

Combined PDA and LDV measurements: Phase discrimination inside a spray using fluorescent seeding particles

by

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ABSTRACT

Laser Doppler Velocimetry (LDV) measurements in the vicinity of reflecting surfaces are still a major problem in many applications of fluid mechanics such as measuring close to walls or wall film surfaces, respectively. Moreover, in any kind of two phase flow a unambiguous separation of the gas and the liquid phase is of particular interest. Commonly used techniques like Phase Doppler Analysers (PDA) with size discrimination are limited to two phase flows where the smallest particle of the dispersed phase is significantly larger than the seeding particles. This condition can rarely be fulfilled in technically relevant spray/air systems. One of the most promising approaches is a phase discrimination using fluorescent tracer particles for the gas phase. In this paper the working principle of the “fluorescent” LDV (FLDV) will be explained. Moreover, the applicability of different fluorescent dyes will be demonstrated. Finally, a comparison between PDA measurements with size discrimination and FLDV measurements inside a hollow cone spray (Fig. 1) will be presented.

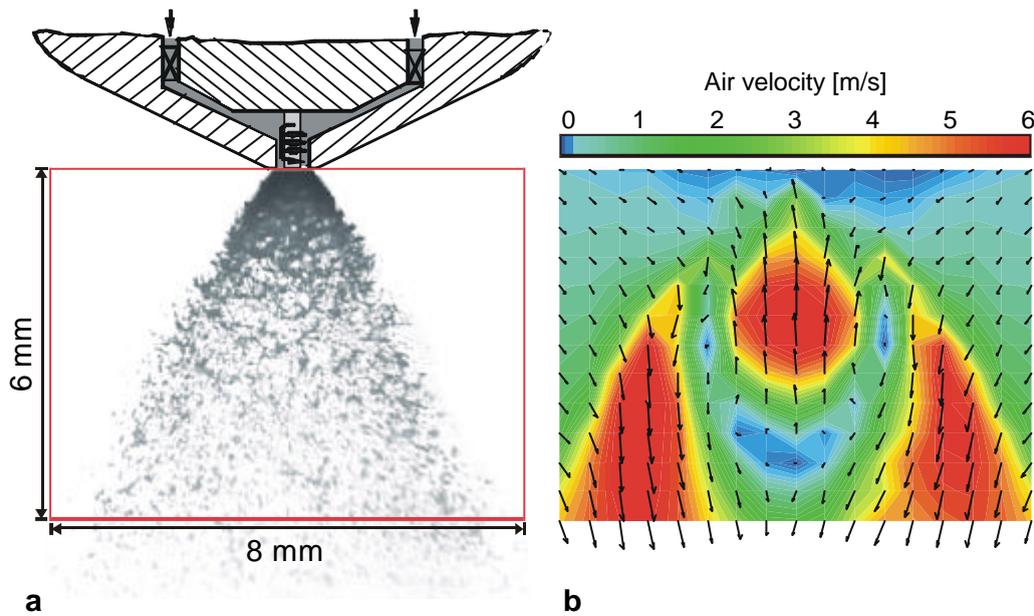


Fig. 1. Visualization of the spray of a pressure swirl atomizer (a) together with the velocity field of its induced air flow determined by Fluorescent LDV (b)

1. INTRODUCTION

The characterization of two phase flows is a major problem in many engineering disciplines. Cyclone separators, technical burners, gas turbines and automobile engines are only some examples representing the variety of applications. For a fundamental understanding of the fluid mechanics and particularly for the necessary improvement of numerical codes the simultaneous measurement of both elements of a two phase flow is of particular interest. Today Phase Doppler Analyzers (PDA) are state of the art instruments to investigate particle size and velocity. To determine the gas phase velocity small tracer particles are often added to the surrounding flow. The key issue to accurately study gas/liquid or gas/solid interaction respectively is a reliable discrimination of the phases in the measurement events. The most obvious approach also proposed by numerous authors (e.g. Hardalupas and Taylor, 1988) is to take advantage of size differences between the particles of the two phases, because in many applications the seeding particles can be kept smaller than the particles of the dispersed phase. Possible discrimination criteria herein are the phase information (Qui et al., 1990), the intensity of the scattered light (Levy, 1986) and diffraction in the near on-axis region (Muste et al., 1996). However, these size discrimination techniques are limited to two phase flows where the smallest dispersed phase particle is significantly larger than the seeding particles. This condition can rarely be fulfilled in the case of a spray/air system. A different approach was proposed by Domnik et al. (1996) using the differences of the algebraic sign in the phase-size relation which occurs, if the refractive index of the seeding material differs significantly from the refractive properties of the dispersed phase. The most promising approach to study spray/air interaction phenomena is the use of fluorescent particles. The ability of separating the Mie-scattered light from the fluorescent signal in a LDA-system was shown by Lemoine et al. (1999) using intensity of the fluorescent light for temperature measurements. Recently, Sommerfeld and Bröder (1999) managed to extract the velocity information from fluorescent tracers in a bubbly flow and recognized an improvement of the results compared to the size discrimination method. However, in the opinion of the authors this technique can be used for spray/air systems also but in this case it is not yet investigated adequately.

