works up to a pressure of p = 100 bar. The pressure holding vessel was designed according to the European pressure directive (PID) and was approved for the use in high pressure natural gas installations.

The Laskin nozzle is arranged under the DEHS level inside the pressure vessel. Two windows allow the supervision of the liquid level as well as the proper function of the atomiser (see fig. 6).

The Laskin nozzle is designed for an overpressure up to 20 bar against the pressure inside the liquid. Because of the small volume inside the vessel a special separation wall was provided. This wall is perforated by a lot of holes allowing only the smaller particles to get to the outlet.

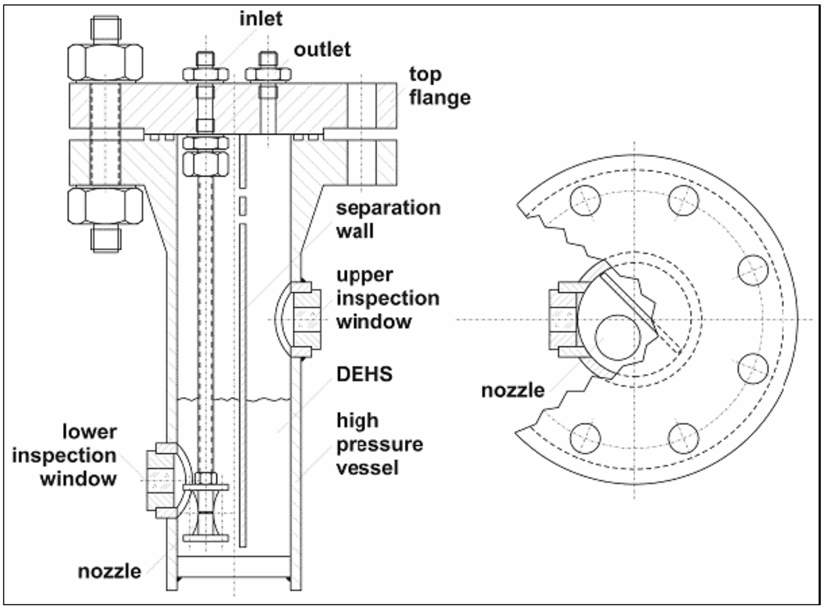


Fig. 6 LDA particle generator for 100 bar applications to seed the natural gas flow

In order to produce particles a pressure difference between the carrier gas (natural gas) at the inlet of the Laskin nozzle and the liquid to be atomised is necessary. First investigations show that an overpressure of 1 bar already leads to a satisfactory particle generation rate. Because the pressure inside the optical test section depends on the adjusted calibration pressure, the pressure difference between Laskin nozzle inlet and the liquid is controlled via a difference pressure regulating valve (see fig. 7).

The control membrane of the regulating valve is mechanically stressed by a spring in addition by the output pressure of the atomiser via a connection pipe. Hence the difference pressure is controllable independently from the outlet pressure of the generator by the spring load. The other parts of the atomiser installation shown in figure 7 are necessary for the operation of the atomiser like filling, pressurisation and depressurisation.

Tests of the generator show very good results concerning the achieved particle concentration and the spatial distribution inside the optical test section.

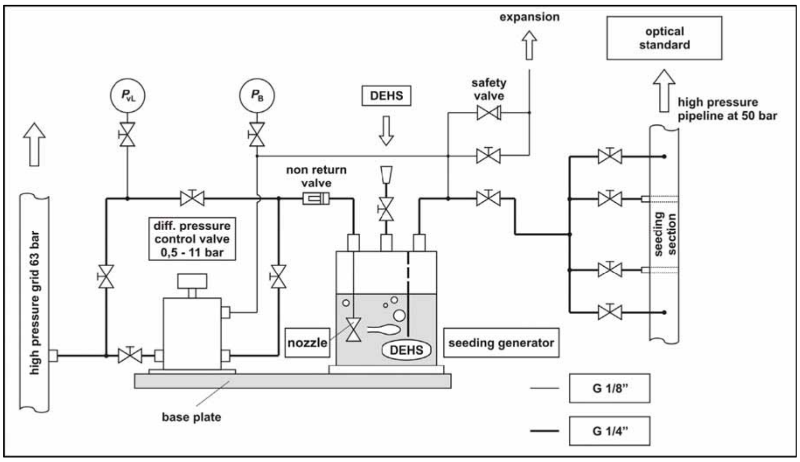


Fig.7 Installation scheme of the LDA particle generator for high pressure flow seeding

