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# Measurement uncertainty budget of an interferometric flow velocity sensor

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## ABSTRACT

Flow rate measurements are a common topic for process monitoring in chemical engineering and food industry. To achieve the requested low uncertainties of 0.1 % for flow rate measurements, a precise measurement of the shear layers of such flows is necessary. The Laser Doppler Velocimeter (LDV) is an established method for measuring local flow velocities. For exact estimation of the flow rate, the flow profile in the shear layer is of importance. For standard LDV the axial resolution and therefore the number of measurement points in the shear layer is defined by the length of the measurement volume. A decrease of this length is accompanied by a larger fringe distance variation along the measurement axis which results in a rise of the measurement uncertainty for the flow velocity (uncertainty relation between spatial resolution and velocity uncertainty). As a unique advantage, the laser Doppler profile sensor (LDV-PS) overcomes this problem by using two fan-like fringe systems to obtain the position of the measured particles along the measurement axis and therefore achieve a high spatial resolution while it still offers a low velocity uncertainty. With this technique, the flow rate can be estimated with one order of magnitude lower uncertainty, down to 0.05 % statistical uncertainty.[1] And flow profiles especially in film flows can be measured more accurately. The problem for this technique is, in contrast to laboratory setups where the system is quite stable, that for industrial applications the sensor needs a reliable and robust traceability to the SI units, meter and second. Small deviations in the calibration can, because of the highly position depending calibration function, cause large systematic errors in the measurement result. Therefore, a simple, stable and accurate tool is needed, that can easily be used in industrial surroundings to check or recalibrate the sensor. In this work, different calibration methods are presented and their influences to the measurement uncertainty budget of the sensor is discussed. Finally, generated measurement results for the film flow of an impinging jet cleaning experiment are presented.

**Keywords:** flow velocity measurement, LDA, laser Doppler profile sensor, measurement uncertainty, shear layer, wall shear stress

## 1. INTRODUCTION

High resolution flow velocity data from within shear layers are vital to simulate film flow processes like cleaning prediction for a impinging jet. To acquire this data, a high resolution flow velocity sensor is needed which can measure the flow profile near walls. Most common solutions for this problem do not offer a sufficient resolution to observe processes like film flow processes. State of the art for flow velocity measurement, like needed for measuring in film flows, is basically the Particle Image Velocimetry (PIV). In principle this technique needs two optical accesses, one for illumination and one for detecting the scattered light.[2] The aimed application that will be presented only offers a single optical access, so that standard PIV can't be applied. The Enhanced versions of stereo-PIV and astigmatic-PIV provide the possibility to measure with an single optical access and deliver the depth-resolution that is needed to measure the flow profile between wall and fluctuating surface wave of the film flow. The relative spatial uncertainty in axial direction is with 6 % for stereo-PIV and astigmatic-PIV not high enough to adequately show the flow structure in the thin film.[3] An approach with the Laser Doppler Velocimeter (LDV) based Laser Doppler Velocity Profile Sensor (LDV-PS) can yield the required spatial and

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velocity uncertainties and is therefore used in this work. To ensure sufficiently low systematic deviations a reliable calibration technique is needed. For calibrating the presented LDV-PS in principle a moving scattering object is observed and the velocity depending signal frequencies are calculated to derive the fringe distance functions. In this work the Laser Doppler Velocity Profile Sensor (LDV-PS) is combined with a triangulation sensor, which is able to measure the distance to a stationary or fluctuating surface. Different calibration approaches are discussed to provide a calibration system that can reduce the systematic deviations of the flow velocity measurement below the statistical uncertainty of the LDV-PS and thereby can calibrate both systems simultaneously. Finally the calibration is tested at a test experiment to determine wall shear stress and the calculation uncertainty at a film flow setup.

## 2. MEASUREMENT PRINCIPLE

For many common flow dynamical problems only few measurement data is available to validate simulation models. This is in particular the case for processes that involve two phase flows. For example in jet cleaning and reactive flows, film flows play a vital part in the chemical processes. Unfortunately not enough measurement data is available to validate new simulation models that aim on optimizing film processes. At this point the LDV-PS can provide valuable data to validate the simulation models. The LDV-PS was optimized in this work to measure the shear layer flow within a 500 µm thin film flow to calculate the wall shear stress at an impinging jet.

