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LASER DOPPLER VELOCITY PROFILE SENSOR: TECHNICAL ADVANCES FOR THE OPTICAL FLOW RATE MEASUREMENT OF NATURAL GAS

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Abstract − The precise measurement of the flow rate of natural gas is of vital economical importance since natural gas contributes highly to the total energy mix. In this paper we report about a laser Doppler velocity profile sensor specifically designed to suit the measurement conditions at the optical test facility of the German natural gas flow rate standard. The profile sensor is an extension of the principle of a laser Doppler anemometer (LDA); however, instead of one interference fringe system with (nearly) parallel fringes two fringe systems - one with converging and one with diverging fringes – are employed. Thereby both spatial resolution and velocity accuracy are more than one order of magnitude better than for a conventional LDA. The data obtained are compared to measurements with a conventional LDA. As a result the shear layer could be resolved more precisely by the profile sensor which yields a more accurate determination of the flow rate. In addition the mean value of the measured turbulence intensity of the core flow amounted to only 0.14 % for the profile sensor, more than one order of magnitude lower than for the conventional LDA. The minimum measured turbulence intensity was 0.07 %, which is, to our knowledge, the lowest value ever measured by optical methods.

Keywords: laser Doppler velocity profile sensor, flow rate measurement, high pressure natural gas

1. INTRODUCTION

The precise measurement of natural gas flow is of vital economical importance [1, 2]. Therefore national metrology institutes, the gas industry and research institutes are permanently making efforts to increase the measurement accuracy. The national German natural gas flow standard is located at the test facility pigsar™ operated by E.ON Ruhrgas AG under supervision of the national metrology institute of Germany (Physikalisch-Technische Bundesanstalt, PTB). Currently a mechanical piston prover is used as a primary flow rate standard. A second independent flow rate standard based on an optical measurement technique is to be developed where an accuracy of ≤ 0.1 % is aimed for [3]. The optical flow rate standard has to operate at natural gas pressures up to 50 bar[1].

Optical flow rate measurement techniques offer the advantage of being non-intrusive and are based on the measurement of the velocity field $v(r,\phi)$ over the cross section of the flow. The volume flow rate Q can then be obtained by integrating over the whole profile:

$$Q = \int_0^{2\pi}\int_0^{R} v(r,\phi) r d\phi dr \, . \tag{1}$$

Hence the measurement is based on the SI units of length and time. If the mass flow rate is needed to be known the temperature and pressure have to be measured to obtain the density.

Imaging techniques like particle image velocimetry (PIV) and Doppler global velocimetry (DGV) facilitate flow field measurements with high spatial resolution. However, for PIV the velocity accuracy is typically in the range of a few percent [4] and hence not high enough to suit the demands of an optical flow rate standard. Conventional DGV can achieve a velocity measurement accuracy of 0.5 m/s with an optimized system [5], which is too low, since the velocity in the core of the natural gas flow is about 14 m/s (relative error: 4 %).

Laser Doppler anemometry (LDA) is a quasi-pointwise technique based on a fringe system formed by two coherent intersecting laser beams. For measuring flow rates by LDA it is advantageous to have a circular symmetric flow profile. In that case (1) reduces to a line integral:

$$Q = 2\pi \int_0^{R_{max}} v(r) r dr. \tag{2}$$

Therefore the flow rate can be measured by the velocity measurement along one radius. However LDA suffers from two limitations which are inherent to the measurement principle. Firstly the spatial resolution is limited by the finite size of the measurement volume which is given by the intersection region of the employed Gaussian beams. This effect is especially obstructive for the measurement of shear

[1] Remark for comparison: The North Stream pipeline in the Baltic Sea operates at pressures up to 220 bar.

