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Comparison of fibre-based phase Doppler analysers

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Abstract. Laser diagnostics techniques are widely used in experimental fluid mechanics. By far the most widely used systems for getting spatial velocity fields and turbulence data are laser Doppler anemometers (LDA). Further, in the cases of two-phase flows phase Doppler analysers (PDA) are typically chosen to measure the size and velocity of the droplets or bubbles. The PDA system is non-intrusive laser technique with high spatial and temporal resolution. Moreover, the PDA system does not require additional calibration as, for example, hot-wire anemometers. However, with a growing number of PDA users, there is a need for verification of the results among the workplaces and systems themselves. The current paper deals with the comparison of two fibre-based PDA systems. The main scope of the investigation is an evaluation of the system's age and the influence of lasers type. One of the systems is older, operated with Argon-Ion laser and the second one is brand new equipped with Diode-pumped solid-state lasers. Both have the same optics and were manufactured by the same company. Various properties of the PDA system are tested to show particular influence on the quality of results when measuring in a spray generated by a small air-blast atomizer.

1 Introduction

Optical and electronic technologies are, in general, well established in fluid mechanics. Nowadays trend increases demands on flow examination with a good spatial and temporal resolution. Laser Doppler anemometry (LDA) has been one of the most used non-intrusive techniques in the experimental fluid mechanics thanks to their small measurement volumes and fast processing enabling detailed flow examination in space and time [1]. The LDA enables point measurement of particles velocity in up to three directions. In the case of two-phase flows, a phase Doppler (PDA) analysers are frequently used to obtain information about a size of droplets or bubbles in the flow. The PDA system includes the LDA for velocity measurement and with an extension of measuring a phase difference in light signals hitting photomultipliers, it estimates a sphericity of a droplet or a bubble [2].

The LDA and PDA techniques underwent significant development during last few decades and play an important role in various research applications, such as combustion of liquid hydrocarbon fuels in automotive and aircraft engines or in power plants, in spray drying processes in inkjet print devices and others [1]. Advantages of LDA and PDA systems are good spatial and temporal resolution, directional response, sensitivity and no need for additional calibration in comparison with, for example, hot-wire anemometers.

Together with a rapid increase of experimental studies aimed at a flow investigation, there is also a need for verification of the experiments and the systems themselves. Moreover, the PDA technique involves numerous complex physical processes which require broad interdisciplinary understanding. There are many ways the system can be set which influences the results significantly. So in every literature research, there should be a question of what was the uncertainty of the measurement and the exact experimental setup and used technique of the previous results.

In a view of evaluation of LDA systems, the researchers focused on a determination of uncertainty of velocity measurements, such as [3] and [4]. In the case of PDA, a frequent aim was to evaluate mass flux [5] or particle concentration [6]. In general, the uncertainty of the droplet size measurements is assumed relatively good, typically in a range from 5 to 10% after amplitude and phase validations depending on the droplet size and optical configuration [7]. The situation is a bit more complicated in the case of real dense spray where more variables influencing the uncertainty of flux measurements are presented such as: obscuration effect, unwanted reflections, trajectory or Gaussian beam effects, slit effect etc. [2].

A number of studies were aimed to compare various sizing techniques e.g. [8–12]. The studies showed that the comparison is possible with relatively good agreement among the instruments. But it was shown that harsh conditions like an unknown refractive index of liquid or dense spray regions make the quality of results dependent on a given experimental setup and technique.

A comparison of various laser Doppler system is relatively rare. For example, [13] used two different PDA processors made by Dantec: Enhanced 58N50 and BSA P80 to measure LDA and PDA data simultaneously to improve system performance. Another study by [5] focused on an

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evaluation of measured mass fluxes by classic PDA and Dual PDA and Qiu and Sommerfeld (QS) on two different atomizers, i.e. the pressure swirl and an air-blast. They pointed out that the improved configurations of the PDA, Dual and QS systems, achieve a better estimation of flux measurements. However, due to a large number of influencing parameters, they made no universal explanation from the obtained results. Other researchers [14, 15] compared the PDA with optical patternator and showed relatively good absorptance agreement. Nevertheless, they also pointed out that the agreement depends on a drop arrival rate which influences the calculated mean diameter used for flux determination.

A recent study focused on a comparison of various configurations of laser systems, a fibre based PDA with an older-classic PDA construction [16]. This showed that there was an only minor deviation in velocities. But the different processors, Dantec P80 and older Dantec Model 58N50 used for data collection had a demonstrable effect on the measured drop size distribution. The main issue here was detectability of droplets with minimal and maximal detectable size. Especially the largest droplets have a significant influence on the spray properties such as flux or Sauter mean diameter, *D32,* used in an evaluation of sprays in combustion applications.