2. LDV WITH FLUORESCENT TRACER PARTICLES

2.1 Theoretical considerations

The theoretical considerations concerning properties and opportunities of using fluorescent light for LDV measurements will be restricted to a dual-beam LDV setup in this paper. In a correctly set up system the intersection region coincides with the focal point of the optical system and the incident laser beams can be described as plane waves. Making use of the linearity of the Maxwell's equations, which allow the superposition of the two light beams inside the measurement volume, one can calculate the maxima and minima in the resultant amplitude of the E-field. The visualization of this interference pattern inside the crossing region has formerly led to the so-called "fringe model". Applying this model, the LDV-signal received by the photodetector can be understood as the result of particles crossing those fringes, see Rudd (1969). Durst (1980) pointed out, that the fringe model is not physically correct as it attributes the squaring and integrating properties of the photodetector to the properties of the scattering particles. In other words the fringes do not exist for light scattering particles unless they have the properties of a photodetector. However, the "Doppler model" which is physically more correct for scattering particles is not capable of explaining the working principle of the Fluorescence LDV (FLDV), mainly because the emitted fluorescent light is due to spontaneous emission and therefore not coherent. As mentioned by Hecht (1987) fluorescence is caused by the interaction of the E-field with the fluorescent dye, therefore the fluorescent seeding particles can be assumed as squaring and integrating detectors themselves. When passing through the measurement volume the seeding particles will detect the amplitude pattern of the E-field and emit fluorescent light in the case of constructive interference of the two waves. The fringe model becomes the physically correct explanation of the functioning of FLDV.

2.2 Optical properties of different fluorescent dyes

Following those considerations it is quite obvious that the fluorescence properties of the seeding particles - fluorescence intensity, onset and lifetime - are of crucial importance for the feasibility of FLDV measurements. These properties are clearly separable by their effects on the quality of the experimental results. The fluorescence intensity is responsible for the signal-to-noise ratio, a varying onset affects the accuracy of the measurement, and the fluorescence lifetime limits the dynamic range of detectable velocities. Four different fluorescent dyes in the red - Rhodamin 6G, Rhodamin B, Sulforhodamin and DCM - were tested with respect to the properties mentioned

above. Ethylene glycol and propylene carbonate were used as solvents due to their physical properties. The measurements were performed by means of time resolved fluorescence-spectroscopy. The dyes were excited with 150fs laser-pulses centered at 400nm (FWHM about 20meV). The pulses were created by a frequency doubled mode locked Titanium:Sapphire-laser pumped by an 15W Argon-Ion-laser. The fluorescence response was measured using a Synchroscan streak-camera with a maximum time resolution better than 2ps.

In order to determine the time between the laser-excitation and the onset of the fluorescence of the dye, measurements in the highest resolving time range of the streak-camera were performed. The total recording time in this mode was 160ps. The accuracy of the system was estimated to about 5ps. An example diagram of the fluorescence response of DCM is shown in Fig. 2a.

The fluorescence lifetime is the property relevant for the upper limit in the dynamic range of frequencies detectable by the FLDV. As the process of spontaneous emission can last more than 10ns in case of fluorescence the largest time base of the streak camera (1.4ns) was chosen and the measurements were performed sequentially. The overall time resolution at this time base was about 20ps. Fig. 2b shows the decay of the fluorescence intensity of DCM using an interference filter which eliminated the laser light.