2.5. LDA and LDA calibration

The optical flow rate measurement is traced back to a precise velocity measurement at the LDA nozzle outlet of the LDA nozzle module. The velocity u of the gas flow is measured by a LDA based on the differential Doppler technique is determined by:

$$u = \Delta x \cdot f_D \quad (3)$$

with f_D as Doppler frequency of the measuring signal generated by the scattered light of tracer particles embedded in the flow and Δx as fringe spacing in the LDA measuring volume. The measuring volume is given by the intersection volume of two laser beams crossing each other by an angle of 2φ . The fringe spacing is ideally given by:

$$\Delta x = \lambda / (2 \sin\varphi) \quad (4)$$

If the optical set-up of the LDA is well aligned and the Gaussian LDA beams cross each other at their beam waists, one can assume that the fringe spacing is constant within the measuring volume (see fig. 8).

Especially if bulky window constructions for the optical access have to be used the real fringe spacing can differ from the calculated one along the length of the measuring volume. Thus the LDA has properly to be calibrated by measuring the local fringe spacing and determining its deviations over the measuring volume length.

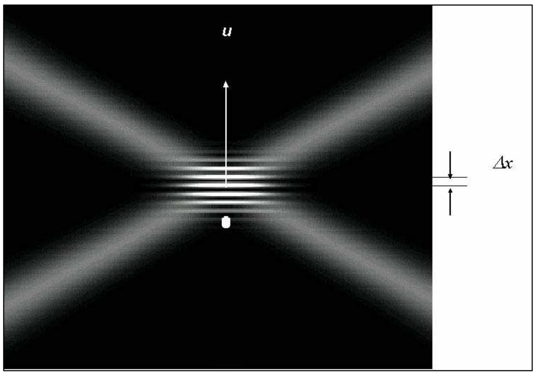
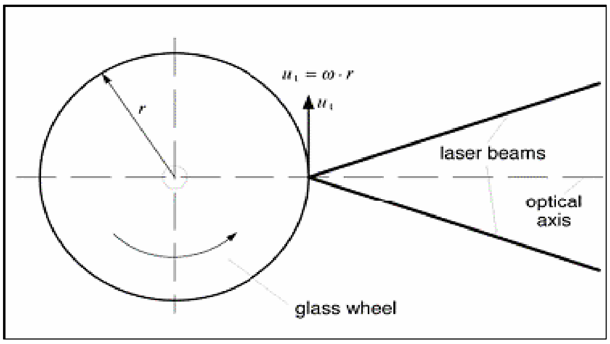


Fig.8 LDA fringe spacing mechanism

The deviation of the fringe spacing within the measuring volume determines the uncertainty of the LDA flow measurement and especially limits the minimal detectable turbulence intensity of the flow.

A calibration method to measure the local fringe spacing inside the measuring volume is to generate precise particle velocities and to measure the Doppler frequency in order to calculate the fringe spacing at different positions of particle transitions in the measuring volume. The most precise method is to use single particles on a rotating glass wheel with its well known diameter driven by a stepping motor to ensure a very constant and accurate speed (see fig. 9).



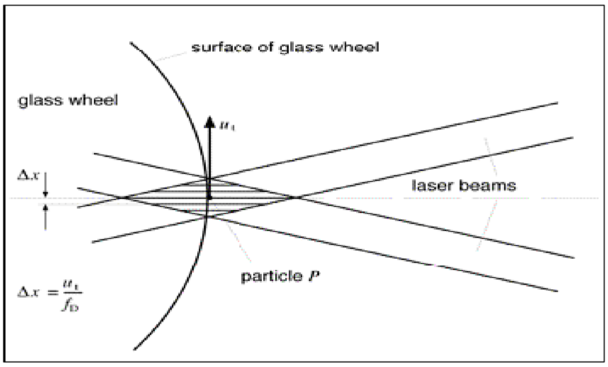


Fig.9 Calibration of the LDA with a rotating glass wheel

For the calibration of the LDA the high pressure glass window (see fig. 10), which is used for the optical access to the LDA nozzle outlet, has to be included. After calibration of the LDA at PTB (see fig.11), the LDA system has been installed and integrated in front of the glass window, which delivers the optical access to the nozzle outlet of the LDA nozzle module of the new optical primary flow rate standard at "pigsarTM" (see fig. 12).