When comparing such a complex system like PDA, there are many variables which play a role in the results quality. There was a series of studies aimed at an evaluation of the measured mass flux within the spray. Especially, measurement of droplet size is critical in many applications. The recent study showed that even two similar PDA systems might measure demonstrable different droplet size spectrum. Thus, our current approach is to simplify the situation to the necessary minimum number of variables which might influence the results. For that purpose, we present a comparison of two identical fibre-based PDA systems which differ in age, used lasers and processors. The rest of components is identical for both systems. For the sake of simplicity, only 1D measurements were performed.

2 Materials and Methods

Experiments were performed at the cold test bench at still ambient conditions and room temperature at two workstations: the Spray laboratory at Brno University of Technology (system A) and at WTtech.cz company (system B).

2.1 Atomizer

The experiments were conducted using a standard twin-fluid air-blast atomizer (air-brush) which is normally used for paint spraying. This atomizer generates stable spray with small droplets, typically smaller than 50 microns. The spray is generated by suction of water into the high-speed air stream which disrupts the liquid into small droplets. This atomizing principle is basically the same as for the air-blast atomizers [17].

The tested liquid was distilled water, experiments were performed at room temperature of 23 °C and atmospheric ambient pressure. The air supply line was equipped with a pressure sensor (BD sensors 331). The pressurized air was taken from a small mobile compressor ABAC pro air compressor 50 Hp3. An air filter and valve were placed into the line behind the compressor. This system (nozzle, sensor, filter and compressor) was used in both experiments i.e. in systems A and B. Therefore, the identical operating conditions were achieved and number of variables which might play a role in the results quality was decreased. The pressure was kept at a given value of 190 ± 5 kPa.

The nozzle was mounted to 3D positioning system. Positioning error of the mount is less than 0.5 mm.

2.2 Principles of PDA technique

The laser Doppler techniques (LDA and PDA) are point-wise optical methods that capture a Eulerian description of the flow using droplet and bubbles or seeding particles. In principle, a continuous-wave monochromatic laser beam is split into two coherent beams that intersect symmetrically in a focal point of transmitting optics. The crossing beams forms the measurement volume, where interference generate series of parallel planes of higher and lower light intensities, so-called fringes. A particle presented in the flow can generate a signal when passing through the fringes in the measurement volume. In order to identify the particle direction, a frequency of one beam is typically shifted using Bragg cell. This principle solves the directional ambiguity and enables to measure the zero velocity. The generated light signal is then collected in the receiving probe using photodetectors which produces a "Doppler burst" signal with a Doppler frequency f_D. This frequency is proportional to the velocity component u_n of the measured particle according to the following relation [2, 18]:

$$f_D = f_B + \frac{u_n}{s} = f_B + \frac{2sin\left(\frac{\theta}{2}\right)}{\lambda}u_n \qquad (1)$$

where λ is the laser light wavelength. The signal is then processed to yield the velocity and arrival time of each measured and validated particle.

The PDA is extension of above described LDA technique and provide an estimation of the particle velocity and size simultaneously. The PDA transmitting optics is the same as for the LDA. However, the PDA uses more complex receiving probe which contains typically three photodetectors. One detector is located in the observation plane while the other two are elevated at an angle with respect to that plane. The signals collected at different angles show a phase difference with respect to each other. This phase difference is proportional to the particle diameter, when assuming spherical object, and it is also dependent on a scattering direction and difference in elevation angles between the detectors. Moreover, it might depend on a particle/fluid refractive index. Using the fringe model, it gives a simple relationship between the diameter and the measured phase shift $\Delta\varphi$:

$$\Delta\varphi = \frac{2\pi D_p n_p}{\lambda}\phi \qquad (2)$$

The parameter ϕ depends on the scattering mode and the PDA configuration. A detailed description can be found elsewhere [2].

2.3 PDA systems

A Two fibre-based PDA systems are described in this section. Generally, the PDA system consists of the laser, transmitting optics, receiving optics, processor and a computer. Schematic layout of the PDA system is in Fig. 1.

In the past, majority of the laser Doppler systems were operated using the gas lasers, namely the Argon-Ion or Helium-Neon. These lasers have the advantage of sufficient laser power output needed for PDA measurements and very good beam quality. Nowadays trend, however, is to use a diode and diode-pumped solid-state lasers which experienced a rapid development in recent years. New diode lasers with improved properties such as high-power and fundamental-mode emission enable usage in laser Doppler techniques [19], but with much higher energy efficiency compared to gas lasers.