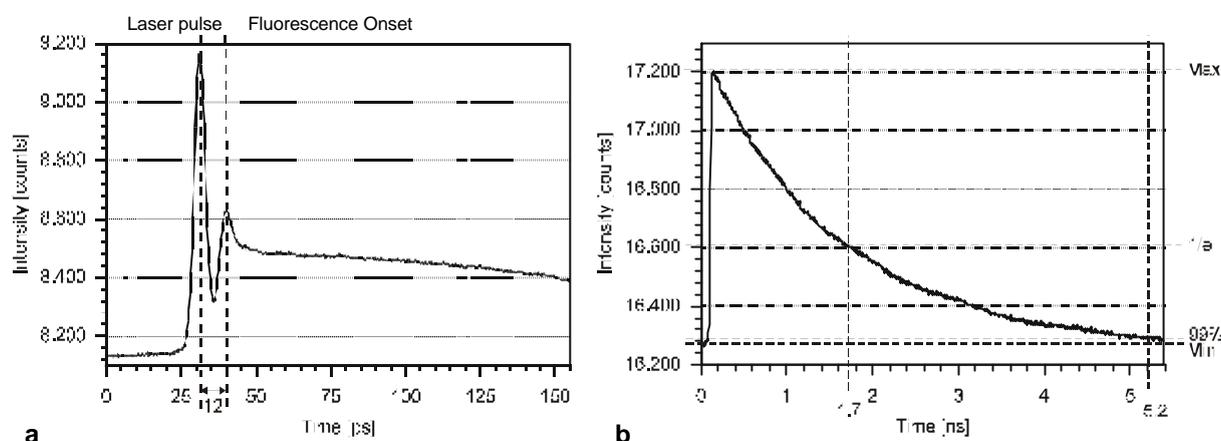


Fig. 2. a) Fluorescence onset of DCM b) Fluorescence lifetime of DCM

The mean time (100 samples) between laser excitation and fluorescence onset can be estimated from the diagram of Fig. 2a by determining the distance between the two intensity peaks. Spectrally resolved measurements showed that the first peak was the laser peak and the luminescence started with the second peak, although the development of the pure fluorescence was missing the peak at the onset. This peak can be explained by an overlay of reflections of the incident laser light. For DCM the fluorescence onset was less than 12 ps, the standard deviation of the onset was less than 3ps. The fluorescence lifetime is defined as the decay of the fluorescence intensity to 1/e of its maximum and was determined to 1.6 ns for DCM. As the modulation depth is of crucial importance for LDV measurements a 99%-criterion was introduced. For DCM the "99%-lifetime" was 5.2 ns. The measurements did not allow to determined the quantum efficiency quantitatively. Nevertheless, the over all impression of the fluorescence intensity of the four examined fluorescent dyes in the red given in Table 1 is in good agreement with literature data (e.g. Antonov and Hohla (1983), Broyer and Chevaleyre (1984)). Moreover, a comparison between lifetimes, onset, absorption, and emission wavelengths is demonstrated.

| Properties | Rhodamin 6G | Rhodamin B | Sulforhod. G | DCM |
|-----------------------------------|-------------|------------|--------------|-----------|
| $\lambda_{\text{Absorption,max}}$ | 524nm | 544nm | 529nm | 481nm |
| $\lambda_{\text{Emission,max}}$ | ca. 580nm | ca. 600nm | ca. 650nm | ca. 650nm |
| Quantum yield | High | Medium | Low | High |
| Lifetime (1/e-decay) | 6.4ns | 3.5ns | 5.8ns | 1.6ns |
| Lifetime (99%-decay) | 14.5ns | 9.4ns | 12.3ns | 5.2ns |
| Onset | < 25ps | <18ps | <35ps | <14ps |

Table 1. Fluorescence properties of four different dyes in the red

Obviously all of the dyes could be easily excited with laser light of a wavelength between 450 and 550 nm. The emission wavelengths are greater than 600 nm. Therefore the fluorescent light can be separated well from the Mie-scattered light for all dyes. The fluorescence intensity was very high for DCM and Rhodamin 6G, the only really weak luminescence was determined for Sulforhodamin. This criterion will be of crucial importance for the FLDV measurements, because light emitted by the fluorescence process is by decades weaker than the elastically Mie-scattered light. The shortest fluorescence lifetime was determined for DCM. Thus the maximum velocity detectable in our LDV setup with DCM would be theoretically about 780 m/s, but also the 280 m/s reachable with Rhodamin 6G should be enough for most applications. The fluorescence onset was less than 35 ps and the variation of the onset which can influence the accuracy of the measurement was less than 5 ps for all of the dyes. This means for the standard LDV (*Dantec*) used in this studies - 40 MHz shift frequency and about 5 μm fringe distance - the accuracy of the resulting velocities with regards to the fluorescence onset is better than 0.1%.

