LDA volume flow rate standard for water using high spatial resolution LDA for traceable measurements in power plants

**M. Juling1, J. Steinbock1, M. Kraume2, T. Lederer1**

*1Physikalisch-Technische Bundesanstalt (PTB), Abbestraße 2–12, 10587 Berlin, Germany*

*2Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany*

*Markus.Juling@ptb.de*

# Abstract

At the Physikalisch-Technische Bundesanstalt (PTB) a laser optical volume flow rate standard (LFS) has been developed to calibrate flow meters on site within a power plant. The velocity profile within the pipe is measured with laser Doppler anemometry (LDA). The profile is integrated to calculate the volume flow rate.

Since conventional LDA has a measuring volume length of about 2 mm, the near wall region cannot be resolved. This leads to an offset of the volume flow rate of about 1.3 %. To overcome this limitation high resolution LDA (HR-LDA) was developed. Therefore, a LDA measuring volume with constant fringe spacing is overlaid with an LDA measuring volume with divergent fringe spacing. In this way, the position of a particle passing the measuring volume can be determined with a resolution of 50 μm. With the HR-LDA the influence of the near wall region on the volume flow rate was reduced from 1.3 % to 0.04 %.

Overall an uncertainty of 0.19 % (k=2) for the LFS was achieved. A comparison of the LFS with the national primary standard for thermal energy (WZP) at PTB with an uncertainty of 0.04 % (k=2) revealed a maximum deviation of 0.07 %.

# 1. Introduction

Precise volume flow rate measurements are crucial for controlling power plants. Currently the volume flow rate in a power plant is measured with Venturi tubes or orifice plates. Since the conditions of the calibration differ widely from the conditions within the power plant, their uncertainty is highly increased by:

- the high temperature of up to 400 °C

- the high pressure of up to 300 bar

- the unknown velocity profile

- the effects of fouling and abrasion

Due to the resulting uncertainty of about 2 %, the power plant process cannot be controlled efficiently. Therefore, the maximum power output is reduced. That is why, PTB has developed a new laser optical volume flow rate standard (LFS) which allows it to calibrate flow meters on site within the power plant to reduce the uncertainty of the flow rate measurement.

For the LFS, the velocity profile within the pipe is measured with laser Doppler anemometry (LDA). The profile is integrated to calculate the volume flow rate.

So far, the uncertainty of the LFS has been limited by the size of the measuring volume. Since conventional LDA has a measuring volume length of about 2 mm, the near wall region of the flow cannot be resolved. This leads to an offset of the volume flow rate of about 1.3 %. To overcome this limitation, high resolution LDA (HR-LDA) was developed and will be presented in this paper.

# 2. Laser optical volume flow rate standard (LFS)

*2.1 LDA*

LDA is used for the LFS to measure the velocity profile. As shown in Figure 1, two laser beams are crossed to form the measuring volume at their intersection. Within this measuring volume the laser beams interfere with fringe spacing *L*.



Figure 1: LDA measuring principle

Particles within the fluid which move through the measuring volume with a velocity *v* will scatter the light. The scattered light is detected with a photomultiplier. The resulting burst signal has a main frequency *fS* which is directly related to the velocity

(1)

*2.2 Experimental setup*

The LDA system is integrated within an LDA probe. To measure the velocity profile within the pipe, the probe is moved with a high precision positioning system so that the measuring volume can be placed anywhere inside the pipe through an optical access, see Figure 2. The velocity profile is measured along a grid with radial paths. Afterwards the profile is integrated to obtain the volume flow rate.



Figure 2: LFS experimental setup

*2.3 Uncertainty*

The expected extended uncertainty for the LFS is smaller than 0.2 % (*k*=2). A comparison with the national primary standard for thermal energy (WZP) at PTB, which uses a gravimetric system and has an extended uncertainty of 0.04 (*k*=2), showed a maximum deviation of 0.07 %.

# 3. High resolution LDA

One of the main contributions to the overall uncertainty of the LFS was the wall effect.

*2.1 Wall effect*

If the flow profile near a boundary wall is measured with LDA, the measured velocities are higher than the real velocities. This wall effect is illustrated in Figure 3.



Figure 3: Wall effect

The reason for the wall effect is that the measuring volume has a finite length, which is about 2 mm for the presented setup. In the near wall region, only part of the measuring volume lies inside the glass pipe. Therefore, the centre of the measuring volume is shifted towards the centre of the pipe. This means that instead of the real velocity *vreal* at the theoretical centre of the measuring volume *rmv,meas* the higher velocity *vmeas* at the shifted centre *rmv,real* is measured. This offset of the measured velocity in the near wall region has been described by many other authors [1], [2], [3], [4], [5]. Uncorrected, the wall effect will result in a much higher measured volume flow rate.