Fig.10 LDA window of the LDA nozzle module optical access

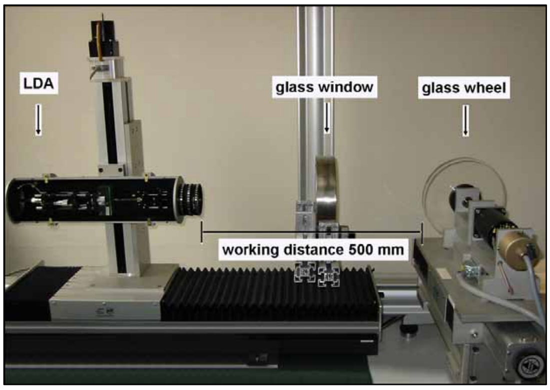


Fig.11 Calibration of the LDA considering the

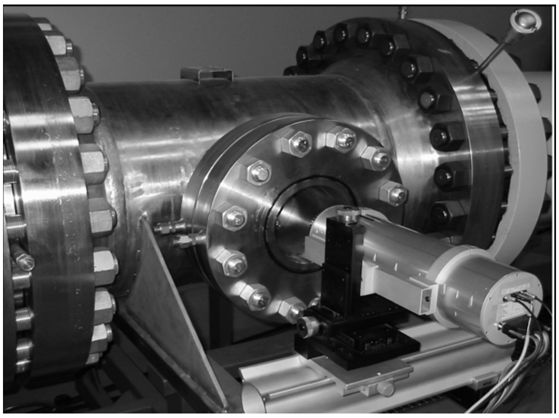


Fig.12 LDA installed at the LDA nozzle module to allow full external optical access to the LDA nozzle

For the LDA measurements up to now two different LDA systems have been used.
One LDA system is a Nd:YAG-laser Doppler anemeometer (see fig. 13) with an output power of approximately 100 mW at a wavelength of 532 nm, a working distance of 500 mm and a fringe spacing of Δx = 3,148 nm.

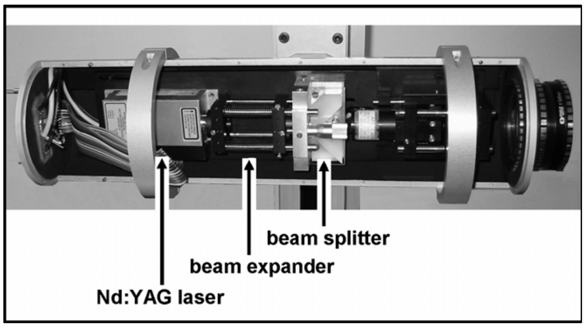


Fig.13 100 mW Nd:YAG LDA used for forward scattering

This system has been used in forward scattering direction according to the LDA arrangement shown in figure 5 for a single point measurement in the middle of the LDA nozzle jet.

A second LDA system is a completely fibre coupled LDA system based on the application of a tapered amplifier diode laser system delivering an optical output power of approximately 500 mW at a wavelength of 850 nm. The system has a fringe spacing of Δx = 8,667 nm and a working distance of 500 mm. The system has been used in backscatter mode in order to measure the velocity profile of the free jet at the LDA nozzle outlet by traversing the LDA (see fig 14)