Both systems used in this paper consist of the same type of the optical parts (transmitting and receiving optics and optical fibres) but they differ in the used lasers and processors. The older system (system A) has Argon-Ion multicolour laser and BSA P80 processor. In contrast, the newer system (system B) which is equipped with diode laser and processor BSA P800-2D. The laser beam is directed from the laser head into, so called, transmitter box which in the case of system A divides a multi-line laser beam into individual colours and provides a frequency shift to one of the laser beams in a pair. The system B uses a monochromatic laser and the transmitting box only splits the beam and provide the frequency shift. The frequency shift is the same for both systems and it is 40 MHz. The transmitter box also focuses the laser beams into the optical fibres which outcomes in the transmitting optics. From transmitting optics there is only one pair of laser beams coming out and intersecting in measurement volume, see Fig. 1. A detailed description of the individual components of the examined PDA system is in Table 1 below.

The scattering angle, the angle between X-axis and receiving optics, was set to 70° due to good Brewster condition. It means that the first order of refraction is dominant and other modes of light scattering on a droplet are minimised, a similar setup was used by [13].

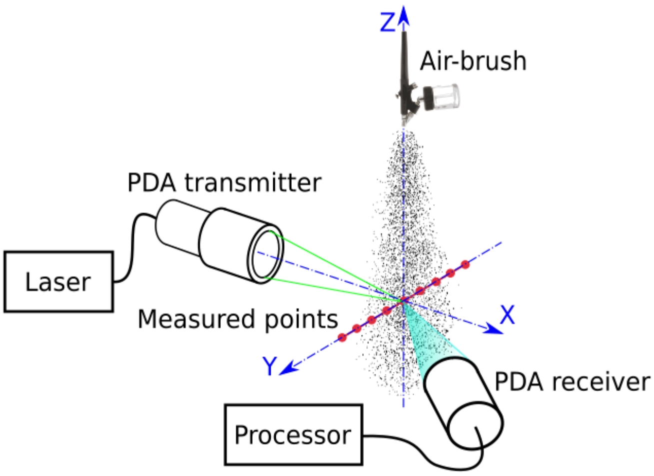

Fig. 1. Schematic layout of the fibre based PDA system.

Table 1. Parameters of the PDA systems.

Component	System A	System B
Laser type	Spectra physics Stabilite 2017 Argon laser	Quantel ELBA-M-546 nm DPSS laser
Wavelength	514.5 nm	546 nm
Processor	BSA P80	BSA P800-2D
Transmitter box	60X41 Transmitter, which splits the beam into its individual colour components, provides a frequency shift and directs the beams into fibres.	
Bragg cell	A cell is implemented inside the transmitter box which gives frequency shift 40 MHz to each beam from given pair.	
Transmitting optics	60X81 2D mm transmitting optics, the focal length of the final lens of 310 mm.	
Receiving optics	57X50 112 mm diameter fiber PDA receiver optics with a spatial filter and focal length of the lens of 500 mm. Slit aperture set to 200 μm.	

2.4 Parameters of the measurement volume

Two intersecting laser beams coming out from the transmitting optics create in the intersecting point so-called measuring volume (m.v.). This ellipsoid consists of layers of high and low intensities of light i.e. fringes. Dimensions of the m.v. depends on a current optical configuration which is the same for both examined laser systems, i.e. systems A and B. The optical setup results in a fringe spacing of 2.2 μm, dimensions of m.v. 0.05×0.05×0.4 mm and a number of fringes equals to 22. The effective volume of m.v. has a shape of an ellipsoid truncated by a slit shaped by a spatial filter placed in the receiver optics [2] as shown in the Fig. 2. We assume that m.v. is symmetric along the main axis. The effective length of the m.v. is determined by the slit used in the receiving optics. In both systems, the slit was set to 200 μm. The PDA receiver enables the usage of different aperture plates inside the PDA receiver. These apertures, so-called masks, are interchangeable and determine the droplet size range which can be measured. In both systems mask B was used.

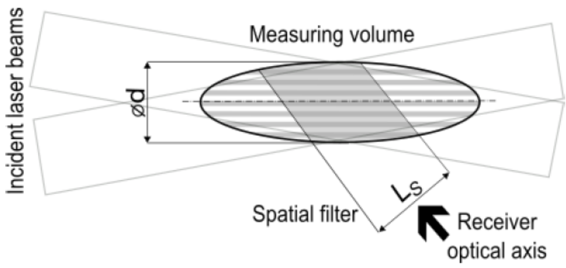

Fig. 2. Measurement volume geometry.