Finally all of the four fluorescent dyes were theoretically suitable the FLDV experiment, whereas DCM seemed to be favorable compared with the others. Though, to assess the applicability only by the optical properties is difficult and further tests about the accuracy of the system were necessary.

2.3 Accuracy and signal quality

As a basic study the differences in signal quality between the fluorescence and the Mie-signals were investigated in a simple 1D-LDV setup. Therefore coincident measurements of Mie-scattering and fluorescence signals were performed with all the fluorescent dyes inside an air flow with an average velocity of about 1m/s. The seeding particles were produced by a nebulizer and their diameter was less than 3 μm . The filter bandwidth was $\pm 2.71\text{m/s}$. The gain was 16dB and the high voltage was 1200V for the Mie and 1800V for the fluorescence signal. For each dye 50 bursts were randomly selected, the signals stored with a fast sampling digital storage oscilloscope and transferred to a data acquisition system. Fig. 3 shows exemplary bursts of the Mie-scattered (a) and the fluorescent light (b) of the same particle.

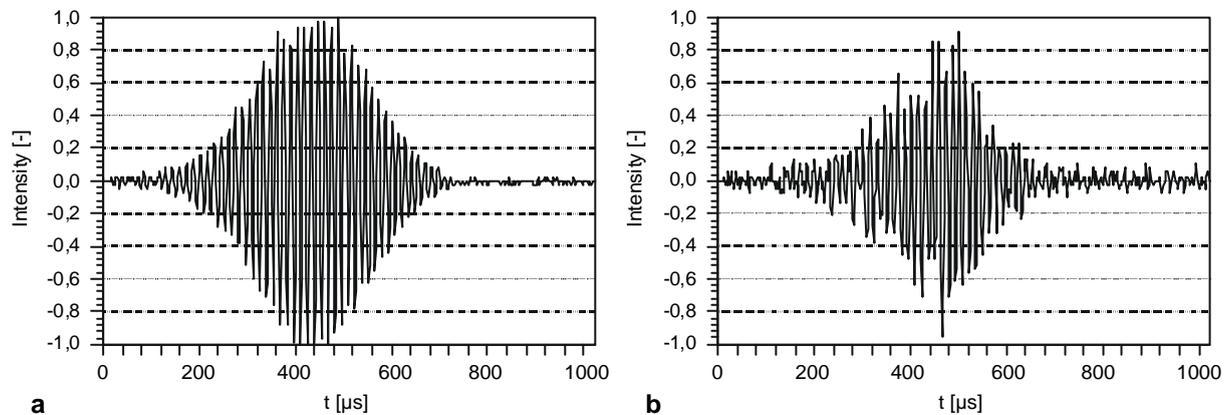


Fig 3. Typical coincident measured LDV bursts a) Mie-scattering b) Fluorescence (DCM)

These sample bursts were representative for particles with DCM as a fluorescent dye. The frequency of the Mie signal was constant within the bursts, and the envelope could be described well by a Gaussian function. Due to the weaker fluorescent signal the high voltage had to be increased. Therefore the fluorescence bursts showed a higher background noise level. The bursts themselves were also superimposed by some irregular frequencies resulting in an disturbed envelope and a broadened frequency peak. Nevertheless, the deviation of the determined frequency was less than 1%, which confirmed the measurements described above.