### 2.1 Laser Doppler Velocity Profile Sensor

The standard technique for flow measurements with only one optical access is the Laser Doppler Velocimeter where two intersecting coherent laser beams generate a fringe interference pattern with parallel fringes.[4] A tracer particle which is mixed to the flow travels through the fringe volume, scatters light and thereby produces a burst signal which can be observed and evaluated. With a priori calibration, the frequency of this burst signal can be used to determine the particle velocity. This standard technique for single optical access also does not offer a sufficient spatial resolution to acquire the flow structure because the standard measurement volume size is set to $100\,\mu\text{m} \times 100\,\mu\text{m} \times 1000\,\mu\text{m}$ . For small focus diameter of the LDV the fringe distance along the optical axis is according to the following equation:

$$d(z) = \frac{\lambda}{2\sin\theta} \cdot [1 + \frac{z\cos^2\theta(z\cos^2\theta - z_w)}{z_R^2 cos^2\theta - z_w(zcos^2\theta - z_w)}] \tag{1}$$

whereas $z$ is the axial position $\lambda$ is the laser wavelength $\theta$ is the crossing angle $z_w$ is the axial position of the beam waist and $z_R$ is the Rayleigh length. For small $z_R$ the second part of the equation is dominant and so the fringe distance $d(z)$ can not be considered as parallel any more. This equation shows a dependency of the slope of the fringe distance from the axial position of the beam waist $z_w$. According to the optical components used, a small displacement of focusing lenses can result in a shift in the axial position in of the beam waist, which directly inflicts a change of the fringe distance along the optical axis. This fact implicates, that with smaller focus diameter a low spatial uncertainty can be achieved, but only with the trade off off increased velocity uncertainty and vice versa. This fact can be overcome by using two distinct contrary defocused fringe systems, like shown in figure 1. By using this behaviour the standard LDV is extended to a Laser Doppler Velocity Profile

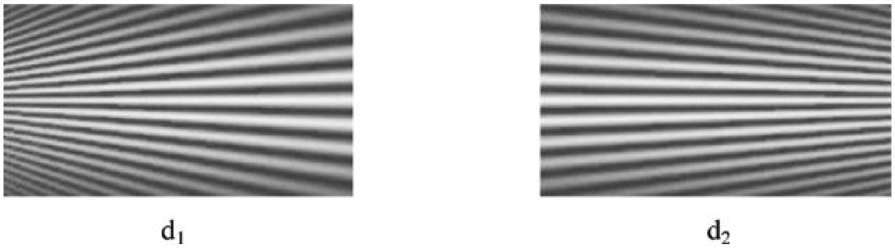


Figure 1. diverging and converging fringe systems of the LDV-PS

Sensor (LDV-PS).[5] With these fan-like fringe systems two burst signals are generated by each particle passing through the measurement volume. The Quotient $q(z) = \frac{f_1}{f_2} = \frac{d_2}{d_1}$ of the Doppler frequencies $f_1$ and $f_2$ is distinct assigned to a axial position by the quotient of the fringe distances $d_1$ and $d_2$ in the measurement volume which is shown in figure 2. By using this fact, the complementarity between velocity and spatial resolution of the LDV can be overcome and by using its extension the statistical spatial uncertainty can be reduced down to 0.85 %, with a velocity uncertainty below 0.18 % like shown in [1].

## 2.2 Measurement Setup

The requirements, the sensor needs to offer to deliver the knowledge addressed from the shear layer are set according table 1. To obtain the flow profile for the test experiment which will be presented in section 2.4 the LDV-PS needs to be adapted to measure the flow profile with respect to the film wave to the burst time for the ensemble averaging. To achieve this, the profile sensor is combined with a laser triangulation sensor to be able to measure the instantaneous film thickness by evaluating to the Fresnel scattered light from the fluid-gas interface at the wave.

Table 1. Resolution and uncertainty requirements for the sensor system.

| Direction | Value |
|---|---|
| axial direction | <20 µm |
| lateral direction | <50 µm |
| velocity uncertainty | <1 % |