2.5 PDA setup

The scope of the present experiment is to map an influence of laser power of photomultipliers sensitivity on quality of results. The signal gain was set to zero value to limit noise which might be generated by the amplification. The only two variables were changed in the experiment: laser power in range from 25 mW up to 100 mW for each laser beam, and sensitivity of photomultipliers in range from 600 V to 1200 V. The rest of the variables which can be set in the software was left at a default value.

To control PDA measurement a PC with a given software is used. In addition to the experimental setup, there is a series of variables which might be sent via software and optimise the measurement conditions. In both systems, a BSA flow software version 6.5 by Dantec Dynamics was used.

As mentioned in the introduction, the main variables which are normally withdrawn from PDA data are droplets mean diameter, *D10,* and, so-called, Sauter mean diameter, *D32*. The *D10* is calculated as a mean value of the measured diameter of all recorded droplets in one position. The *D32* is the diameter of the drop whose ratio of volume to surface area is the same as that of the entire spray [17]. It is used for mass transfer, combustion and reaction application due to its sensitivity to the large droplets. The *D32* is calculated according to the following relation:

$$D32 = \frac{\sum N_i D_i^3}{\sum N_i D_i^2} \tag{3}$$

where *N* is a number of drops and *D* is a drop diameter.

3 Results and discussion

In this section the results are discussed to obtain a general information about the spray and to determine the best possible region for comparative measurements. Further, the comparison between the two system is made and concluding remarks are withdrawn at the end.

3.1. Preliminary results - spray examination

The preliminary measurements were performed to map the spray. Five axial distances downstream from the nozzle were examined; 10, 20, 30, 40 and 50 mm. Sample results are shown in the Fig. 3. Images: a), b), c) shows contours of the data rate in three planes. It is clear that in the plane closest to the nozzle exit, the highest frequencies, up to 8.5 kHz, are reached close to a centre of the spray. The data rate then decreases with growing axial distance. A plane at 50 mm from the nozzle then reaches a maximum of 900 Hz which points on a rapid decrease in the droplet concentration. This could be caused by the evaporation of droplets and by entrainment of air into the spray and consequent spray-air interaction [20].

A similar trend was observed in the case of mean axial velocities, Fig. 3 images: d) e) f), where the maximum values were measured closest to the nozzle, up to 75 m/s. The highest velocity is reached in a centre of the spray. The velocity then decreases with the axial distance and reaches values of 30 m/s at 50 mm downstream from the nozzle. Moreover, the velocity field gets more uniform which supports the assumption of the spray-air interaction mentioned above.

From the results above it is deduced that the best possible region for comparative measurements is close to the nozzle due to the high data rate and wide range of different conditions as results of high and low concentration of the droplets inside the spray, i.e. centre of the spray and the edges respectively. It is also evident that the spray is not perfectly symmetrical. Therefore, the results from both systems can be affected by positioning error of the nozzle with respect to m.v.

3.2 Preliminary results - repeatability

A series of nine measurements were performed to get the repeatability of the velocity and size measurements in the PDA system. One radial profile was measured from -5 to +5 mm in the Y-axis direction with a step of 1 mm. 20,000 samples were collected in each measured point or the measurement was finished after five seconds to save the measurement time.

Mean measured values of basic spray properties are shown in the Table 2. below. Repeatability of each property is calculated as a deviation from the mean value. The value of repeatability in the table is a mean value calculated from the measured points in a given profile. Average repeatability of the *D10* value is 0.27 %, the *D32* is 0.58 % and for the velocity is the average repeatability equal to 0.96 %. The repeatability is assumed to be within acceptable range. Thus, further we focus on testing selected parameters of the PDA.

3.3 Sensitivity

The effect of sensitivity was investigated by changing the voltage of photomultipliers from 600 V to 1200 V but with constant laser power of 25 mW. The velocity profiles in top part of Fig. 4 show that the lowest measured sensitivities (600 V and 700 V) yield demonstrably lover values than the rest of the regimes. This behaviour is the most obvious in the centre of the spray. The outer regions tend to show opposite trend i.e. the higher velocity is achieved at lower sensitivity and vice versa. These differences are linked with different measurable particle sizes, as discussed below. In the spray centre, where a dense spray region is located, the small particles are not measured using low sensitivity, see middle part of Fig. 4. The measured large particles have no time to accelerate enough to reach the velocity of the air flow. On the spray boundary, the effect is opposite. The velocity is smaller there and also the smallest droplets are rapidly decelerated by the surrounding stationary air. Since only the large droplets are measured in the case of 600 and 700 V, the velocity is higher there compare to the other sensitivities. The regimes with sensitivity above 1000 V show a small deviation from the main trend in the data.