For a fundamental characterization of the quality of the bursts a detailed signal analysis had to be performed. The signal to noise ratio (SNR) is defined as the ratio of the signal energy to the noise energy. Therefore an ideal burst with the properties of the real signal has to be created and subtracted from the real signal to extract the noise energy. This ideal burst was aligned to the real signal by means of a Gaussian modulated cosine function with

the frequency, the phase angle, the amplitude, and the burst width of the original burst. Moreover, the SNR was averaged over 50 samples of the different fluorescent dyes, respectively. The results are shown in Table 2.

| | Rhodamin 6G | Rhodamin B | Sulforhod. G | DCM |
|----------------------------------|-------------|------------|--------------|-------|
| SNR _{Fluorescence} [dB] | 3.96 | 5.07 | - | 9.57 |
| SNR _{Mie} [dB] | 22.57 | 27.09 | - | 22.45 |
| Data rate (Fluoresc./Mie) [-] | 0.60 | 0.1 | - | 0.53 |

Table 2. Comparison of the signal quality of different fluorescent dyes in the red

As above mentioned valid bursts could not be detected for Sulforhodamin. This can be explained by the weak fluorescence signal found within the investigations of the fluorescence lifetime and onset described in chapter 2.2. For the other dyes a significant higher SNR was determined for the Mie signal than for the fluorescence bursts. The best signal was obtained from the luminescence of DCM. It was about twice as high as the SNR of Rhodamin 6G and B, but 4 times lower than the corresponding Mie-SNR. Regarding to the data rate of valid bursts Rhodamin 6G and DCM could realize about 50% to 60% of the Mie signal (approx. 500 Hz) whereas the data rate of Rhodamin B was less than 10%.

Before real two phase measurements in the spray were realized preliminary tests were performed to ensure the accurate functioning of the whole system including data acquisition and processing. Investigating some spray/air flow with and without fluorescent seeding particles it could be demonstrated that the fluorescent light was clearly separable from the Mie-signal for DCM, Rhodamin 6G and Rhodamin B. Only with Sulforhodamin valid FLDA bursts could not be detected with any optical or experimental setup.

To check the accuracy of the FLDA the seeding particles were examined without the spray. Coincident measurements were performed with the fluorescence in the backward and the Mie-signal in the forward scattering mode to ensure that identical particles were evaluated. The velocity difference of each individual particle was less than 1%. Moreover, subsequent evaluations of Mie-signals and fluorescent signals in the backward scattering mode showed very similar velocity distributions with a deviation of the mean value of again less than 1% for all the dyes.

Summarizing, the properties of the FLDV signals can be described as noisy, but accurate with respect to the gained velocity information. The highest signal quality of all fluorescent dyes under investigation could be determined with DCM. Therefore the measurements demonstrated in the following were performed with DCM solved in propylene carbonate.

3. EXPERIMENTAL SETUP

To verify the theoretical considerations the FLDV in combination with a standard PDA was applied to a simple two phase flow experiment. The experimental and the optical setup is shown in Fig. 4. The experiments were carried out in an atmospheric test rig with good optical access to study spray/air interaction phenomena. A pressure-swirl atomizer forming a hollow-cone spray at a nominal cone angle of 45° served as an injection nozzle. For this model investigation pure water was injected into nearly quiescent ambient air at an injection pressure of 0.5 MPa. In order to provide a continuous supply of tracer particles a slight background flow from a compressed air supply passing a nebulizer and feeding a ring channel was used.

An aerosol of droplets (diameter <3µm) from a solution of DCM in propylene carbonate produced by a nebulizer (Laskin-nozzle principle) was used to seed the surrounding air flow. The flow was stabilized by a vacuum pump and homogenized by an insert of honeycombs in the sump.