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layers where an averaging over the steep velocity profile occurs. Secondly the fringes of the interference system are not exactly parallel, but they show a spacing variation along the optical axis which is due to the curvature of the Gaussian beams. This effect leads to a decreased accuracy of the velocity measurement and hence to an inaccurately high measured value of the turbulence degree (*virtual turbulence*). Both effects are complementary to each other, since a strongly focused beam would yield a high spatial resolution but – due to the high wave front curvature – also a high virtual turbulence.

In order to overcome these drawbacks the laser Doppler velocity profile sensor [6] was developed. It is based on the employment of two fringe systems superimposed in the same measurement volume. This allows for the determination of both lateral particle velocity and axial position of the particle within the measurement volume. Therefore both spatial resolution and velocity accuracy are improved by more than one order of magnitude. The profile sensor introduced in this paper [7] was specially developed with a fiber optics based measurement head of 560 mm working distance to suit the requirements for the measurement at the flow rate test facility.

2. THE OPTICAL FLOW RATE TEST FACILITY

In the used set-up of the optical flow rate test facility natural gas at a pressure of 50 bar flows through a nozzle of 63.6 mm diameter with a contraction ratio of 49:1. The flow created has a nearly flat top velocity profile with a turbulent shear layer of about 3 mm thickness, which contains between 5 % and 10 % of the volume flow. The flow is seeded by DEHS tracer particles with a mean diameter smaller than 1 µm. A critical nozzle is used for controlling the flow rate to keep it constant. Two optical windows of 4 cm thickness made of borosilicate glass constitute the access for the sending optics and the forward scattering receiving optics of the profile sensor.

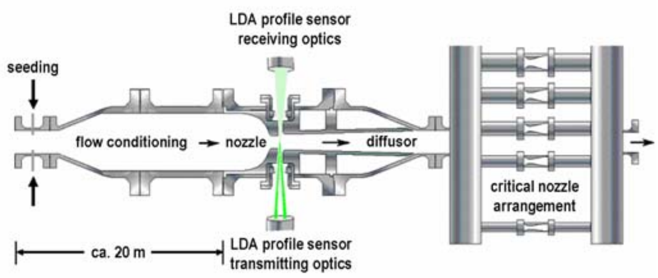

Fig. 1: Optical flow rate test facility with seeding section, nozzle, diffusor and critical nozzle scale

3. THE LASER DOPPLER VELOCITY PROFILE SENSOR

The laser Doppler velocity profile sensor is based on an extension of the LDA principle. However, instead of one single fringe system with (nearly) parallel fringes two distinguishable superposed fringe systems – one with diverging, one with converging fringes – are utilized (Fig. 2). This fringe distortion is achieved by placing the beam waist in front of and behind the beam crossing region, respectively [6]. Calibration of the profile sensor consists in determining the fringe spacings $d_1(z)$ and $d_2(z)$ as a function of the axial position z. This is achieved by use of a mounted pinhole passing the measurement with known velocity and at known positions z. The calibration before the gas flow measurement was performed through a glass window identical to the installed windows. The spatial calibration function q is obtained as the quotient of the fringe spacings:

$$q(z) = \frac{d_1(z)}{d_2(z)} . \tag{3}$$

A particle passing the measurement volume emits two burst signals with frequencies f_1 and f_2, from which the axial particle position z can be obtained by use of the spatial calibration function:

$$\frac{f_2}{f_1} = \frac{v/d_2(z)}{v/d_1(z)} = \frac{d_1(z)}{d_2(z)} = q(z) . \tag{4}$$

The particle velocity is then obtained from the local fringe spacing:

$$v = d_1(z) * f_1 = d_2(z) * f_2 . \tag{5}$$

Thus the laser Doppler velocity profile sensor facilitates the resolution of the particle position within the measurement volume, leading to an increase in spatial resolution and velocity accuracy by more than one order of magnitude compared to a conventional LDA.