The sensor concept was realised by a breadboard design where the measurement volumes of the triangulation sensor and the LDV-PS are superimposed. The system concept is shown in figure 3 directly together with the test experiment. The LDV-PS that was introduced in section 2.1 was realised by wavelength multiplexing with a 532 nm and a 561 nm laser sources. The beam waist diameter and defocusing can be adjusted by the lens pairs in front of the sources. Both beams are superimposed and splitted by an prism beam splitter and get of axis but in parallel to the front lens of the sensor. The triangulation sensor is based on a 670 nm as a third wave length because the beams of the LDV-PS are tilted to the optical axis, which limits the spatial resolution due to the enlargement of the detected spot on the camera. The red laser beam is also guided to a lens pair to position the beam waist an then guided to the optical axis by a tilted mirror, so that all beams hit the front lens in a parallel manner. The front lens gathers all beams to the measurement volume which is at a distance of 80 mm, in the focal plane of the front lens. A particle which passes through the measurement volume scatters light which is detected by a Keplarian telescope and collected to a multi mode fiber. This fiber is connected to a demultiplex unit which separates the wavelengths by dichroic mirrors and guided to avalanche photo detectors for conversion to an electrical signal. This signal is detected with a digitizer card and evaluated by a measurement PC. Furthermore the measurement volume is observed by an telescope with the magnification of 1 : 4 connected to the line camera with a pixel size of 8 µm. The realized setup offers an lateral spatial resolution of 40 µm for the triangulation sensor at the gas liquid interface with a measurement range of approximately 2.5 mm. The LDV-PS has a measurement volume length of 600 µm and a width of 60 µm with fringe distance of 3.7 µm to 4.6 µm for 532 nm and 5.3 µm to 4.1 µm for 561 nm. As tracer particles for the velocity measurement silver coated micro spheres with a mean diameter of 10 µm were used and thereby a spatial resolution of about 5 µm was achieved.

## 2.3 CALIBRATION

To be able to produce reliable validation data for the film flow the measurement uncertainty of the LDV-PS needs to be considered, which was presented in [6] as:

$$\frac{\sigma_v}{v} = \frac{1}{\sqrt{2}} \frac{\sigma_f}{f} \tag{2}$$

Whereas the relative statistical uncertainty of the Doppler frequency $\frac{\sigma_f}{f}$ is mostly affected by the signal evaluation, systematic deviation are not. The velocity of the particle $v$ is calculated by

$$v = f_i \cdot d_i(z(q(f_1, f_2))) \tag{3}$$

from the Doppler frequency $f_i$ of one of the fringe distance and the corresponding fringe spacing $d_i$ which is estimated by the quotient of both measured Doppler frequencies through the calibration data presented in figure 2. The uncertainty for the quotient $q$ is also only determined by the uncertainty of the calculation of the Doppler frequencies. Whereas the fringe distance $d_i$ in contrast is not only depending on the signal evaluation, but also on the calibration and adjustment of the setup. The evaluation of fringe distance uncertainty according [7] leads to the uncertainty budget for the fringe distance to:

$$d = \frac{u \cos\theta}{f_D} \tag{4}$$

$$\sigma_d = \frac{1}{f_D}\sqrt{(\cos\theta\sigma_u)^2 + (\frac{\delta d}{\delta f_D} u \cos\theta)^2 + (u \sin\theta\sigma\theta)^2} \tag{5}$$

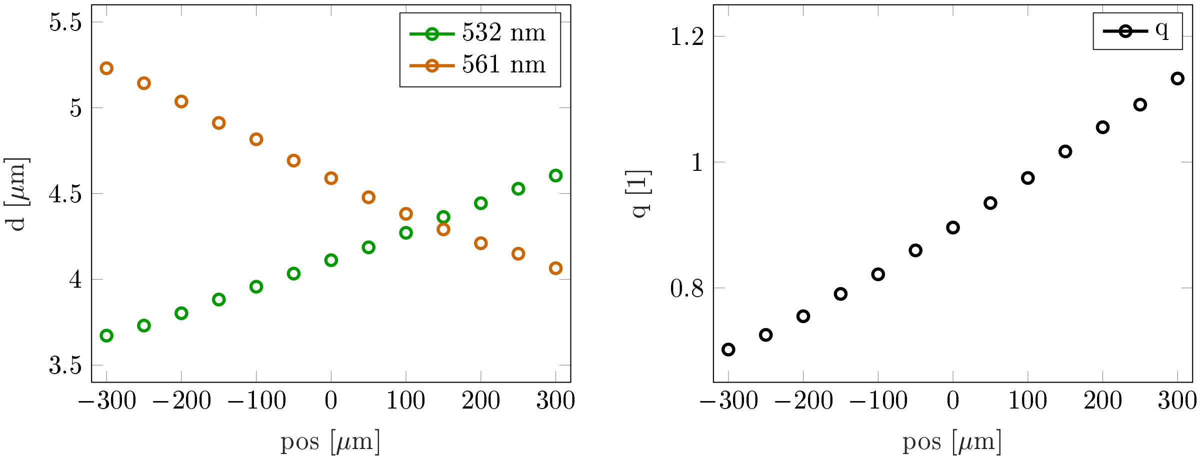
where $u$ is the velocity of the calibration object, $\theta$ the angle under which the particles moves through the measurement volume and $f_D$ the Doppler frequency measured for the particle. With uncertainties according table 2 $\theta$ and $\sigma$ can be neglected. Whereas the uncertainty of the velocity $u = 2\pi r f_{rot}$ is determined by the radius of the rotation orbit $r$ and the rotation frequency of the calibration object. With an uncertainty for the radius of approximately 1 % for common calibration method this is the most significant origin of systematic deviations.