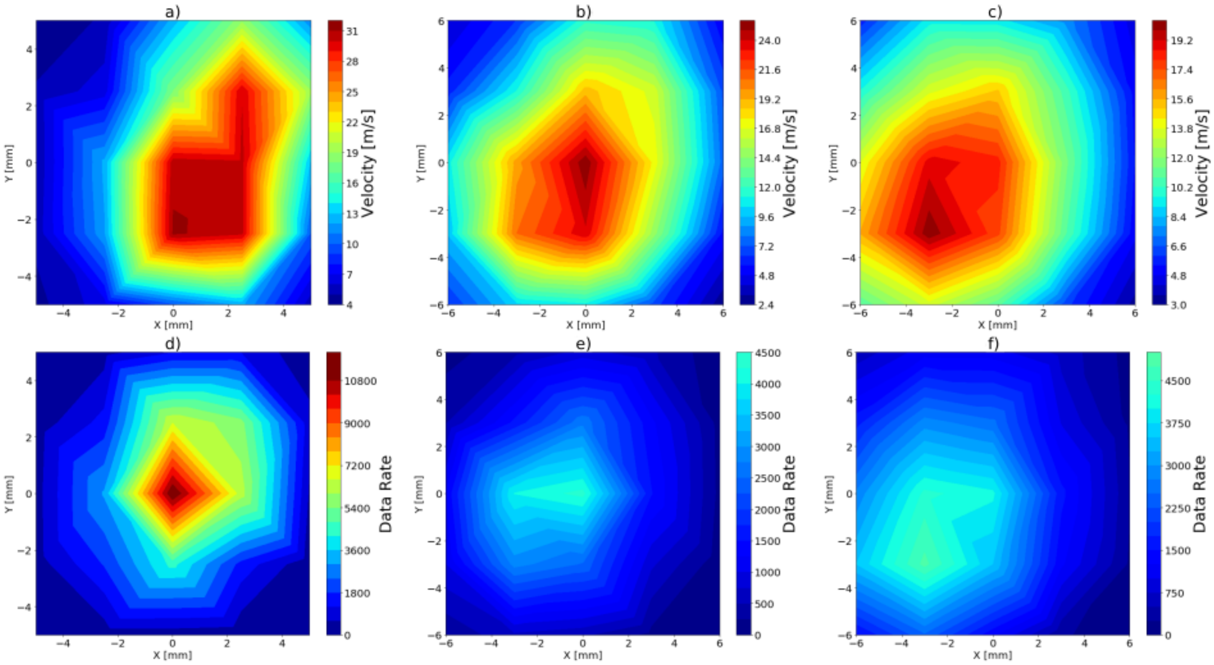

Fig. 3. Contours of the data rate in three axial distances from the nozzle: a) 10 mm, b) 20 mm, c) 30 mm. Bottom: Contours of mean axial velocity in three distances from the nozzle: a) 10 mm, b) 20 mm, c) 30 mm.

Table 2. System B, statistics made from 9 measurements.

Radial Position	***D10***	**Repeatability of *D10***	***D32***	**Repeatability deviation of *D32***	**Mean velocity**	**Repeatability of velocity**
[mm]	**[µm]**	**[%]**	**[µm]**	**[%]**	**[m/s]**	**[%]**
-5	9.25	0.23	21.4	0.66	16.40	0.69
-4	8.28	0.16	19.3	0.51	27.43	0.98
-3	7.77	0.11	18.9	0.27	43.12	0.84
-2	7.77	0.10	19.5	0.55	48.64	1.24
-1	8.16	0.15	21.9	0.54	43.29	0.91
0	8.47	0.13	23.8	0.50	34.69	0.90
1	8.73	0.20	23.9	0.70	27.82	1.29
2	9.20	0.20	24,0	0.72	22.13	1.17
3	10.33	0.30	24.9	0.59	16.35	0.82
4	11.78	0.50	27.1	0.61	13.17	0.78
5	14.00	0.91	30.2	0.75	10.83	0.98

The influence of the sensitivity on the diameter statistics is shown in the Fig. 4 below. The mean diameter, *D10,* shows a clear trend that the *D10* decreases with an increase in sensitivity. This is expected results because at low sensitivity only larger particles reflect sufficiently strong light signal which can be detected. When the sensitivity reach value of 1100 V then, even for higher sensitivities, the results are very similar. This means that for the value of 1100 V system reaches its limit for detection of the smallest droplets. Similar behaviour can be observed for the *D32* profiles, see bottom part of Fig. 4. The highest *D32* values are reached for the lowest sensitivity and vice versa. The sensitivity strongly influences the visibility of the smallest droplets.
The results seems to be relatively stable when the sensitivity reaches value of 1100 V. When comparing the systems A and B it can be seen that only the results from 600 V differs demonstrably. System A reaches values from 34.4 to 40.5 µm and the System B reaches values from 39.6 to 57.4 µm.