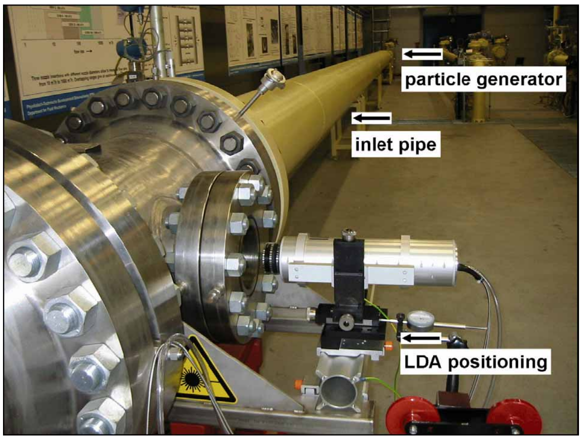
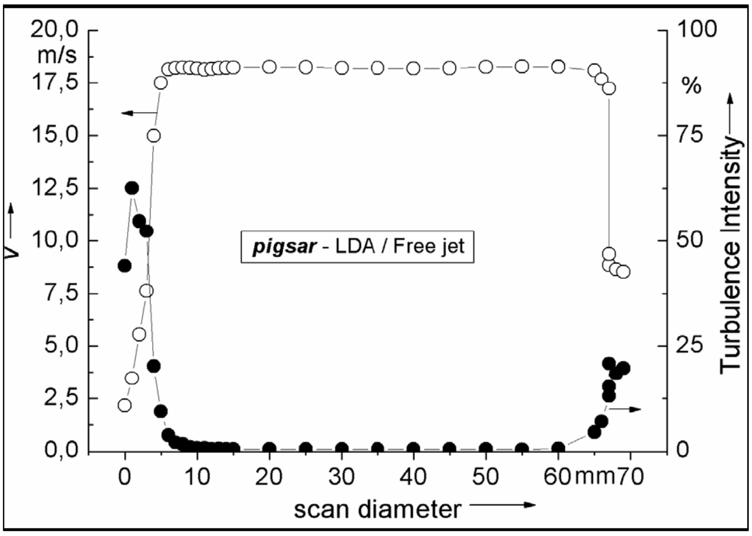


Fig.14 LDA for backscatter measurements

3.0 Measuring results

3.1. Profile measurement of the free jet

For a velocity profile measurement of the free jet downstream of the LDA nozzle outlet the laser power in the LDA measuring volume of the backscatter LDA (see fig. 14) was in the range of 250 mW – 300 mW. Figure 15 shows the obtained velocity profile which is top hat shaped as expected (see fig.1).



Quelle: pigsar™

Fig.15 Measured velocity and turbulence profiles at the exit plane of the LDA nozzle

The basic idea of the applied high contracting ratio nozzles is to get very symmetrical top hat shaped velocity profiles to allow a very repeatable and fast profile measurement. Once the boundary layer has been measured, the volume flow rate measurement can be reduced to a single point measurement (center line velocity measurement).

3.2. LDA single point flow rate measurement

Under the assumption of a top hat shaped flow profile, the volume flow rate can be approximated by a single point velocity measurement in the middle of the free jet (center line) at the LDA nozzle outlet. In that case the uncertainty can be estimated to be less than 0,5 %. To reduce the uncertainty for the volume flow rate measurement, the velocity profile in the boundary layer of the gas flow at the LDA nozzle has to be considered in addition. Figure

16 shows the software operating surface for the first flow rate measurement based upon a single point velocity measurement at the LDA nozzle outlet of the LDA nozzle module.

Figure 17 shows an exemplary measuring result presented during commemorative event of the 10th anniversary of the "*pigsar*™" calibration facility of E.ON Ruhrgas Company and PTB in Dorsten on December 10th in 2003.