*2.2 Measuring principle*

To reduce the influence of the wall effect, high resolution LDA was set up. The measuring principle of this HR-LDA is illustrated in Figure 4. It is based on the work of [6].



Figure 4: Measuring Principle HR-LDA

For the HR-LDA two measuring volumes with different interference patterns *L*(*r*) and laser light wavelengths are overlaid. One measuring volume has constant fringe spacing (green), while the other one has diverging fringe spacing (orange). A particle that moves through both overlaid measuring volumes will generate two bursts. The ratio between the frequencies *fS1* and *fS2* of these two bursts is proportional to the ratio of the fringe spacing *L*1 and *L*2 of the two measuring volumes at the position *rP*, where the particle moved through the measuring volumes.

(2)

In this way a spatial resolution inside the overlaid measuring volumes can be achieved.

*2.3 Experimental setup*

So far, this measuring principle has been applied to various gas flows, for example [7], [8]. The challenge was to apply the measuring principle to a liquid pipe flow through a complex optical access with several phase interfaces and varying refraction indices.

Therefore, two standard LDA probes were used, see Figure 5. The probes can be positioned with two separate high precision positioning system such that the two measuring volumes can be overlaid anywhere across the entire pipe cross section.



Figure 5: Experimental setup HR-LDA

*2.3 Calibration*

One LDA probe uses a 532 nm Nd:YAG laser and has constant fringe spacing. The other LDA probe uses a 561 nm Nd:YAG laser and has converging fringe spacing. The fringe spacing of the LDA probes was measured and adjusted with a rotating disk velocity standard. Figure 6 shows the measured fringe spacing for four repeated measurements. Linear functions are fitted to the measured fringe spacing. These functions are later used with equation 2 to determine the particle position inside the measuring volume.



Figure 6: Fringe spacing of the LDA probes

*2.4 Positioning*

In order to overlay both measuring volumes inside the pipe, a very low uncertainty for the positioning of the LDA probes is necessary. Therefore, two positioning systems with an uncertainty of less than 67 μm were developed. Furthermore, a measurement method, which uses reflections on a glass marking on the pipe, was developed to precisely align the LDA probes with the positioning system and with the pipe. With this method, an angular deviation of the alignment below 0.005 ° can be achieved, which results in a positioning uncertainty for the measuring volume of less than 4 μm.

# 4. Experimental results

*2.1 HR-LDA*

The result of an HR-LDA measurement is shown in Figure 7 for a measuring position at a radius of 37.23 mm, which is 0.27 mm away from the glass pipe wall at a radius of 37.5 mm. Instead of just a velocity distribution, which would be the result of a standard LDA, the HR-LDA yields the axial velocity over the position at which the particle crossed the measuring volume for every single particle. Therefore, the velocity gradient along the measuring volume can be seen.



Figure 7: Particle velocity and position inside the measuring volume

To further investigate the near wall velocity gradient, overlapping HR-LDA measurements were conducted along a radial path. The result is shown in Figure 8 for the near wall region.



Figure 8: Results of HR-LDA

The Figure shows the 2D frequency distribution, which represents the number of bursts with a certain velocity and position. For further data analysis the mean velocities for several analysis windows along the radial coordinates are calculated. The window width and interval and, therefore, the resolution are set to 50 μm. The resulting mean velocities are shown with white triangles in Figure 8.

In Figure 9, the results of HR-LDA are compared with the results of standard LDA.



Figure 9: Comparison of standard LDA and HR-LDA

As predicted by the wall effect, the velocities measured with standard LDA are much higher compared to the velocities measured with HR-LDA. Especially in the near wall region the deviation is as high as 29 %. Consequently, the uncorrected standard LDA measurements lead to a deviation of up to 1.3 % for the integrated volume flow rate compared to the HR-LDA measurements. The HR-LDA measurements therefore confirm the wall effect and show that for standard LDA measurements a correction of the wall effect is necessary. Based on the HR-LDA measurements, an analytical correction with an uncertainty of 0.04 % was developed, which can be applied to the standard LDA measurements. Therefore, the influence of the wall effect was highly reduced with HR-LDA.

# 3. Conclusion

For the laser optical volume flow rate standard at PTB, high resolution LDA has been developed which reduces the spatial resolution of LDA from 2 mm to 50 μm. Thereby, the wall effect was corrected and its influence on the uncertainty was reduced from 1.3 % to 0.04 %.

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