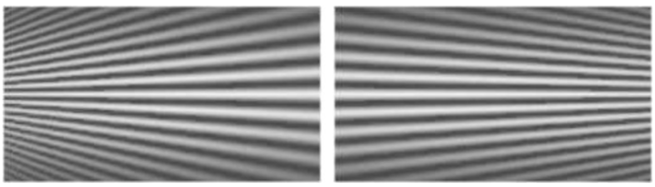

Fig. 2: Two superposed distinguishable fringe systems with divering and converging fringes form the measurement volume

Because of the safety restrictions and the set-up of the flow rate test facility several requirements were imposed on the profile sensor measurement head. Firstly the working distance of the sensor had to be > 500 mm. Secondly no electrical components were allowed in the testing hall. Thirdly the measurement had to be performed through a 4 cm thick borosilicate window. To avoid dispersion effects a measurement system based on frequency division multiplexing (FDM) with a 5 W Nd:YVO_4 laser at 532 nm was developed [8] (Fig. 3). Three acousto-optical modulators (AOMs) were used to obtain four beams with slightly different frequencies that were coupled into fibers leading to the measurement head.

Scattering light was detected by a single avalanche photodiode detector whose electronic signal was filtered and down-mixed to obtain the two Doppler frequencies corresponding to the two fringe systems.

The measurement head is shown in Fig. 4. Four 25 m long polarization-maintaining single-mode fibers providing the sending light are connected to separate sending units, which contain a collimating and a focusing lens. Since the lenses are passed on-center aberration effects are minimized, entailing low values of beam quality factor M^2 of 1.0-1.3. The working distance of the sensor amounts to 560 mm. In the current configuration the sensor can measure velocities up to 50 m/s.

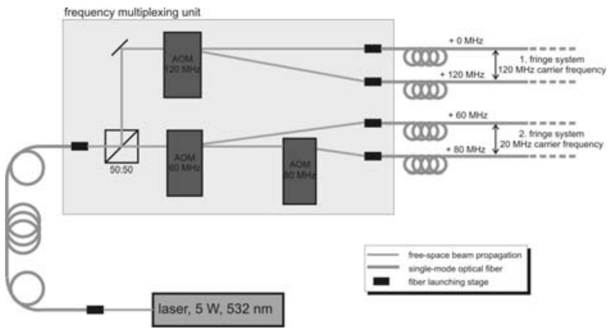

Fig. 3: Frequency division multiplexing unit. By use of three AOMs a total of four beams with different frequencies are generated

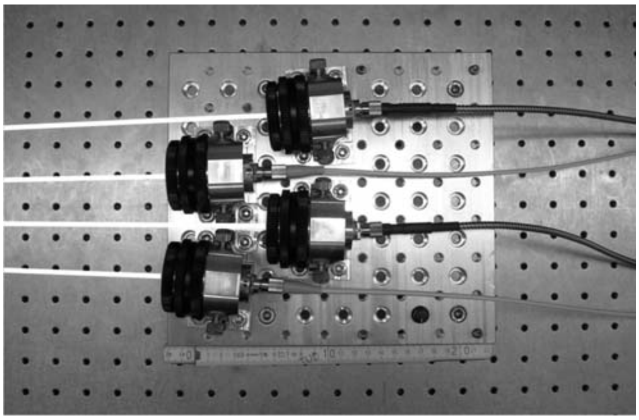

Fig. 4: The measurement head of the profile laser system consisting of four separate sending units with collimation and focusing lens. The light is delivered by polarization-maintaining fibers