Table 2. uncertainty contribution for the calibration of the LDV-PS

| Contribution | Value |
|---|---|
| $\theta$ | 1° |
| $r$ | 0.5 mm |
| $f_D$ | 0.1 % |
| $f_{rot}$ | 0.1 % |

For the calibration of the in section 2.2 presented system also an adapted calibration technique is needed, to calibrate both systems simultaneously. The state of the art technique for calibrating interference fringe based velocity measurement systems like the LDV is a to measure the scattered light reflected from a optical raw rotating surface.[8] This technique was not applied here because it is basically difficult to measure with a sensor system build for detecting single particles at surfaces where in principle many virtual particles (surface roughness) move through the measurement volume simultaneously. Therefore for the LDV-PS commonly a technique with a single scattering object is used, where a pinhole or wire is mounted on a rotating plate and moved laterally through the measurement volume with a well defined velocity. Commonly, calibration objects for the LDV-PS are pinholes which allow a high signal to noise ratio, due to the ability to detect the scattered light in forward detection.[7]

The systematic deviation for radial orbit can be decreased if an indirect calculation of this radius is performed like presented in 9. By measuring multiple times at different yet unknown radial position, but known differences between the radial position, which is achievable by using a step motor stage and a slit for calibration. The actual radial position can be extrapolated out of the calibration data and thereby the uncertainty of orbit radius can be significantly reduced. With this approach a calibration uncertainty of the fringe spacing of below 0.24 % can be achieved, which implies, that the systematic measurement deviation for the sensor is then below the actual systematic measurement uncertainty of 1 %. The presented calibration method is not suited for the simultaneous calibration of profile sensor and triangulation sensor due to the fact, that it uses a different detection optic for calibration and for measurement. So an adapted version with an tungsten wire as a reflecting scatterer was used instead of a slit. With these adaptation the same capabilities could be achieved and furthermore both sensor systems could be calibrated simultaneously. The measured fringe distances and the calibration function $q(z)$ can be seen in figure 2.



fringe distance measurement along the optical axis    quotient calibration function for the LDV-PS

Figure 2.

### 2.4 AIMED MEASUREMENT OBJECT

The established sensor system was used to measure the flow at a simplified jet cleaning experiment. Water is pumped with pressure of 0.5 bar through the nozzle, with an inner diameter of 5.2 mm, down to the base plate like shown in figure 3. The water hits a transparent acrylic glas surface, which enables the optical access from

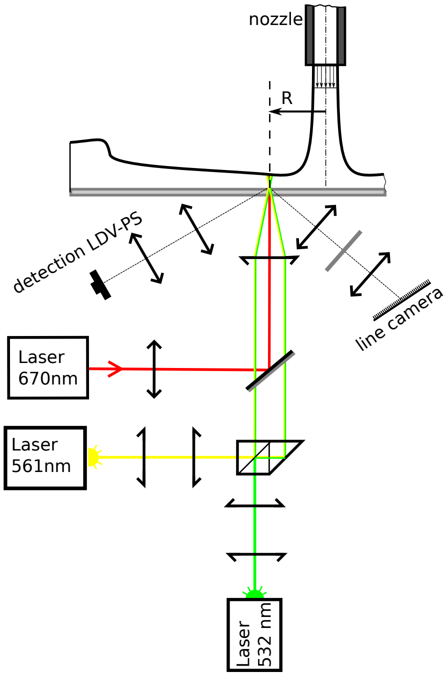


Figure 3. measurement setup mounted to experimental jet flow setup.

below and flows radially away from the impinging point. The relevant measureand, that can be obtained from this simplified experiment is the flow structure in the water film and the evolution of wall shear stress along the radial extension.