3.4 Laser power

The influence of the laser power was investigated changing the laser power output from 25 mW to 100 mW using constant sensitivity of 1000 V. The velocity profiles are shown in a) and b) of **Chyba! Nenalezen zdroj odkazů.**. There is only a small influence of the laser power on the velocity profiles. This means that even the lowest laser power used in this experiment seems to be sufficient for detection of the smallest droplets in the spray and further increase does not change the results. Note here, that the laser power and sensitivity should act in the same way. The lowest laser power regime investigate was found sufficient in the previous chapter and further increase in laser power should result in even stronger signal.

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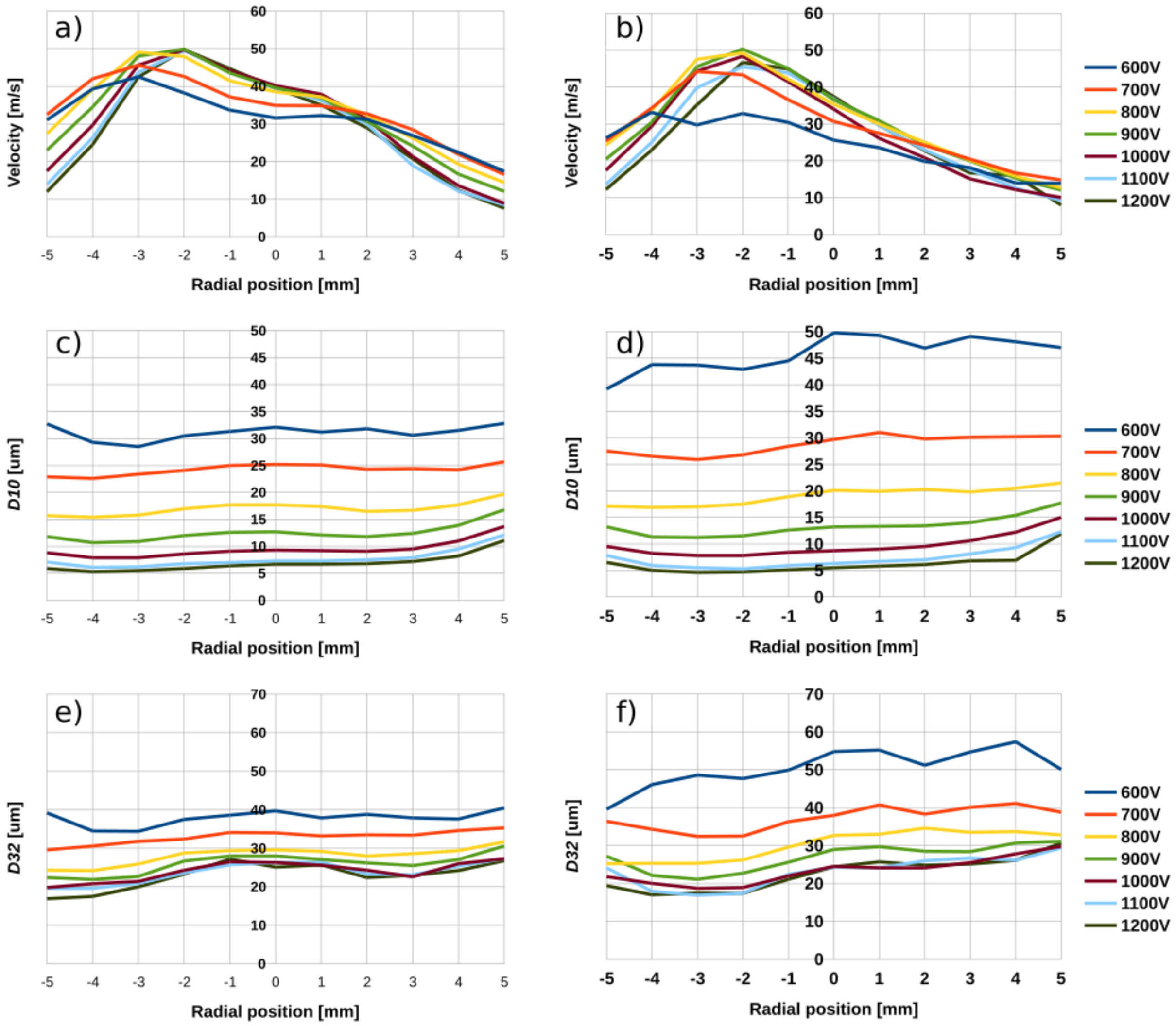

Fig. 4. Effect of the photomultiplier sensitivity: a), b) radial profiles of mean axial velocity in the axial distance of 10 mm from the nozzle, c), d) radial profiles of *D10* and e), f) radial profiles of *D32*. Left column a), c), e): system A. Right column b), d), f): system B.