4. MEASUREMENTS AND RESULTS

For each passing particle the profile sensor records its lateral velocity and axial position. For the profile evaluation the data were allocated to intervals (slots) with an equal width of 200 µm. Within a slot the mean velocity and the turbulence degree σ_v/v could be calculated by averaging. By traversing of the sensor the whole nozzle velocity profile was obtained. For comparison reference measurements with a conventional LDA with a measurement volume of 300 µm x 300 µm x 1 mm were performed. In this measurement the traversing direction was along the short axis of the LDA to minimize the spatial averaging effect. Fig. 5a and 5b depict the data for both cases. The measurements of both sensors clearly show the top-hat profile of the nozzle flow. However the top line of the mean velocity profile shows stronger deviations from a straight line for the reference LDA than for the profile sensor. The turbulence intensity in the central region measured by the profile sensor reached values as low as 0.07 % with an average of 0.14 %. This value directly affects the statistical error of the flow rate. For the reference LDA a value of about 2 % was obtained. This large value is due to the effect of virtual turbulence coming from the curvature of the fringes as described in Section 1. The measured turbulence is not inherent to the flow itself, but comes from the velocity measurement uncertainty of the conventional LDA. An upper bound for the real flow turbulence is given by the turbulence intensity measured by the profile sensor. This measurement shows that for this flow measurement the velocity accuracy is more than one order of magnitude higher for the profile sensor than for the conventional LDA.

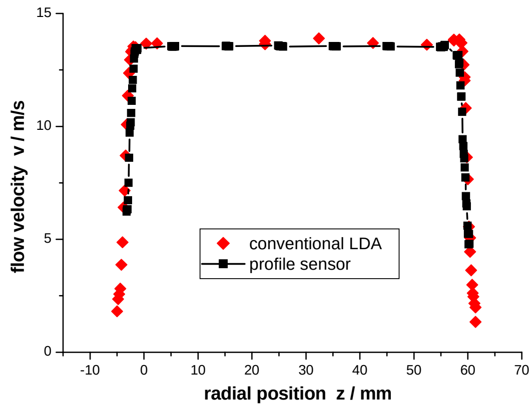

Fig. 5a: Measured mean velocity profile for profile sensor and conventional LDA

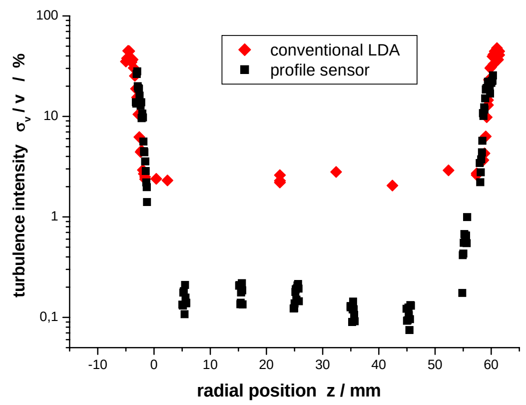

Fig. 5b: Measured turbulence profile for profile sensor and conventional LDA

Fig. 6a and 6b show the measured mean velocity profile and the profile of the velocity standard deviation of the shear layer region for profile sensor and reference LDA. The mean velocity profile of the profile sensor has a steeper slope, which indicates that the spatial averaging effect is smaller than for the LDA. However the effect is expected to be small, since the averaging length amounted to 300 µm for the LDA (given by the measurement volume) and 200 µm for the profile sensor (given by the slot size). For more conclusive results the measurement would have to be performed down to velocities close to zero. Due to the effect of virtual turbulence the standard deviation profile shows consistently higher values for the reference LDA than for the profile sensor. However in relative values this effect is not as large for the shear layer region as for the central region since the measured standard deviation is mostly due to real turbulence inherent in the flow stemming from wall friction.

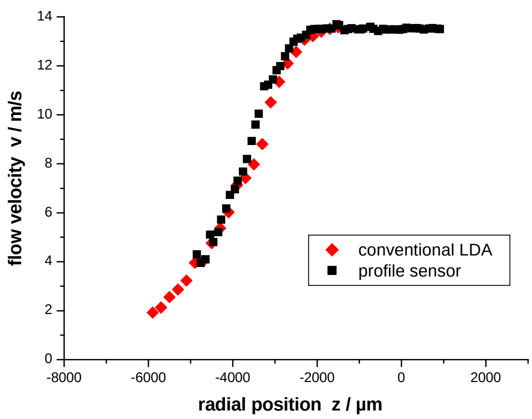

Fig. 6a: Measured mean velocity profile of the shear layer for profile sensor and reference LDA