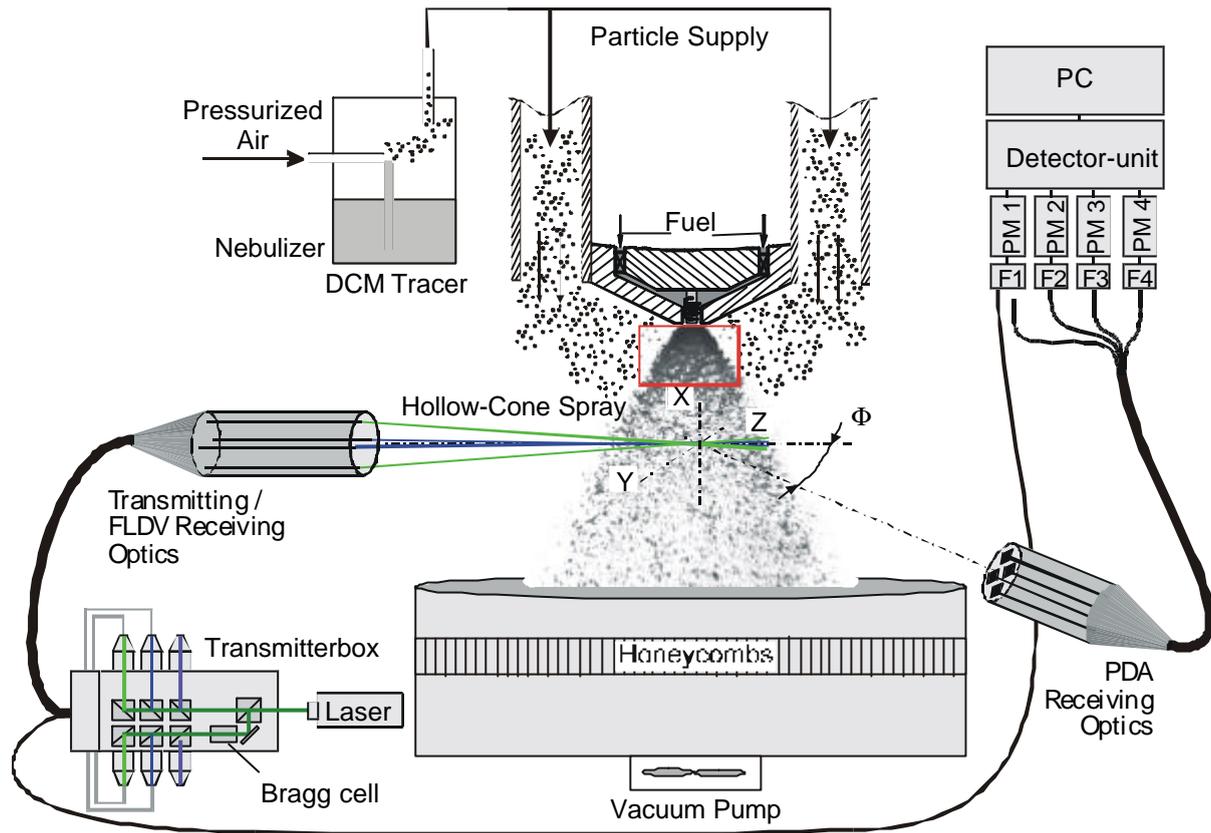


Fig. 4. Experimental Setup

The optical setup of PDA and FLDV is demonstrated in Fig. 4, too. For the PDA measurements a conventional *Dantec* Dual PDA system was used. A 5W Argon-Ion laser (Coherent) in multi-mode operation served as a light source. The multi-wavelength laser beam is split into two beams one of which passes the bragg-cell to be shifted with a frequency of 40 MHz in order to avoid ambiguity of the flow direction. Subsequently both of the beams are split into different colors for the two components (488nm and 514.5nm) and are linked to the transmitting optics via optical fibers.

For the FLDV measurements the system was modified. Within the transmitting probe a lens focused the backward scattering light of the intersection volume onto another slit shaped spatial filter in front of an optical fiber. This fiber is connected to the Filter F1 instead of the PDA fiber. The 514.5nm band pass filter was replaced by an OG 590 low pass filter in order to separate the fluorescent signal of the seeding particles from the Mie-signal of the spray droplets. Data acquisition and signal processing were performed by standard Dual PDA components.

4. RESULTS

One exemplary result of consecutive PDA and FLDV measurements of the present two phase flow is demonstrated and discussed in the following. As the cone structure of the spray was found to be symmetric, the two phase flow was investigated only in one vertical cross sectional plane through the center of the nozzle orifice. The most interesting region of the spray was the area close to the nozzle orifice (6x3.5mm as shown in Fig.4) demonstrating the advantages of the FLDV over a PDA using a size discrimination scheme to separate spray and air flow. Fig. 5a shows the velocities of the air, Fig. 5b the velocities of the spray droplets of diameters less than 3 μm. The absolute velocities are indicated as contour plots.