A clear trend can be seen in the *D10* profiles c) and d) of Fig. 5. The value of *D10* decreases as the laser power increases for both systems. However, the *D32* profiles seems to be relatively unaffected by the laser power as shown on e) and f) of Fig. 5. There are only small variations in the *D32* profiles. Majority of the variations are within a range of 10 µm without any distinguishable trend. In contrast, the laser power has crucial influence on the *D10* profiles whereas the *D32* are relatively unaffected. This feature points on a fact that when the laser power is increased the mean diameter and also that the system is able to detect the smaller droplets. The portion of the largest droplets seems to be unaffected as illustrated by the *D32* profiles. This means that the laser power determines the mean value of diameter to which the system is focused but the number of largest particles remains relatively unchanged. This is due to the fact that the largest particles are more likely to be detected by the system than the small ones. It is also a manifestation of the effective measurement volume which is dependent on the droplet size [2].

Note here, that too strong signal oversaturate the photomultipliers and the signal is therefore rejected. This effect should tend to reduce *D32*, but it is not evident here.

The system A differs slightly in the regime of the lowest laser power (25 mW). It reaches higher values of *D10* comparing the system B. The values are in a range of 9 to 11.8 um.

3.5 Diameter statistics

For a global evaluation of results an integral value of D32 is used so called Integral Sauter mean diameter (ID32) [21]. This value is used for global evaluation of spray especially for combustion applications when analysing PDA data. It can be calculated from the following relation:

$$ID32 = \frac{\sum_{i=2}^{n}(r_i \cdot D_{30,i}^3 \cdot f_i)}{\sum_{i=2}^{n}(r_i \cdot D_{20,i}^2 \cdot f_i)}$$