## 3. EXPERIMENTAL RESULTS

This calibration can now be used to evaluate the measurement data obtained at the film flow setup presented beforehand. The measurement data of the near wall profile is shown in figure 4. The presented data was measured at a radial distance of 10 mm from the impinging point with volume flow rate of 9 l/min, a distance from nozzle to plate of 100 mm, with nozzle of an inner diameter of 5.2 mm. The left plot shows the entire flow profile over the film which was approximately 480 µm thick based on the triangulation data. The shear layer has a thickness of approximately 80 µm. Valid measurement data could be acquired down to a distance of 30 µm to the wall even without the use of florescent tracer particles. The mean flow velocity measured in the film was 8.1 m/s with an standard deviation of 0.41 m/s, which corresponds to a relative standard deviation of 5 % which greater a the uncertainty of the sensor with 1 % and therefore originating from flow turbulence. With the measurement data close to the wall a linear regression was calculated which leads to the slope of the flow profile. With:

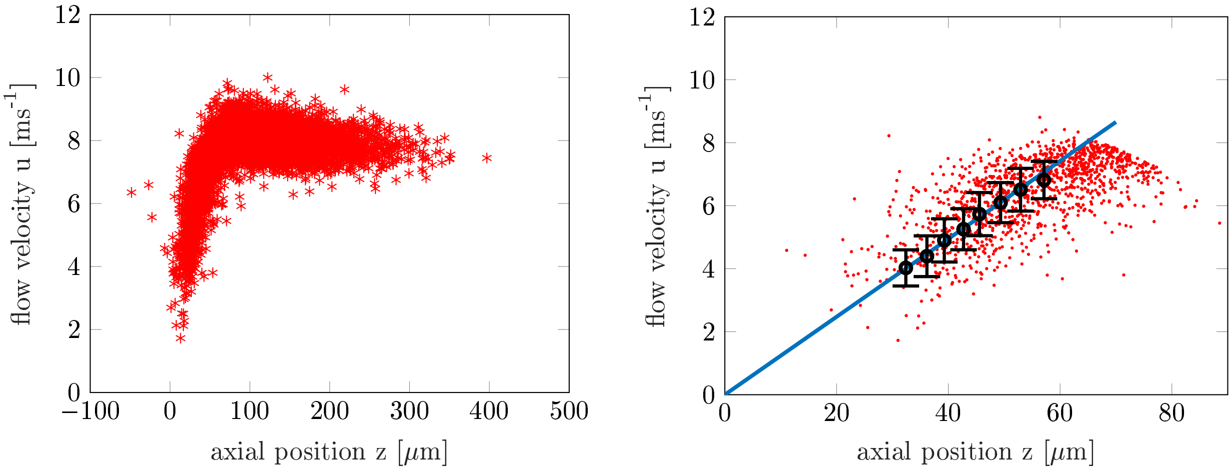


Figure 4. mean flow of the impinging jet and fit for calculating the wall shear stress

$$\tau = \eta \frac{d_u}{d_z} \tag{6}$$

this slope can be used to determine the wall shear stress $\tau$. With the dynamical vicousity $\eta$ at 20 °C of 1 Ns/m$^2$, the wall shear stress could be estimated to 123.714 kN/m$^2$. With the slope $m = \frac{d_u}{d_z}$ the uncertainty of the wall shear stress can be calculated to:

$$\frac{\sigma_\tau}{\tau} = \frac{1}{\tau}\sqrt{(m\sigma_\eta)^2 + (\eta\sigma_m)^2} \tag{7}$$

With $\eta = 1\,\mathrm{Ns/m^2}$, a relative uncertainty $\frac{\sigma_\eta}{\eta} = 5\,\%$, $m = 0.123\,\mathrm{(m/s)/m}$ and a relative uncertainty for the slope $\frac{\sigma_m}{m} = 10\,\%$ the wall shear stress can be estimated with an uncertainty of 11.18 %.

## 4. CONCLUSION

High resolution flow velocity data from within shear layers are vital for flow rate measurements. In this work the Laser Doppler Velocity Profile Sensor as a tool to measure flow velocities with high spatial and velocity resolution and the corresponding uncertainty budget was presented. Systematic errors during the calibration of this sensor where traced back to orbit radius uncertainties and a calibration technique was proposed which delivers estimation of radial position and thereby the velocity of the calibration object so that the systematic deviation of the fringe spacing can be decreased below the statistical uncertainty originating from the measurement itself. The calibration was use to measure the flow velocity profile within a thin film flow from an impinging jet experiment and thereby measurement was conducted within 30 µm range from the wall without the use of fluorescent tracer particles. This sensor can now be used to acquire the knowledge needed to optimize impinging jet cleaning processes.

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