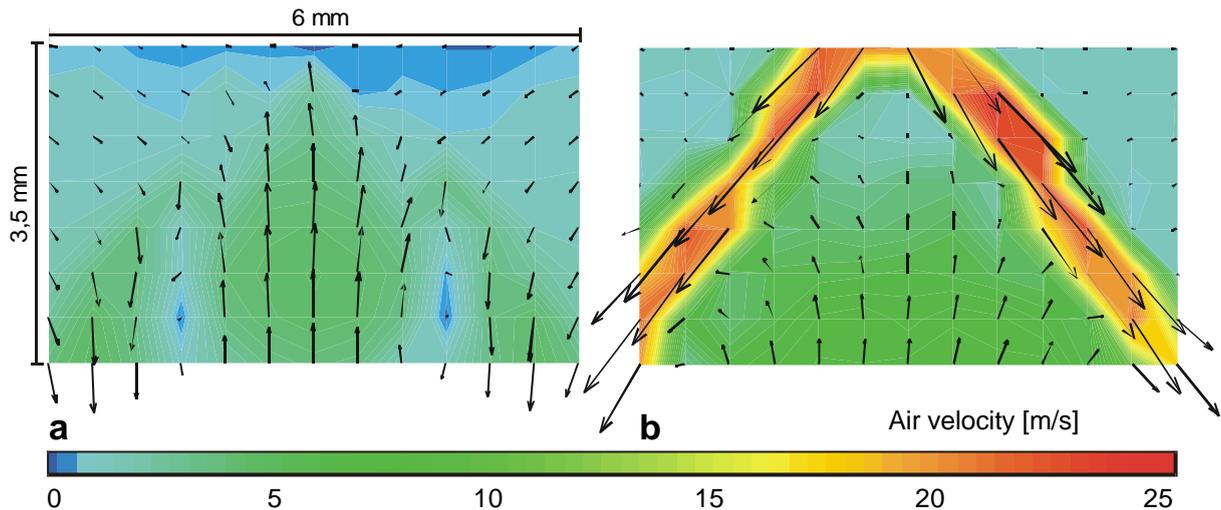


Fig. 4. a) FLDV measurements of the air flow b) PDA measurements of spray droplets $<3\mu\text{m}$

The strong difference in the velocity distribution between the seeding particles and the spray droplets smaller than $3\mu\text{m}$ is obvious. The droplets had a high initial momentum and could not be assimilated to the air flow within the region of interest ($<4\text{mm}$ away from the nozzle orifice).

Investigating the measurements in detail air entrainment could be determined in the vicinity of the nozzle with the FLDV technique, but hardly with the PDA. Regarding to the FLDA the air was accelerated into the spray cone from about 1 m/s up to 6 m/s. Inside the hollow cone a large recirculation zone with maximum velocities of about 6 m/s in reverse direction was found. As mentioned above the PDA measurements overestimated the air velocities – up to 25 m/s - in the spray cone region. Inside the hollow cone the PDA measurements show significantly lower velocities than the FLDA due to the higher inertia of the spray droplets.

SUMMARY AND CONCLUSIONS

A thorough and detailed characterisation of a two phase flow requires velocity and size of the dispersed phase and the velocity of the continuous phase. A combination of PDA and FLDV provides all these information due to a strong unambiguous separation scheme of the dispersed and the continuous phase. The results of the investigation presented in this paper can be summarised as follows:

- The working principle of the FLDV technique could be explained applying the fringe model for the FLDV instead of the Doppler model.
- The optical properties of four different fluorescent dyes in the red were compared with respect to fluorescence lifetime, onset and intensity. All of them were found theoretically suitable for FLDV whereas DCM seemed to be favourable due to the shortest lifetime and a high luminescence output.
- Measurements of the signal quality of the fluorescence bursts showed a decrease in the SNR value of up to 10 times compared to the simultaneously recorded Mie-bursts. However, it was again DCM being superior to the other fluorescent dyes. Handling the bursts with modern signal processors does not cause any problems or errors.
- Comparative FLDV and PDA measurements with size discrimination inside the hollow cone spray of a pressure swirl injector used in gas turbines showed the advantages of the FLDV technique. The comparison between PDA with simple size discrimination showed that small spray droplets had a high initial momentum and could not be assimilated to the air flow within the region in the vicinity of the nozzle orifice.

In combination with the PDA technique the FLDV can provide all the information required for an improvement and a better validation of numerical codes. A integrated PDA/FLDA system could solve a lot of fluid mechanical problems in two phase flows.

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