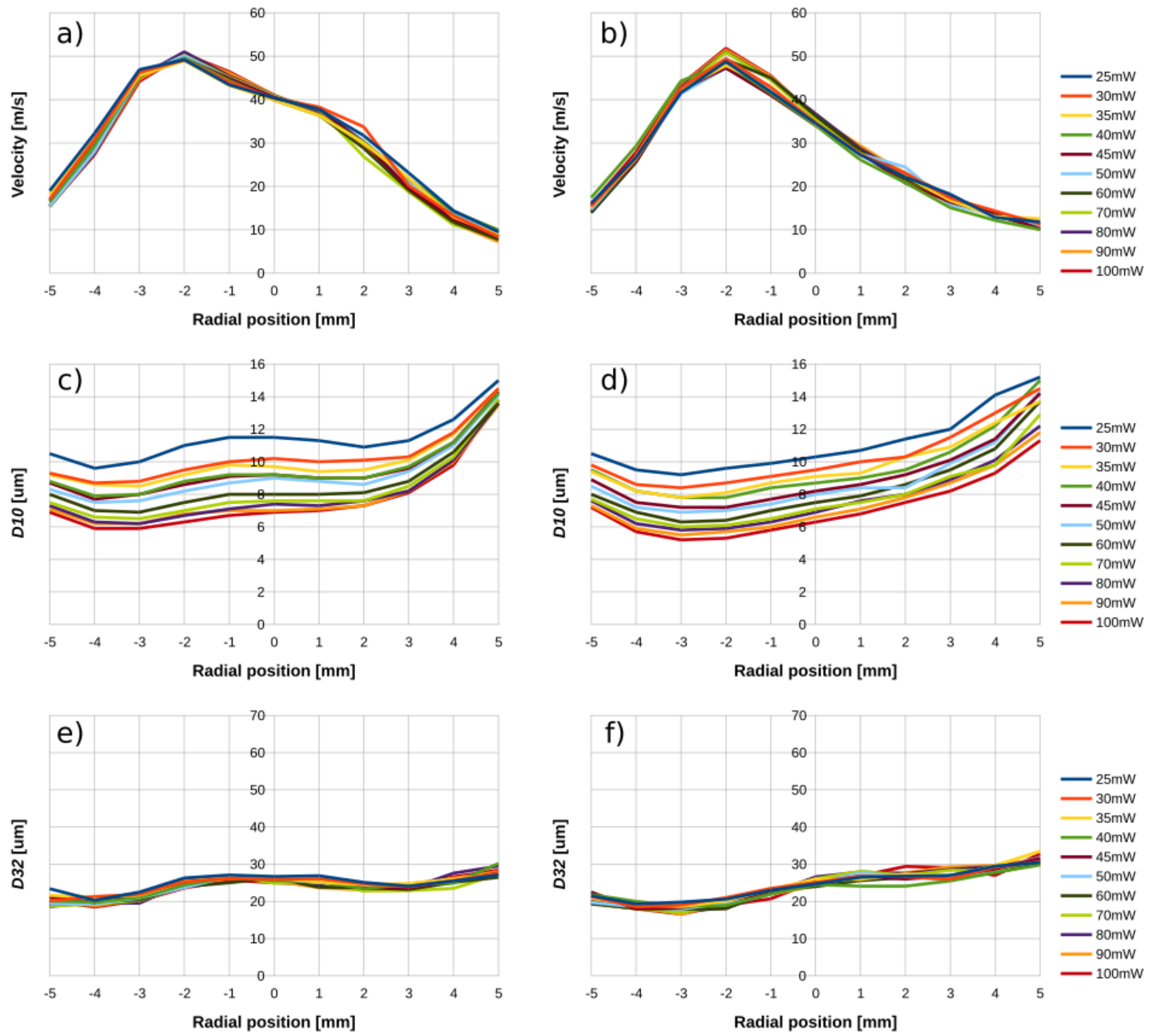

Fig. 5. Effect of laser power. From top: radial profiles of mean axial velocity in the axial distance of 10 mm from the nozzle, radial profiles of *D10* and radial profiles of *D32*. Left: system A. Right: system B.

where *r* is the radial distance from the centre of the spray, *D* is a droplet diameter and *f* is a mean data rate (number of measured droplets per second) at a given point.

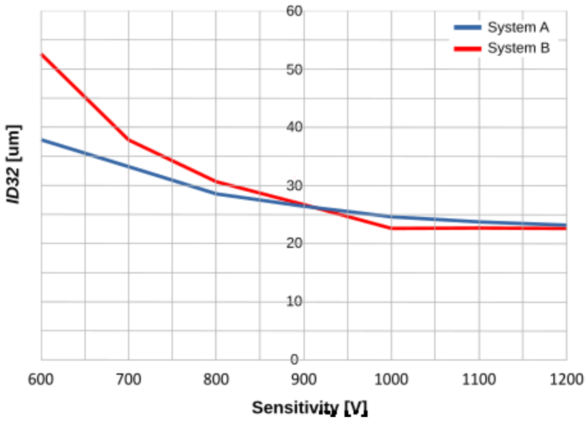

Fig. 6. Systems compared by ID32 varying sensitivity of photomultipliers.

A clear trend can be seen when comparing ID32 and sensitivity of both systems, see Fig. 6. The ID32 grows when sensitivity decreases. This corresponds to findings mentioned in the sections above. Low sensitivity means that large particles are detected and the small ones do not reflect sufficiently strong signal to be measured. Interestingly, the ID32 values are nearly the same for both systems. The largest difference in ID32 is 14.7 which corresponds to 5.8 % from the measurement range. This difference is at the lowest sensitivity, 600 V. The difference between the systems then decreases with growth of sensitivity. At the sensitivity of 800 V and higher the difference is very small, below 1 % from the measurement range. Thus, from this threshold of sensitivity the systems show nearly the same results in quantitative evaluation of droplet size.

4 Conclusion

Two similar PDA systems were compared under various laser power and photomultiplier voltage - sensitivity. The older system used Argon-Ion laser and Dantec BSA processor P80 while the newer one used a diode-pumped solid state laser and P800 processor.

The repeatability error of both system was found to be less than 1 %.

Low sensitivity setups were unable to measure the smallest droplets and therefore the droplet mean diameter, *D10*, and Sauter mean diameter, *D32*, were overestimated. This effect diminishes for sensitive higher than 1000 V. Note here, that this results is valid for 25 mW of laser beam power.

Increasing the laser power above this value generate stronger signal, but its effect on *D32* and velocity profiles is negligible. Only *D10* was affected as it decreases with increasing laser power output because stronger signal allows the smallest droplets become measurable.

When both PDA systems compared, differences are less than 5 % for sensitivities > 900 V and all the laser power investigated.

The proper PDA setup should be tailored for a given application. Higher sensitivity and laser power allows to measure very small droplets, but their effect on *D32* and velocity is usually small. If the spray contains wide distribution of droplet sizes, too high laser power may lead to oversaturation of photomultipliers and underestimation of *D32*.

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