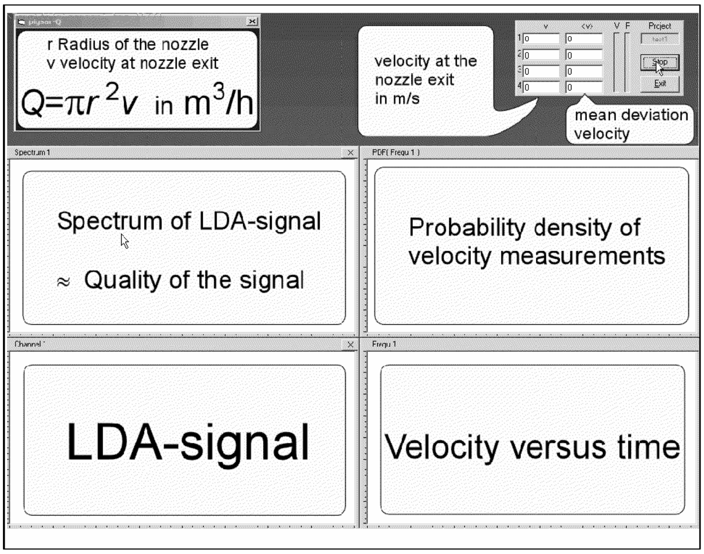
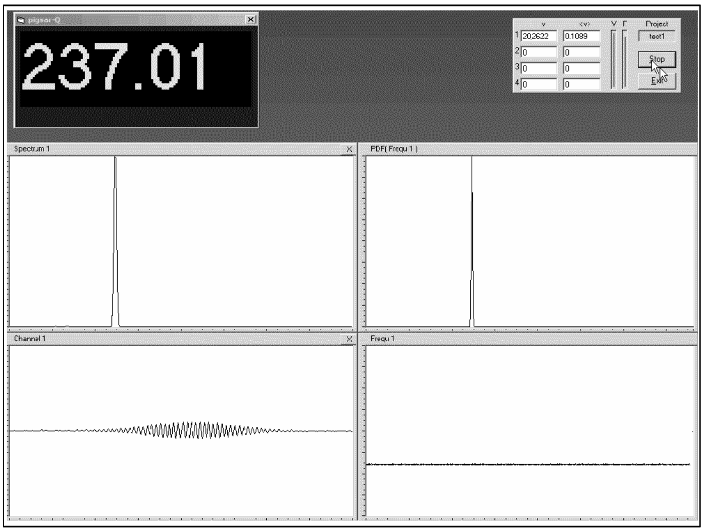


Fig.16 Software operating surface for optical flow rate measurement for high-pressure natural gas based on LDA



237.01

1 20,2622 0.1089
2 0 0
3 0 0
4 0 0

test1

Fig.17 Exemplary result of the first volume flow rate measurement with the new optical primary standard for natural gas; each LDA signal represents the volume flow rate with an uncertainty of 0,5%

4.0 Conclusion

The working principle of the new optical flow rate primary standard for natural gas under high pressure has been described and first measurement results have been presented. As the flow rate measurement is directly traced back to the definition of the volume flow rate by measuring the flow velocity profile across a well defined surface a wide flow rate range can be covered without the conventionally used staggering techniques. Therefore, a single-step primary standard for natural gas has been realized.

In a first step the uncertainty of the volume flow rate measurement based on the application of the LDA technique can be estimated to approximately 0,5 %. This uncertainty will be reduced by considering the boundary layer of the flow at the LDA nozzle outlet in a next step.

In the near future two completely different realizations of the unit natural gas cubic meter at high pressure will be available.

5.0 Acknowledgment

The authors thank Dr. Gehlhaar of TU-Dresden for the close cooperation during the development and construction of the generator. Further the authors like to address the support given by the Company TOPAS concerning the construction of the Laskin nozzle.

6.0 Reference

- Bradshaw, P.; Ferriss, D.H.; Atwell, N.P.: Calculation of boundary-layer development using the turbulent energy equation. In: J. Fluid Mech.; Cambridge U.K. 1967, Vol. 28, part 3, p. 593-616
- G.-G. Börger: Optimierung von Windkanaldüsen für den Unterschallbereich, Dissertation an der Ruhr-Universität Bochum (1973)
- Dopheide, D., Taux, G., Krey, E.-A., 1990: "Development of a New Fundamental Measuring Technique for the Accurate Measurement of Gas Flowrates by Means of Laser Doppler Anemometry", Metrologia 27, 65 – 73, 1990
- [4] Müller, H., Strunck, V., Mickan, B., Kramer, R., Dopheide, D., Hotze, H.-J., 2003: „Optisches Durchflussnormal für HD-Erdgas: Voraussetzungen für einen LDA-Einsatz", Lasermethoden in der Strömungsmesstechnik, 11. Fachtagung 2003, 8.1 – 8.6, ISBN: 3-00-011903-5