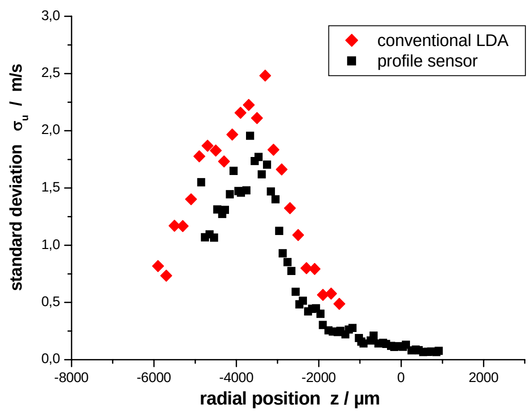

Fig. 6b: Measured profile of the velocity standard deviation of the shear layer for profile sensor and reference LDA

For the measured profile data a tanh-profile fit was performed by a least-square algorithm to obtain the total flow rate Q by (2). The turbulence profile was used to estimate the statistical uncertainty σ_Q of the flow rate, resulting in:

$$Q = (153.80 \pm 1.00)\frac{m^3}{h}. \tag{6}$$

A reference value was deduced from the mass flow rate determined by the critical nozzle scale which was calibrated by the piston prover primary standard:

$$Q_{ref} = (154.32 \pm 0.42)\frac{m^3}{h}. \tag{7}$$

The relative systematic deviation of measured flow rate and reference value amounts to

$$\frac{\Delta Q}{Q} = \frac{Q - Q_{ref}}{Q_{ref}} = -0.33\%. \tag{8}$$

5. CONTRIBUTION OF THE CALIBRATION TO THE MEASUREMENT BUDGET

The flow rate measurement is based on the flow velocity measurement by equation 5. The frequency can be estimated with an accuracy close to the Cramer-Rao lower bound [9]. The fringe spacing is known from calibration by

$$d = \frac{v_x}{f} = \frac{\Omega r}{f}, \tag{9}$$

where v_x denotes the pinhole velocity, r the radial distance of the rotating pinhole, Ω the rotation frequency of the disc and f the measured Doppler frequency. The by far biggest contribution stems from the radius r which is only known with an accuracy of about 0.5 %. Ω has a relative accuracy of $< 5*10^{-4}$ and f can be measured close to the Cramer-Rao lower bound. Using a calibration tool with a better known radius (as described in [3]) would improve the reliability of the measured flow rate significantly.

Other sources of uncertainty might be contributed by the statistical reliability of the profile and the missing data near zero velocity.

6. CONCLUSIONS AND OUTLOOK

A novel laser Doppler velocity profile sensor was designed and applied for the flow rate measurement of high pressure natural gas. The velocity measurement accuracy is increased by more than one order of magnitude compared to a conventional LDA, which is especially visible in the central flow region with a low average turbulence intensity of 0.14 %. The minimum measured turbulence intensity amounted to 0.07 %, which is, to our knowledge, the lowest value determined by any optical method. The measured shear layer shows a slightly higher slope for the profile sensor which is most likely due to its higher spatial resolution. Both velocity accuracy and spatial resolution directly affect the accuracy of the flow rate uncertainty.

Several improvements are expected to further reduce the uncertainty significantly:

- Use of a calibration tool with higher accuracy
- Use of a glass window of higher optical quality
- Profile measurement down to zero velocity
- Acquisition of a higher number of data points

The use of a laser Doppler field sensor [10] which measures the flow velocity in two coordinates and three velocity components can lead to an even further improvement.

In conclusion it seems possible that the aimed uncertainty of 0.1 % for the flow rate uncertainty can be met by using the profile sensor.

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